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Construction of a global disaggregated dataset of building energy use and floor area in 2010

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ABSTRACT

This paper presents the construction of a dataset of energy use in 2010 by buildings in 10 regions spanning the entire world, broken down by sector (residential and commercial), end use (space heating, space cooling, ventilation, water heating, lighting, cooking, and miscellaneous (mostly plug) loads) and energy source (fossil fuels, district heat, biofuels, solar and geothermal heat, and electricity). Combined with estimates of the residential and commercial floor area and of population in each region, this 4-dimensional disaggregation gives an estimate of building energy intensities (kW h/m^2/yr) or per capita energy use for each end use/energy source combination in each sector and region. This dataset provides a starting point that can be used in scenarios of future building energy demand but also serves to highlight discrepancies, uncertainties, and areas where improved data collection is needed.

1. Introduction

In order to project into the future, one must first know where one is today. There is a wide variation in the residential and commercial floor area per person in different parts of the world today, and in the energy intensity (energy use per unit of floor area, typically given as kW h/m^2/yr) in different regions. With growing per capita income, both per capita floor area and building energy intensity will tend to increase, and the impact on total building energy use will be further multiplied by continuing population growth. At the same time, dramatic reductions in building energy intensity for certain end uses (heating in particular) in many countries have occurred over the past 2–3 decades, and significant further reductions are anticipated [1]. There is also the potential for switching between energy forms, such as from fossil fuels for heating to electric heat pumps, or from electric chillers to solar-driven chilling systems. The net effect of these opposing tendencies has important implications for the required investments in energy supply systems, energy security, and efforts to reduce emissions of greenhouse gases. Developing scenarios that span the range of possible future building energy demand is necessary in order to plan for future energy needs, to address energy-security concerns, and to develop policies aimed at reducing greenhouse gas emissions and other environmental impacts of building energy use.

In order to be able to construct scenarios of plausible alternative futures, a 4-dimensional matrix of energy use in buildings is here proposed, with a breakdown by region, building type (residential and commercial), end use and energy source. A full decomposition on a worldwide basis of building energy of this nature has not been published. However, partial sums – each with disaggregation in 2 or 3 of the 4 dimensions outlined above – are available and can be used to construct a fully disaggregated 4-dimensional matrix of building energy use. Because there are more unknowns than formal constraints in performing such a disaggregation, more than one solution to the disaggregation problem exists. However, qualitative knowledge concerning the relative importance of different energy sources for different end uses in various world regions, as well as national level surveys in key countries, can be used to greatly narrow the range of possibilities.

The purpose of this paper is to present the methods and results of a 4-dimensional disaggregation of global building energy use in 2010. This disaggregation is used as the starting point for a series of scenarios of future global building energy use presented in Harvey [2], but could be used by others with an interest in exploring alternative possible futures of building energy use at a regional-to-global scale. As will be seen, there are significant discrepancies between some of the datasets used here, or between the results obtained here and previously published statements of building

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energy use (or floor area) for specific energy uses in specific regions. These discrepancies serve to highlight the uncertainties inherent in any disaggregation of building energy use, and indicate areas where further data collection is needed.

2. World regions used here

For the analysis presented here, the world is divided into 10 different regions—namely, the 11 world regions used in the *Special Report on Emission Scenarios* (SRES) of the Intergovernmental Panel on Climate Change (IPCC) [3] Appendix 3, except that South Asia and Pacific Asia have been combined into one region, and South Korea has been placed here in the Pacific-Asia OECD region alongside Japan, Australia and New Zealand. The 10 regions used here, the regional population and purchasing power parity (PPP) GDP in 2010 (which are used to scale some of the energy use data), and climate data (which are also used for scaling energy use data) are given in Table 1. With the exception of placing South Korea in the Pacific OECD region, these regions also align with the five regions used in computing greenhouse gas emissions for the IPCC *Representative Concentration Pathways* (RCP) scenarios [4].[1]

3. Energy use datasets

This paper uses a mixture of partially disaggregated and fully (for our purposes) disaggregated datasets. The partially disaggregated datasets are: (1) the national estimates of building energy use by building type (residential and non-residential, referred to here as "commercial") and by energy source (fossil fuels, district heat, biofuels, solar and geothermal heat, and electricity) that are published in the annual *Energy Balances* reports of the International Energy Agency [5,6], (2) two 3-dimensional arrays of partially disaggregated estimates of energy use in 2010 that were used as the starting point for the 2012 edition of the IEA's *Energy Technology Perspectives* scenarios [7], henceforth referred to as ETP2012. The two 3-D arrays from ETP2012 are (i) global sums of energy use for each sector, end use and energy type (i.e., with no regional disaggregation), referred to as ETP2012-1, and (ii) sums over all energy types for four regions (OECD Americas, OECD Europe, OECD Pacific, and non-OECD) for each end use in each sector (i.e., with no disaggregation by energy type), referred to as ETP2012-2. These three dataset sets are presented in Tables OS.1–OS.3, respectively (where OS indicates Online Supplement).

Global totals by sector and energy source are compared in Fig. 1.[2] On a global basis, biofuels are the single largest source of energy in the residential sector, followed in decreasing order by fossil fuels, district heat and electricity. In the commercial sector, electricity is the single largest source of energy, followed by fossil fuels, district heat and biofuels. Total global energy use in the residential sector is almost three times that of the commercial sector.

For various reasons, including data confidentiality, the IEA is unable to provide the full 4-dimensional decomposition of the data used as the 2010 starting point of their scenarios. In principle, a matrix equation could (with some simplifying assumptions) be derived and used to decompose the datasets, but the resulting matrix has a singularity, so a solution is not possible. Thus, we constructed our own regional breakdown of energy use by sector, end use and energy type.

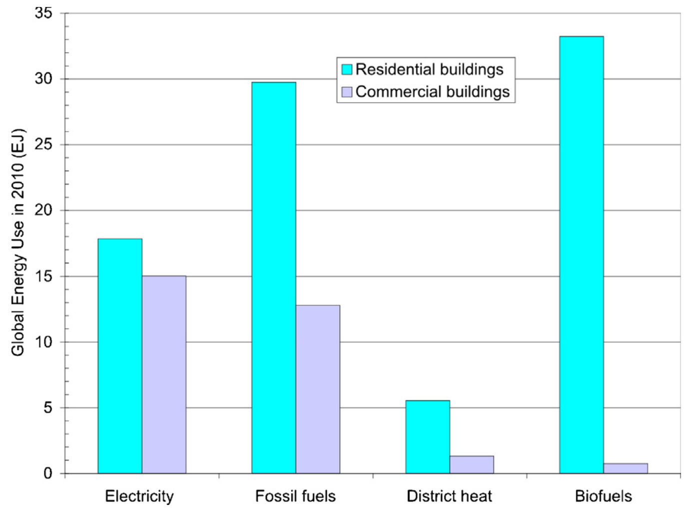

Fig. 1. Global energy use in 2010 by different fuels or electricity, for residential and commercial buildings.

We directly obtained the desired disaggregation from published estimates for PAO, NAM, WEU and EEU. The datasets used are described in the Online Supplement (including Fig. OS.1 and Table OS.4). For LAM we extrapolated data from Brazil + Mexico only (for commercial buildings) or from Brazil + Argentina + Chile + Mexico (for residential buildings), while we extrapolated estimates for China to CPA and from India to SPA. Partial data for Russia were used to create a fully disaggregated dataset, which was then extrapolated with adjustment to FSU. All these datasets were adjusted (usually slightly) so that the fuel amounts (summed over all end uses) match the fuel totals in the IEA *Energy Balances*.

Disaggregated energy datasets could not be found for any countries in the MENA and SSA regions. Total energy uses for specific end uses in each region were instead obtained by multiplying the energy use of some reference region by the ratio of some driving factor in MENA or SSA to that in the reference region. For SSA, the reference region is LAM + CPA + SPA for all end uses in both sectors. For MENA, the reference region used is FSU for space and water heating (because fuels are highly subsidized in both regions), NAM for space cooling, and LAM + CPA + SPA for all other end uses. The driving factors used are: for space heating, floor area times population-weighted mean heating degree days (HDD); for water heating, population for residential buildings and GDP for commercial buildings (times a factor of 0.6 in MENA)[3]; for space cooling, floor area times population-weighted cooling degree days (CDD) times mean gross domestic product (GDP) per person; for lighting, ventilation, and appliances: floor area times GDP/P; for cooking: population for residential buildings, floor area times GDP/P for commercial buildings. Regional mean HDD and CDD values were computed as described in Harvey [2]. The total energy use for each end use was then distributed among the various energy types in a manner thought to be reasonable but with the constraint that the total energy use (summed over all end uses) for a given type match the IEA *Energy Balances* total for that type as closely as possible. Finally, the amounts of energy by a given energy type in SSA or MENA were scaled by the same factor for all energy uses such that

[1] The correspondence between the five RCP regions and the ten regions used here is as follows: OECD90 = NAM + WEU + PAO; Reforming Countries = EEU + FSU; Asia = CPA + SPA; Middle East + Africa = MENA + SSA; and Latin America is the same for both breakdowns.

[2] The datasets used here contain separate estimates for coal, oil and natural gas (among other sources), and the region-end use decomposition developed here retains these distinctions, but to simplify the presentation, only the aggregate fossil fuel estimates are presented in Fig. 1 and subsequent figures and tables. The complete decomposition is available in electronic form as an Online Supplement.

[3] Due to its warmer climate, the amount by which source water would need to be heated to reach a temperature of 55 °C would be about only 0.6 that for FSU, the reference region used for residential water heating energy use in MENA.

Table 1
The regions used here and their population (from UNDP [23]), GDP (from IMF [13]) and average per capita GDP in 2010.

Region	Population (millions)	GDP (billion PPP 2010US$)	GDP/P (2010US$/person)	Population-weighted mean	
				HDD	CDD
PAO (Pacific Asia OECD)[4]	201	6844	33,990	2109	653
NAM (North America)	348	15,861	45,516	2573	717
WEU (Western Europe)[5]	484	14,982	30,923	2795	296
EEU (Eastern Europe)	119	1965	16,489	3336	254
FSU (Former Soviet Union)	286	3262	11,412	4414	313
LAM (Latin America)	586	6429	10,966	335	1613
SSA (Sub-Saharan Africa)	813	1815	2232	56	2180
MENA (Middle East and North Africa)[6]	424	3790	8930	637	1821
CPA (Centrally planned Asia)[7]	1484	10,791	7270	2178	931
SPA (South and Pacific Asia)[8]	2148	8866	4127	348	2430
Global	6896	74,604	10,819		

HDD and CDD are heating-degree-days and cooling-degree-days, respectively, in units of K-day and computed as described in [2].

the total energy use (summed over all end uses) for a given energy type exactly matches the IEA *Energy Balances* total.

For residential buildings, the combination of initial scalings produces total energy uses (summed over all end uses and energy types) that is 55% below the IEA *Energy Balances* total for SSA and 10% below for MENA, with 95% of the discrepancy in SSA due to too little biomass energy. There is essentially no space heating demand in SSA, so biomass energy use can arise only from the scaled water heating and cooking demand. When biomass energy use is scaled to match the IEA *Energy Balances* total, it more than doubles the per capita water heating and cooking energy use compared to the initial estimate obtained from the initial scaling. However, the very high water heating and cooking energy use in SSA (shown later) is plausible given the very low efficiency with which biomass is used.

All of the datasets used here give cooking as a separate end-use category in the residential sector. In the commercial sector, all the datasets except that for PAO have cooking as a separate category; for PAO, cooking is part of 'other' (with miscellaneous electricity uses). The amount of fuel assigned to the 'other' category is given by the total fuel requirements (from the IEA *Energy Balances*) minus the amounts assigned to space heating and hot water, but these are constrained not to exceed the total energy use (from ETP2012-1) assigned to these end uses. If we assume that the fuel components so-assigned to 'other' are solely for cooking, the deduced cooking energy intensity for the PAO commercial sector (85 kW h/m^2/yr) is many times that of any other region, and greater than the space heating energy intensity (60 kW h/m^2/yr). There is the possibility that 'other' includes energy used for on-site cogeneration of heat and electricity. To get a reasonable cooking energy intensity, we would need to assume that about 80% of fuel energy in the 'other' category is for cogeneration. Assuming a typical electricity:heat (including waste heat) ratio in cogeneration of 25:75, the implied electricity production is about 50 TW h/yr. Total electricity production by cogeneration in PAO was about 61 TW h in 2010 according to the IEA *Energy Balances*, but the majority of this would have been in the industrial sector (in Japan, the ratio of industrial:commercial cogeneration is about 1:9 [8]). Thus, cogeneration cannot account for the large fuel amounts assigned to 'other', and we cannot assign more fuel use to space and hot water heating (and less to 'other') without exceeding the space and water heating energy demand. Thus, we conclude that there is an inherent inconsistency between the space and water heating end use totals for PAO from ETP2012-2 and the fuel totals for PAO from the IEA *Energy Balances*. To obtain reasonable commercial cooking energy intensity in PAO, we assign 80% of the 'other' fuel use back to space heating. This more than doubles the space heating energy intensity, from 60 kW h/m^2/yr to 126 kW h/m^2/yr, but the latter is consistent with independent estimates (discussed later) of the average heating energy intensity of commercial buildings in Japan.

The commercial sector datasets for FSU, LAM, SSA, MENA, CPA and SPA, although having cooking as a separate category, have ventilation and miscellaneous electrical loads lumped together as 'other'. In FSU, LAM, MENA and CPA, 45% of 'other' electricity is assumed to be for ventilation and the rest miscellaneous loads, while in the very poorest regions, SSA and SPA, only 20% of 'other' is assumed to be ventilation.

One potential check on the disaggregation obtained above is to compute the average energy intensities (kW h energy use per m^2 of floor area per year, kW h/m^2/yr) for various energy uses in each of the regions, and to check that the resulting averages are consistent with published surveys of energy intensities (as distinct from estimates of aggregate national energy use) and to check that any differences between regions are reasonable. However, this requires estimates of the building floor area that are consistent with the data concerning total national or regional energy use. As discussed below, there are significant differences among various estimates of floor area in many regions.

4. Floor area

Estimates of regional residential and commercial floor areas are available from a variety of sources. Floor area estimates for 2010 are available for the four ETP2012 regions, and were distributed among the 10 regions used here on the basis of GDP.[9] Ürge-Vorsatz et al. [9] (henceforth, ÜV2012) provide estimates of floor area in 2005 for the 10 regions used here; their residential estimates have been scaled here to 2010 estimates by population while their commercial estimates have been scaled by GDP. A third set of estimates is available for commercial buildings in 2010 from McNeil et al. [10] (henceforth, M2013).[10] They estimated commercial floor areas for the EU-27 plus 14 countries that accounted for 81% of global GDP

[4] Australia, New Zealand, Japan, South Korea.

[5] Includes Turkey and Cyprus.

[6] Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, UAR, Yemen and Algeria, Egypt, Libya, Morocco, Sudan, Tunisia.

[7] China, Cambodia, Laos, Mongolia, North Korea, Vietnam.

[8] All other countries in Asia.

[9] In particular, OECD Pacific, OECD Americas and OECD Europe floor areas were scaled down to NAM, WEU and PAO (NWP) floor areas based on GDP ratios, with the excess allocated to the non-NWP region, then the total non-NWP floor area was allocated to the seven non-NWP regions in proportion to the contribution of each region to the total non-NWP GDP. This is equivalent to assuming that floor area per capita varies in direct proportion to GDP per capita but with different proportionality factors for the 3 OECD regions and for the entire non-NWP region.

[10] Floor areas used by M2013 were not published in M2013 but were kindly provided by Michael McNeil. M2013 estimated national floor areas as the product of estimates of (i) the economically-active population, (ii) the employment rate, (iii) the service sector share of employment, and (iv) floor space per employee.

and 64% of global population in 2010, including at least one country in each of the 10 regions considered here except MENA. The total floor area of the countries available in a given region was scaled to that of the total region in proportion to GDP.

Additional estimates and the manner in which they have been scaled here are as follows:

- Residential and commercial floor areas in 2010 are taken directly from the Canadian and US energy datasets given in the Online Supplement and summed to give the NAM areas.
- The total residential and commercial floor areas of WEU countries in the Odyssee dataset with floor data estimates (accounting for 73% and 44% of WEU GDP, respectively) are scaled to those of the entire WEU assuming floor area to be proportional to GDP.
- The total residential floor area of EEU countries in the Odyssee dataset with residential floor data (accounting for 74% of EEU GDP) is scaled to the entire EEU assuming floor area to be proportional to GDP, while the EEU commercial floor area is estimated assuming the EEU:WEU commercial floor area ratio to be the same as the GDP ratios (there being no commercial floor area data for EEU in the Odyssee dataset).
- Commercial floor area for MENA was estimated by developing a relationship between floor per capita and GDP per capita for the 15 estimates in M2013, and applying this to the MENA population and GDP/P (details are given later).
- Residential floor areas in 2005 for China and India are taken from Eom et al. [11] and Chaturvedi et al. [12], respectively, and scaled by population to 2010 values, then by GDP to values for CPA and SPA, respectively.
- Commercial floor areas in 2005 for China and India are also deduced from [11,12], respectively, and scaled to CPA and SPA values in 2005 based on the ratio of CPA:China and SPA:India GDPs in 2005, then further scaled to 2010 values based on the change in GDP from 2005 to 2010.

For variations over short periods of time (such as from 2005 to 2010), it is a reasonable first approximation to assume average per capita residential floor areas to be constant, because even if new buildings are substantially larger (due to rising income), the effect of only five years of new residential space on average per capita floor area will be small. However, it is reasonable to scale up spatially (i.e., from India to all of SPA) in proportion to total GDP, as this is equivalent to assuming that floor area per capita varies in proportion to GDP per capita, which is also a reasonable first approximation. Variations in the commercial sector floor area over time, however, can be expected to be more directly related to GDP than to population, although not increasing as fast as GDP due to the possibility of increased worker productivity and longer working hours as GDP increases. M2013 provide estimates of floor areas in both 2005 and 2010, and these ratios are used to scale up the ÜV2012, Eom et al. [11] and Chatuverdi et al. [12] estimates from 2005 to 2010. Using inflation-corrected GDPs for 2005 and 2010 from IMF [13], the floor area ratios in M2013 imply that commercial floor area varies with GDP^n, where n ranges from 0.43 (India) to 1.08 (Mexico), with a weighted average of 0.7.

These regional floor area estimates are shown in Online Supplement Fig. OS.2, and the corresponding per capita floor areas are shown in Fig. OS.3. With regard to residential floor areas, the ETP2012-based estimates are larger than any other estimate for most regions, especially EEU, FSU, LAM and MENA, but there is generally good agreement among the various estimates for NAM, WEU and CPA. For commercial floor area, there is almost a factor of 2 difference among the various estimates for MENA and EEU, about a factor of 2 variation for FSU, SSA and SPA, and a factor of 3 variation for CPA, but relatively good agreement for PAO, NAM, WEU and LAM.

4.1. Choice of residential floor area estimates

The resulting per capita floor areas can be used as a basis for choosing among the different floor area estimates. On this basis, the residential floor areas for EEU, FSU, LAM and MEA estimated from ETP2012 all appear to be too high. In particular, the per capita floor area deduced here from ETP2012 for EEU is about 56 m^2/person, which is larger than for WEU and more than twice as large as the 25.5 m^2/person average given by Ecoheat and Power [14] for the 10 newest EU states (which is comparable to the 26.2 m^2/person given by ÜV2012 [9] and 24.2 m^2/person estimated here from the Odyssee dataset). The ETP2012-based estimates of per capita floor area for FSU and LAM are comparable to that of WEU, and the per capita floor area for MEA is larger than that of EEU as given by any estimate except from ETP2012 itself. Recall that the ETP2012 floor areas for these regions were obtained by allocating the floor area for the single ETP2012 non-OECD region among these regions (and SSA) in proportion to regional GDP. An alternative approach is to assume that per capita floor area among EEU, FSU, LAM, SSA and MEA varies in direct proportion to per capita income (using the EEU per capita floor area from Odyssee as the reference). The resulting per capita floor areas are shown in Fig OS.3a, and seem to be more reasonable except possibly for SSA, for which the resulting per capita floor area is only 3.3 m^2, compared to 9.9 m^2 according to ÜV2012.

In light of the above, the following floor area estimates are adopted for the residential sector: ETP2012 OECD-Pacific for PAO, the national datasets for NAM, Odyssee for WEU and EEU, ÜV2012 for FSU, SSA and MEA, scaling of the EEU floor area by GDP for LAM, and the estimates based on scaling of [11,12] for CPA and SPA, respectively. The resulting per capita floor areas in WEU and EEU are 42 m^2 and 26 m^2, respectively, for an overall European average of 39 m^2. The latter compares well with the EU-27 average of 41 m^2/person that can be deduced from Bertoldi et al. [15].[11] The resulting per capita floor area in FSU is 24.4 m^2, which is close to the average for Russia of 22.4 m^2 given by Paiho et al. [16]. However, per capita floor area for Ukraine, Latvia and Estonia are estimated by [17] as 23.3, 27.0 and 29.7 m^2, respectively, which would tend to make the FSU average greater than for Russia alone. The resulting global residential floor area for 2010 is 152.0 billion m^2, which can be compared with 180.0 billion m^2 from ETP2012 and 131.3 billion m^2 if the ÜV2012 regional estimates for 2005 are scaled by population only. The largest differences from ETP2012 (or from our disaggregation of the ETP2012 non-OECD total) are for EEU and LAM (56% smaller), MENA (46% smaller) and SSA (31%) larger.

4.2. Choice of commercial floor area estimates

With the exception of PAO, NAM, WEU and EEU, there are very large differences among the various estimates of regional commercial floor area. Floor area estimates for CPA in 2010 derived from ÜV2012 and [11] are far larger than those derived from ETP2012 and M2013.

We can test the plausibility of the country-level commercial floor areas from M2013 by computing and comparing the overall building energy intensities, which can be obtained by dividing the total energy use for a given country (from the IEA *Energy Balances*) by the M2013 floor area for the corresponding country. Results are shown in Fig. 2a. As the computed average energy intensity of

[11] Bertoldi et al. [14] give an average EU-27 dwelling area of 99.2 m^2 and an average occupancy of 2.4 persons.

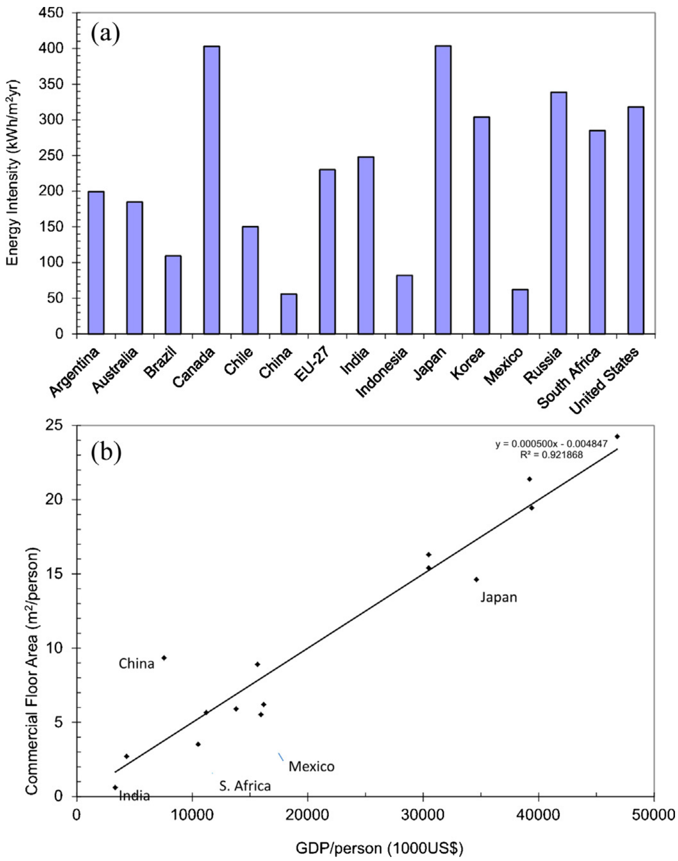

Fig. 2. (a) Energy intensity of commercial buildings computed from the total energy use in 2010 for the indicated countries (as given by the IEA *Energy Balances* report for 2010) and the floor areas in 2010 used in McNeil et al. [10]. (b) Commercial floor area per capita vs. GDP per capita for the same countries as show in (a). Identities of selected data points are given.

commercial buildings in India is about 3 times that in Indonesia (and almost 5 times that in China), and there is no reason to expect there to be a substantial difference, it would appear that the floor area for India estimated by M2013 (which is similar to that given by Chaturvedi et al. [12]) is too small, by as much as a factor of 3. The largest average commercial energy intensity according to M2013 is for Canada (about 400 kW h/m^2/yr), but this is consistent with the Canadian dataset mentioned earlier. The Japanese energy intensity is surprisingly large (403 kW h/m^2/yr, the same as for Canada and one third larger than the energy intensity of 304 kW h/m^2/yr in neighbouring South Korea), but is consistent with other estimates presented later.

As discussed later, the average commercial building energy intensity for CPA given in Fig. 2a (56 kW h/m^2/yr) appears to be too small, implying that the M2013 floor area for China is too large. One way to test the plausibility of the various floor area estimates is to plot floor area per capita vs. GDP per capita; a smoothly increasing relationship is expected. Such a plot is shown in Fig. 2b. Although there may be special circumstances that cause the data for any one country to deviate from the trend line, the deviations seen in Fig. 2b suggest that the M2013 floor areas for India and S. Africa are too small and the floor area for China is too large (as suggested from Fig. 2a).

The floor area for EEU given by ÜV2012 is about half that deduced from ETP2012-2. The ODYSSEE dataset contains estimates of national commercial floor areas for countries constituting about 40% of WEU GDP. Extrapolating the sum of these floor areas to the entire WEU region and to EEU based on GDP gives the 'Other' floor area estimates for WEU and EEU shown in Fig. OS.2b; as seen from Fig. OS.2b, the value so-obtained for WEU is comparable to other estimates, while the value for EEU closely matches that deduced (by scaling) from ETP2012 but is substantially larger than the ÜV2012 or M2013 estimates.

Estimation of commercial floor area for China is particularly difficult, and different approaches yield wildly different results. M2013 estimated a floor area in China of 9.3 billion m^2 in 2005 and 12.5 billion m^2 in 2010. If we use the M2013 estimate of Chinese floor area in 2010 and the IEA *Energy Balances* total commercial energy use in China in 2010 (2.52 EJ), the resulting mean energy intensity is 52.5 kW h/m^2/yr. Estimates of the proportions of different building types, proportions of different kinds of heating and cooling equipment, and efficiencies of this and other equipment are presented in Zhou et al. [18] and are used in Tables OS.5 and OS.6 to compute a mean energy intensity for commercial buildings in China in 2010 of 93.4 kW h/m^2/yr. Combining this with the total energy use from the IEA *Energy Balances* yields a commercial floor area of 7.47 billion m^2, which closely matches the value of 7.9 billion m^2 for 2011 adopted internally by the IEA (Peng Chen, personal communication, Oct. 2013). Other estimates of the national mean or regional energy intensity for different building types in China are summarized in Table OS.7 and suggest an even higher mean energy intensity, which would imply a yet lower building floor area.[12]

The regression equation associated with the trendline shown in Fig. 2b (after adjusting the Chinese floor area downward as described above) is used to provide an alternative estimate for the commercial floor area in MENA.[13] As seen from Fig. OS.2b, this estimate is about 50% larger than the ÜV2012-based estimate but comparable to the ETP2012-based estimate.

In light of the above, we have adopted the following regional estimates for commercial floor area: for PAO, from ETP2012 (which is almost the same as M2013); for NAM, from national datasets (which also are almost the same as M2013); for WEU and EEU, scaled from ODYSSEE (being about 10% smaller than M2013 in both cases); for MENA, from the regression equation mentioned above; for CPA, a floor area of 7.96 billion m^2 (obtained by scaling up the estimate of 7.47 billion m^2 for China based on the ratio of CPA:China GDPs)[14]; for SSA and SPA, scaled ÜV2012 estimates (chosen because they are the largest of the estimates, giving what are thought to be more reasonable energy intensities); and for FSU and LAM, from M2013. The resulting global commercial floor area is 39.2 billion m^2, which can be compared to 37.0 billion m^2 from ETP2012 and 43.2 billion m^2 scaled from M2013.

4.3. Comparison of resulting per capita floor areas

Fig. 3a presents the per capita residential and commercial floor areas adopted here. The largest per capita floor areas occur in NAM, followed by WEU and PAO. Of particular note is the relatively high per capita residential floor area for CPA, which at 28 m^2/person is slightly higher than for EEU or FSU. However, the relatively high per capita residential floor are for China (obtained from [11]) is supported by the estimates of Hu et al. [21]), who indicate mean

[12] In particular, the national average energy intensities derived here from Zhou et al. [18] and given by Zhou et al. [19] are, respectively: 72 and 80 kW h/m^2/yr for offices; 193 and 135 kW h/m^2/yr for hotels, and 165 and 95 kW h/m^2/yr for hospitals. From [18], a mean energy intensity of retail buildings of 120 kWh/m^2 yr is derived in Table OS.6, whereas Feng et al. [20] indicate energy intensities ranging from 250 to 350 kW h/m^2/yr over 11 widely-distributed cities in China (although their analysis may not be representative of the existing stock).

[13] The regression equation is: Per capita floor area (m^2/P) = 0.000518 GDP/p ($/P)−0.6497, R^2 = 0.962.

[14] This estimate is 40% smaller than the estimate obtained by scaling the M2013 estimate for China to CPA based on GDP (13.3 billion m^2) and 53% larger than the estimate (5.18 billion m^2) obtained by multiplying the ETP2012 non-OECD floor area by the ratio of CPA: non-OECD GDP.

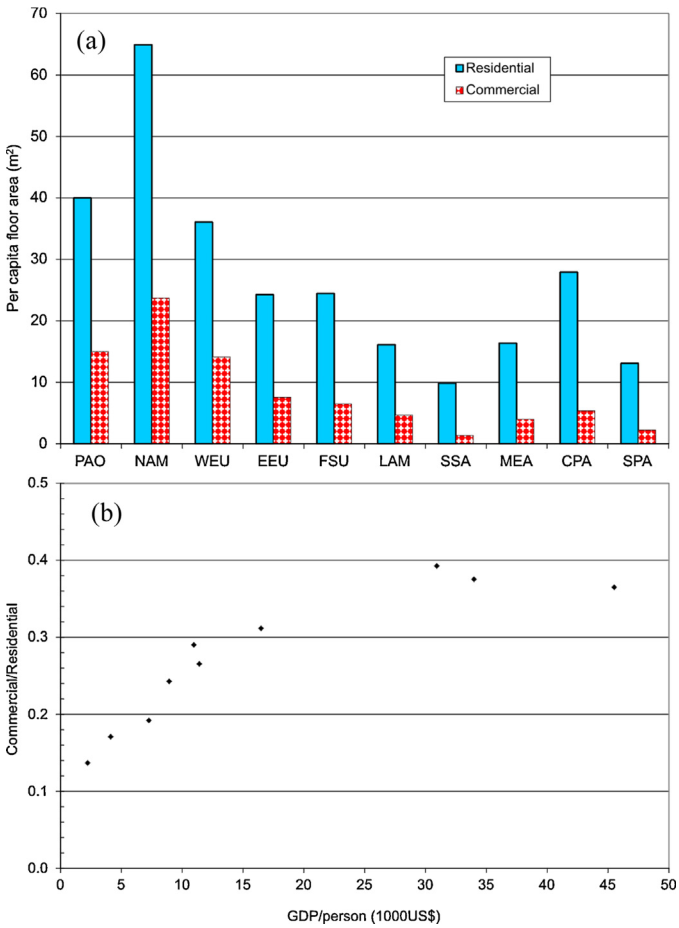

Fig. 3. (a) Per capita residential and commercial floor areas resulting from the preferred choice of total floor areas. (b) Ratio of commercial to residential floor area (using the preferred choices) vs. per capita GDP.

urban and rural residential floor areas in 2010 of 30 m^2/person and 34 m^2/person, respectively. A cross-check on the reasonableness of the floor areas adopted here is provided by plotting the ratio of commercial floor area to residential floor area versus per capita GDP. This is shown in Fig. 3b, where it is seen that this ratio is very small at low per capita income (reflecting the lack of services at low income levels), but increases smoothly to a saturation ratio of just under 0.4 for per capita incomes of $30,000 or more; there are no significant outliers in this plot (which is not the case for some other choices of floor area).

5. Energy intensity results

5.1. ETP2012 energy intensities

Prior to examining the energy intensities for each of the 10 world regions used here, it is useful to examine – as benchmarks – energy intensities computed from the original ETP2012 datasets. Fig. 4 shows the average residential and commercial building space heating, water heating, space cooling, lighting, cooking (residential sector only) and 'other' energy intensities for the four ETP2012 regions, based on the ETP2012 energy uses and floor areas for these regions.[15] The relative values in the residential

[15] As noted earlier, we have transferred 80% of the fuel portion of 'other' for commercial buildings in PAO to space heating to avoid unrealistically large cooking energy intensity.

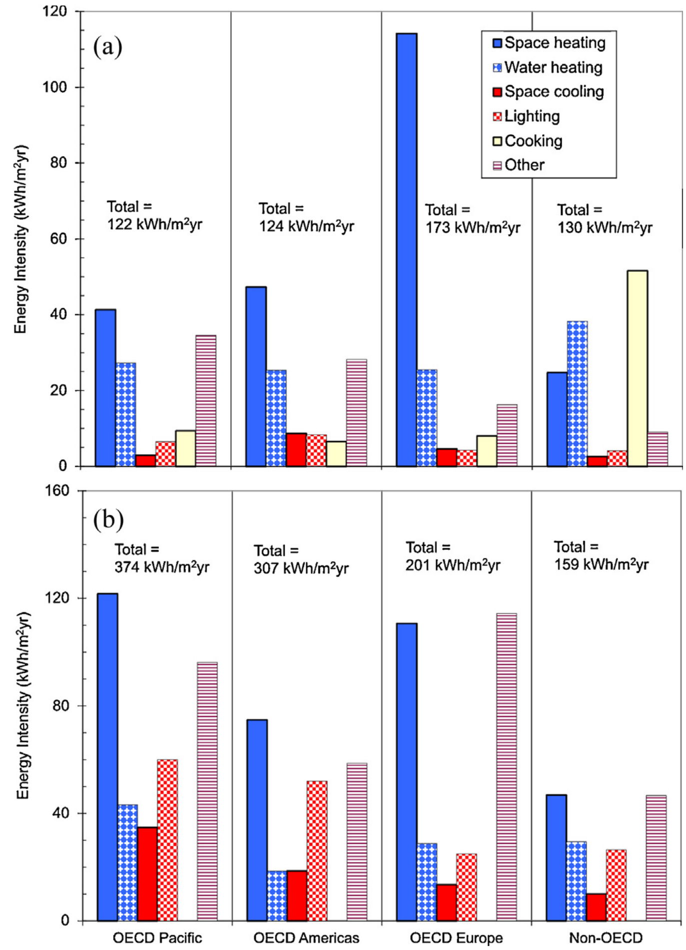

Fig. 4. Average energy intensities for space heating, water heating, space cooling, lighting, cooking and other for the four regions in the ETP2012-2 dataset, computed from the ETP2012-2 energy amounts and floor areas. (a) Residential, and (b) commercial buildings. 'Other' for commercial buildings includes cooking.

sector are reasonable in light of regional differences in climate and cultural values related to energy use or (in the case of PAO) in light of independent data (presented in Section 7). Residential cooking energy intensity for the non-OECD region is far larger than for any other ETP2012 region, and is a consequence of relatively high per capita cooking energy use (due to the use of inefficient biomass-based cookstoves) and the low per capita floor area.

The total commercial-building energy intensities for the ETP2012 OECD regions are roughly consistent with those for the corresponding countries in Fig. 2a, namely: 374 kW h/m^2/yr for OECD-Pacific vs. 347 kW h/m^2/yr for the weighted mean for Japan, Korea and Australia (which account for 98% of OECD-Pacific GDP); 307 kW h/m^2/yr for OECD-Americas vs. 318 kW h/m^2/yr for USA; and 201 kW h/m^2/yr for OECD-Europe vs. 230 kW h/m^2/yr for EU-27.

As seen from Fig. 4, the largest space heating energy intensity in the residential sector occurs in OECD-Europe, whereas in the commercial sector the largest space heating energy intensity occurs in OECD-Pacific.

5.2. Energy intensity by end use and energy type

In this subsection, we briefly discuss our full 4-dimensional decomposition of energy use; Figs. OS.4 and OS.5 give the energy intensities by end use and energy type as obtained here for the residential and commercial sectors, respectively. Also given are energy intensities by end use in 2010 from ETP2012 for the OECD-Pacific, OECD-Americas and OECD Europe regions.[16] In both the residential and commercial sectors, total energy intensities derived here for a given end use are generally close to those from ETP2012 for PAO, NAM and WEU, even though the energy intensities for NAM and WEU were derived independently of ETP2012; exceptions in the residential sector are WEU cooling (much smaller here) and NAM miscellaneous (much larger here), while exceptions in the commercial sector are PAO space heating (larger here, due to inclusion of speculative cogeneration), NAM cooling (about 80% larger here), WEU cooling (20% smaller here), and PAO and NAM miscellaneous (much smaller here). Overall, the results presented here indicate that there is substantial uncertainty in any of the disaggregated energy use estimates: probably ±10% for NAM, and −50% to +100% for the other regions.

A substantial amount of oil-product energy (probably kerosene) is used for residential lighting in CPA and SPA according to Fig. OS.4c, but none is indicated for SSA. This is because oil-product use for lighting is reported in the datasets used here for CPA and SPA, but the sum of these two exceeds the total global oil-product use for lighting as given by ETP2012-1 for 2010 by a large margin (0.87 EJ vs. 0.48 EJ). We estimated total energy use by end use in SSA through various scaling relationships, but have no direct estimate of oil-product lighting use in this region, but it is likely comparable, on a per capita basis, to that in CPA and SPA.

The energy required to produce 'domestic' hot water (that is, hot water for personal hygiene and dish and clothes washing) includes the energy required to heat supply water to the desired temperature, as well as energy losses from the heating equipment, energy required to offset standby losses (where storage water heaters are used) and distribution losses from the water heater to the hot-water outlet (if point-of-use water heaters are not used). The ratio of delivered hot water (or more precisely, the energy content of the delivered hot water relative to that of the supply water) to total energy used for heating hot water is referred to as the *energy factor* (EF), and depends on the heating equipment, the nature of the hot water system, and the water use patterns. Given estimates of the relative proportions of different energy sources for hot water, and of typical standby and delivery losses in each region, the energy content of delivered hot water can be estimated. Here, we adopt the energy factors used by ÜV2012 (Annex), namely: 0.92 for electric water heating; 0.8 for fossil fuel water heating; and 0.18 for biomass water heating in all regions except PAO, NAM and WEU (where 0.37 is used, due to the assumed use of more efficient biomass heaters than in other regions). However, we assume somewhat lower EFs in NAM (0.6 and 0.75 for fossil fuels and electricity, respectively), reflecting the greater use of storage water heaters with standby losses and greater distribution losses due to longer supply lines in the larger residences of NAM than elsewhere.

Fig. OS.6 gives the estimated per capita energy used for residential water heating in each region as estimated here and by ÜV2012, as well as the average energy factors used here (which depend on the relative amounts of different energy sources in the various regions), and the resulting energy content of delivered hot water. SSA and SPA have very low average energy factors because a large portion of hot water in these regions is produced by burning biomass. According to the estimates made here, annual per capita energy use for domestic hot water ranges from 1.1 GJ/person in LAM to 6.3 GJ/person in FSU—a variation by almost a factor of six.

[16] The former is the same as PAO, OECD Americas includes Chile and Mexico but should be close to NAM in energy intensity, and OECD-Europe should be an 86:14 weighting (based on floor areas) of the WEU and EEU energy intensities in the residential sector and an 88:12 weighting in the commercial sector.

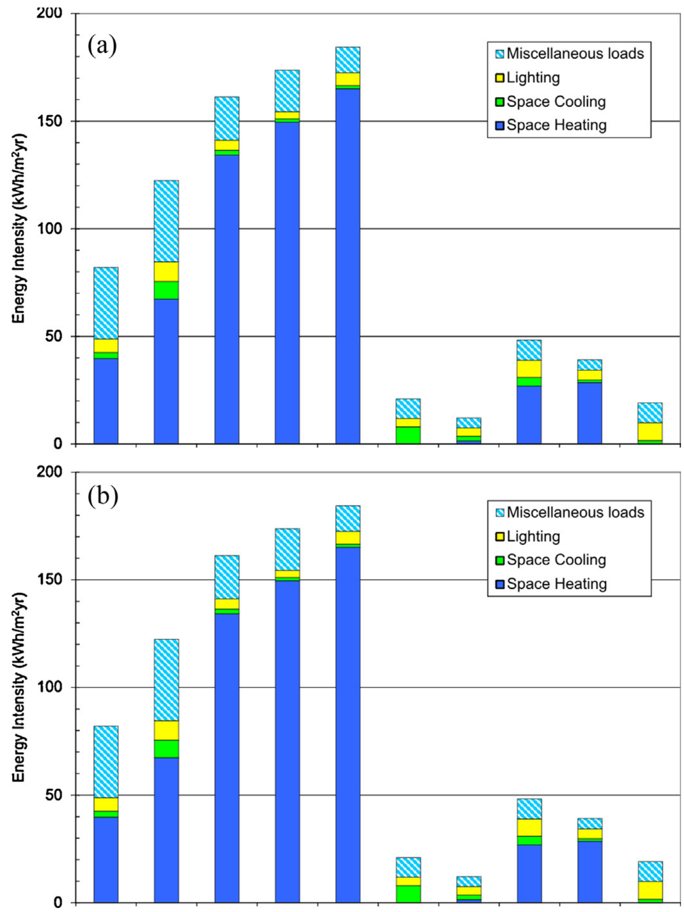

Fig. 5. Summation of regional average energy intensities for various residential building end uses in terms of (a) kW h/m^2/yr and (b) GJ/person-yr.

The largest regional difference in the per capita energy content of delivered hot water is almost a factor of 12.

5.3. Overall energy intensity

In this subsection, we sum over all energy types for each end use and stack the sums for each end use so that the total energy intensity can be directly compared between regions. Fig. 5a shows the results for the residential sector in terms of average energy intensities for various end uses, excluding hot water and cooking. It is inappropriate to present hot water and cooking energy use in terms of energy use per unit floor area; in the case of SSA, hot water and cooking energy uses are particularly large in terms of kW h/m^2/yr because of very inefficient use of biomass, yet residential floor area per person is very small, so the hot water and cooking energy intensities in terms of floor area are meaningless 110 kW h/m^2/yr and 260 kW h/m^2/yr, respectively. Hot water and cooking energy use are more directly related to population, so Fig. 5b gives average per capita energy use for hot water and cooking, as well as (for comparative purposes) the per capita energy use for residential heating and cooling, lighting and miscellaneous loads (largely appliances and consumer electronics). In the five cold regions (PAO, NAM, WEU, EEU and FSU), space heating is the dominant energy use in the residential sector (less so for PAO), while in the five hot regions, water heating is the dominant residential energy use. Cooking accounts for over half of residential energy use in LAM and SSA, and a significant fraction of the total in MEA, CPA and SPA. Hot water energy use is suspiciously small in LAM.

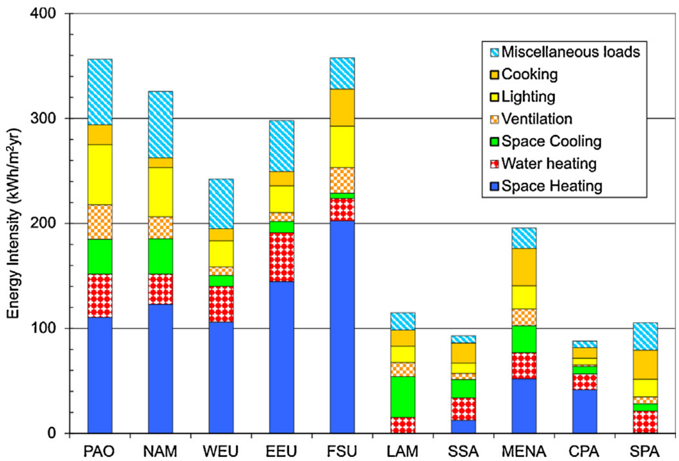

Fig. 6. Summation of regional average energy intensities for various commercial building end uses in terms of $kW\,h/m^2/yr$.

Fig. 6 summarizes the results for the commercial sector. Surprisingly, heating energy intensities in commercial buildings in PAO, NAM and FSU are modestly larger than for residential buildings, in spite of the likely smaller average surface to volume ratio for commercial buildings and the large internal heat gains in commercial buildings.[17] There is a wide variation in the hot water energy intensity between regions, with the hot water intensity for FSU being substantially (and suspiciously) smaller than in EEU or even WEU.[18] Water heating requirements are very small for office, educational and administrative buildings, but can be very large for food service, hotel, hospital and laboratory buildings (see [1]). Differences in the hot water energy intensity between regions may therefore partly reflect differences in the relative proportions of different types of commercial buildings, as well as in equipment efficiency and hot water demand within any given commercial building segment.

Fig. 6 indicates that PAO (which is dominated by Japan) and FSU have the largest overall average commercial building energy intensity of any region; in the case of FSU, this is due to a high space heating energy intensity, while for PAO it is due to uniformly high non-heating energy intensities and follows from the ETP2012-2 data given in Table OS.3. The large overall PAO energy use and also the breakdown assumed here are, however, consistent with the magnitudes of various energy intensities given by Murakami et al. [22] for representative buildings in Japan. Their data for both residential and commercial buildings are compared with results obtained here (and with M2013) in Table OS.8, and support the very large miscellaneous and ventilation energy use deduced here for commercial buildings (although the ventilation energy use for hospitals in Japan given by Table OS.8 is suspiciously low). The estimated heating energy intensity for commercial buildings in Japan ($147\,kW\,h/m^2/yr$) is comparable to that obtained here ($126\,kW\,h/m^2/yr$) after assigning 80% of 'other' fuels to space heating, and provides additional justification (in addition to the need to give a more realistic cooking energy use) for this transfer. There is excellent agreement between the residential energy intensities given in [22] and obtained here for PAO.

As noted above, commercial floor area estimates for CPA are particularly uncertain, and we have opted for an estimate lower than most. The resulting heating energy intensity in CPA ($44\,kW\,h/m^2/yr$) is about half what would be expected based on the population-weighted mean HDD for China in comparison to NAM (see [2]), but is consistent with behavioural habits in China (accepting colder temperatures during the heating season, as discussed in [2]) and would be smaller still if a larger floor area estimate had been used. The lighting and ventilation energy intensities (6.7 and $1.6\,kW\,h/m^2/yr$), while still very low compared to other regions, are more plausible than if any of the larger 2010 floor area estimates for China, reviewed earlier, were adopted here.

The overall energy intensities given in Figs. 5 and 6 for both residential and commercial buildings in MENA are small compared to the energy intensities of modern buildings (with air conditioning and mechanical ventilation) in this region, but appear to be consistent with the energy intensity of traditional buildings. Table OS.9 indicates energy intensities of $270–300\,kW\,h/m^2/yr$ in the United Arab Emirates (UAE) and $300–350\,kW\,h/m^2/yr$ in Saudi Arabia for contemporary residential buildings, compared to a MENA average here of $182\,kW\,h/m^2/yr$ (including hot water and cooking energy use, $74\,kW\,h/m^2/yr$ without these two uses), and $55\,kW\,h/m^2/yr$ for traditional housing in UAE. In contemporary housing in SA and UAE, the vast majority ($\sim$50% or more) of energy use is for space cooling. In contrast, Liu et al. [23] Fig. A2.2 indicate that only 7% of residential electricity use in Egypt in 2002 was for air conditioning. Consistent with this, the per capita residential energy use in Egypt in 2010 was about 7 times less than that for UAE (i.e., about 630 kW h vs. 4100 kW h). This in turn could explain the factor of two differences in the overall energy intensity of residential buildings in MENA and that of contemporary buildings in the UAE and Saudi Arabia.

5.4. *Relative energy use by end use and by energy source*

We conclude by highlighting summary information, given in Online Figs. OS.7 and OS.8, on the relative breakdown of global energy use by energy source for different end uses, and on the relative contribution of different end uses to total energy use in cold and hot regions as a whole. Fig. OS.7 gives the relative contribution of different energy sources, on a global basis, to those end uses that are not provided solely by electricity. As shown in Fig. 1, biomass is the single most important energy source in the residential sector; as seen from Fig. OS.7a, it supplies 20% of space heating, 50% of water heating, and 70% of cooking energy needs on a global basis. Interestingly, about 25% of lighting energy use is in the form of oil products, although the fraction of illumination supplied from oil products is only a few percent due to the extremely low efficacy of lighting with liquid fuels. In the commercial sector, fossil fuels account for 65–85% of space and water heating and cooking energy use, and 5% of cooling energy use (through absorption chillers) on a global basis.

Finally, Fig. OS.8 gives the relative importance of different end uses to total building energy demand on a global basis. Space cooling energy use is a larger fraction of total residential building energy use in cold (PAO + NAM + WEU + EEU + FSU) than in hot regions (LAM + SSA + MENA + CPA + SPA), even though the cooling proportion in cold regions is diluted by the substantial space heating requirements in these regions. In the commercial sector, space cooling is relatively more important in hot regions than in cold regions.

6. Concluding comments

This paper has presented the first, freely-available 4-dimensional decomposition of global building energy use. Energy use is estimated for 2010 for 10 regions, 2 sectors (residential and

[17] The internal heat gain would be the portions of the lighting and miscellaneous energy uses that occur during the heating season, as well as part of the heating-season water heating, ventilation and cooking energy use. People in buildings also supply heat, at a rate of about 75 W/person.

[18] This may reflect a smaller proportion of commercial buildings (such as restaurants) with large hot water requirements.

commercial), 7 end-uses (space heating and cooling, ventilation, hot water, lighting, cooking, and miscellaneous electrical uses) and 7 energy types (coal, oil, natural gas, district heat, biofuels, solar + geothermal energy, and electricity). This is a matrix of energy use with 980 entries, although 380 of these are of necessity zero and another 40–50 entries happen to be zero, so there are about 550 non-zero entries in the matrix (about 27–28 per sector per region).

There are major uncertainties concerning the breakdown of energy use, in particular outside PAO, NAM, WEU and EEU. There are also large uncertainties concerning building floor areas outside these regions, although our choice of floor area estimates yields a relatively smooth relationship between the commercial/residential floor area ratio and GDP per capita. Even if total building energy use is thought to be relatively accurate, the substantial uncertainty in floor area translates into substantial uncertainty in the present-day energy intensity (kW h/m^2/yr) and thus in the potential for energy intensity to increase with increasing income (for a given set of technology assumptions). A smaller estimate of present day floor area implies that energy intensity is relatively high, which in turn implies a greater potential for increasing efficiency to offset the impact of increasing provision of energy services. This in turn implies a smaller increase (or even a decrease) in energy intensity in the future. At the same time, a smaller estimate of present-day floor area implies a greater potential for per capita floor area to increase in the future with increasing per capita income. These two uncertainties cancel out to some extent.

This dataset can be used as a starting point for relatively detailed, global scale scenarios of future building energy use, where one may wish to calculate the effect of specific changes in the energy intensity of new or renovated buildings for specific end uses, and the effect of varying degrees of switching between energy sources. To this end, the full decomposition of building energy use is available as an Excel spreadsheet in the online supplement. A scenario application of this decomposition can be found in Harvey [2].

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enbuild.2014.03.011.

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Online Supplement

1. Partly disaggregated datasets

Table OS.1. Energy use (EJ) in 2010 from IEA [1, 2].

Region	Energy Type					
	Fossil Fuels	District Heat	Bio-Fuels	Solar and Geothermal	Electricity	Total
Residential Buildings						
PAO	1.65	0.07	0.07	0.03	1.58	3.40
NAM	6.21	0.00	0.52	0.06	5.74	12.53
WEU	7.00	0.56	1.36	0.16	3.06	12.14
EEU	1.05	0.38	0.44	0.01	0.44	2.30
FSU	3.45	2.73	0.19	0.00	0.77	7.14
LAM	1.37	1.12	0.39	0.00	1.10	3.99
SSA	0.27	0.00	10.50	0.00	0.31	11.07
MENA	2.80	0.00	0.29	0.05	1.41	4.55
CPA	3.97	0.69	8.46	0.08	1.89	15.09
SPA	2.00	0.00	11.01	0.00	1.55	14.57
TOTAL	29.76	5.55	33.24	0.39	17.85	86.79
Commercial Buildings						
PAO	1.81	0.03	0.02	0.01	2.00	3.88
NAM	4.22	0.06	0.09	0.00	5.31	9.68
WEU	2.62	0.33	0.07	0.02	2.96	6.00
EEU	0.43	0.09	0.03	0.00	0.40	0.97
FSU	0.82	0.74	0.05	0.00	0.77	2.39
LAM	0.26	0.00	0.03	0.00	0.84	1.14
SSA	0.12	0.00	0.09	0.00	0.16	0.37
MENA	0.35	0.00	0.06	0.00	0.79	1.19
CPA	1.62	0.06	0.00	0.04	0.79	2.52
SPA	0.54	0.00	0.30	0.00	0.99	1.83
TOTAL	12.79	1.32	0.74	0.08	15.01	29.96

Table OS.2. Global energy use (EJ) in 2010 by building sector, end use and energy type used in IEA [3]. This dataset is referred to as ETP2012-1.

Sector	Energy Type					
	Fossil fuels	District Heat	Biomass	Solar and Geothermal	Electricity	Total
Space Heating						
Residential	15.52	3.00	6.18	0.11	1.20	26.00
Commercial	5.80	1.04	0.21	0.07	2.64	9.76
Water Heating						
Residential	7.78	1.35	11.40	0.13	1.35	22.01
Commercial	2.05	0.21	0.17	0.03	1.22	3.69
Space Cooling and Ventilation						
Residential	0.00				2.51	2.51
Commercial	0.31				1.68	2.00
Lighting						
Residential	0.48				2.73	3.21
Commercial	0.00				4.69	4.69
Cooking						
Residential	5.94	0.17	16.78	0.02	0.87	23.78
Other						
Residential					9.23	9.23
Commercial	4.78		0.16	0.02	4.66	9.62
All Uses						
Residential	29.73	4.51	34.36	0.26	17.88	86.74
Commercial	12.94	1.25	0.55	0.13	14.89	29.75
Totals from IEA Energy Balances *for comparison*						
Residential	29.76	5.55	33.24	0.39	17.85	86.79
Commercial	12.79	1.32	0.74	0.08	15.01	29.96

Table OS.3. Energy use (EJ) in 2010 by building sector, end use and region used in IEA [3]. This dataset is referred to as ETP2012-2.

Sector	Region				
	OECD Americas[1]	OECD Europe[2]	OECD Pacific	Non-OECD	Total
			Space Heating		
Residential	5.14	9.04	1.20	10.63	26.00
Commercial	4.05	2.33	0.67	2.71	9.76
			Water Heating		
Residential	2.75	2.02	0.79	16.45	22.01
Commercial	0.62	0.90	0.47	1.70	3.69
			Space Cooling and Ventilation		
Residential	0.94	0.36	0.08	1.11	2.51
Commercial	0.62	0.42	0.38	0.58	2.00
			Lighting		
Residential	0.91	0.34	0.19	1.78	3.21
Commercial	1.73	0.78	0.65	1.53	4.69
			Cooking		
Residential	0.71	0.63	0.27	22.16	23.78
			Other		
Residential	3.06	1.29	1.00	3.88	9.23
Commercial	3.20	1.83	1.90	2.70	9.62
			All Uses		
Residential	13.50	13.68	3.54	56.02	86.74
Commercial	10.21	6.26	4.07	9.21	29.75

2. Disaggregated datasets

The regional datasets used here are described.

For NAM: Energy use by end-use and energy type (oil, natural gas, biomass, steam and electricity) for the residential and commercial sectors in Canada in 2010 was taken from NRCan [4, 5]; energy use by end use and energy type (fuels, electricity) for the US residential sector in 2009 was taken from the 2009 *Residential Energy Consumption Survey* (RECS) [6] and applied to 2010, whereas commercial sector energy use by end-use and energy type (fuels, on-site renewable energy and electricity) projected to 2010 was taken from [7]. As the US RECS data do not have separate totals for lighting and cooking, data projected to 2010 in the *Buildings Databook* [8] were used for these end uses. The Canadian commercial sector data do not have cooking as a separate category, so the US commercial cooking estimates for 2010 times a factor of 0.1 were applied to Canada (and subtracted from the NRCan 'Other' category). The US and Canadian estimates were then added to give the NAM end use-energy type breakdown. The final NAM totals over all end uses for a given energy type were then adjusted by the same factor (for each type) such that the totals by energy type match the IEA *Energy Balances* totals. The unadjusted and adjusted totals are compared in **Table OS.4.**

[1] Canada, Chile, Mexico and USA
[2] Western Europe + Czech Republic, Hungary, Poland, Slovak Republic and Slovenia

Table OS.4. Comparison of unadjusted data from national datasets (ND) and IEA *Energy Balances* data [1,2]								
	Energy Type							
	Coal	Oil	Natural Gas	District Heat	Bio-mass	Solar+ Geothermal	Elec-tricity	Total
North America								
Residential - ND	0.00	1.23	5.24	0.00	0.56	0.00	6.03	13.07
Residential - IEA	0.00	1.01	5.20	0.00	0.52	0.06	5.74	12.53
Commercial - ND	0.01	0.51	3.57	0.00	0.15	0.02	5.29	9.54
Commercial - IEA	0.06	0.75	3.40	0.06	0.09	0.00	5.31	9.68
Western Europe								
Residential - ND	0.14	1.91	4.50	0.63	1.26	0.00	2.78	11.22
Residential - IEA	0.39	1.92	4.68	0.54	1.34	0.16	3.06	12.10
Commercial - ND	0.01	0.61	1.95	0.41	0.09		2.30	5.37
Commercial - IEA	0.02	0.84	1.76	0.33	0.07	0.02	2.95	5.98
Eastern Europe								
Residential - ND	0.36	0.05	0.53	0.36	0.41	0.00	0.39	2.11
Residential - IEA	0.36	0.09	0.60	0.38	0.44	0.01	0.44	2.30
Commercial - ND	0.05	0.06	0.30	0.09	0.08		0.36	0.94
Commercial - IEA	0.06	0.07	0.31	0.09	0.03	0.00	0.40	0.97

For Western and Eastern Europe: We have made use of a combination of data from the ODYSSEE dataset [9], Bertoldi et al. [10] and the ETP2012-2 dataset. ODYSSEE provides estimates of energy use by sector, energy type and some end uses for each country in the EU-27 plus Switzerland and Norway for 2010, although data are missing for 2-6 countries for most end-use energy type combinations. Missing data were estimated here from neighboring countries or groups of countries that had data, with the energy use in the countries with and without data assumed to be proportional to GDP. Bertoldi et al. [10] provide total electricity use for residential and commercial buildings in each EU-27 country, but they provide an end use breakdown only at the aggregate western and eastern European levels. In the residential sector, ODYSSEE provides separate energy use estimates for space heating, water heating, cooking, cooling+ventilation, lighting, and 'other' end uses. The WEU and EEU sums of the electricity estimates for these end uses (including countries where energy use was estimated) generally differ substantially from the sums given by Bertoldi et al. [10], as illustrated in **Figure OS.1.** The Bertoldi estimates rely on the ODYSSEE database but are supplemented with additional information. Thus, for end uses where [10] provide electricity use estimates, these are used in place of the ODYSSEE-based estimates.

In the commercial sector, ODYSSEE gives only total energy use (by energy source) and energy use for space heating, but there are such large gaps in the space heating data that we have adopted the following approach instead: coal, oil, district heat and biomass energy uses from the IEA *Energy Balances* for both WEU and EEU are partitioned solely between space and water heating based on the overall space:water heating ratio given in ETP2012-2 for OECD-Europe; ODYSSEE natural gas use is partitioned between space heating, water heating and cooking in the same proportions as in NAM (for lack of a better alternative); and Bertoldi space+water heating electricity use is partitioned into space heating and water heating based on the ETP2012-2 overall ratio of space to water heating energy use. Bertoldi electricity use estimates are directly used for ventilation+cooling, lighting, and 'other' uses.

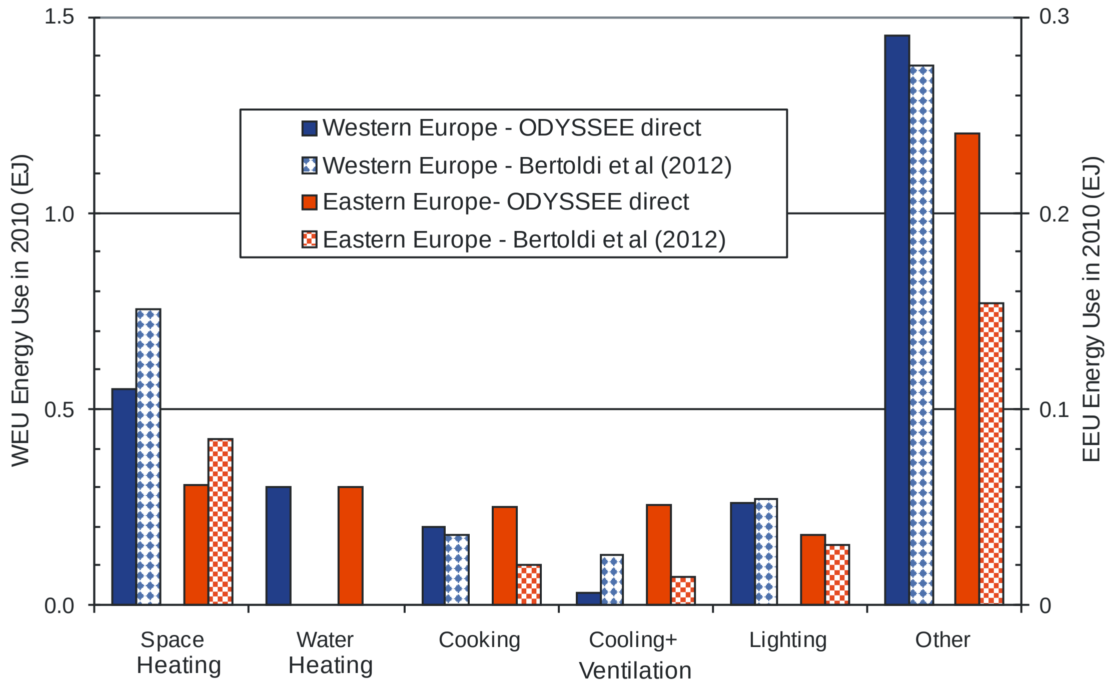

Figure OS.1. Comparison of energy use in 2010 in Western Europe (left scale) and Eastern Europe (right scale) residential buildings as obtained from the ODYSSEE dataset [13] and as given by Bertoldi et al. [10].

As with NAM, the final energy uses were adjusted such that totals over all end uses for each energy type match the IEA *Energy Balances* totals; the unadjusted and adjusted totals are compared in **Table OS.4.**

For PAO: The ODYSSEE dataset provides estimates of residential energy use in 2008 in Australia, Japan, New Zealand and South Korea (which together make up PAO) for the same energy types and end uses as for European countries. The PAO sums over all end uses for each energy type are very close to the IEA *Energy Balances* sums for 2010, while at the same time the sums over all energy types for each end use very closely match the ETP2012-2 sums for 2010. With very slight adjustments to the ODYSSEE data, it is possible to exactly and simultaneously match 11 out of 13 possible sums, with a deviation of no more than 0.003 EJ for the remaining two sums. For the commercial sector, the ODYSSEE data are inadequate. Thus, we rely on the ETP2012-2 energy totals by end use for OECD-Pacific, and distribute the energy use for space and water heating and cooking (where more than one energy type can be used) based on our judgment and the need to match the PAO totals (from the IEA *Energy Balances*) for each energy type as closely as possible. This requires assigning most of the space and water heating energy use (taken from ETP2012-2 for the OECD-Pacific region) to oil and natural gas, and assigning just over 25% of OECD-Pacific ‘Other’ to oil and natural gas each and 44% to electricity.

For FSU, Residential: Lychuk et al. [11] provide a breakdown of total energy use in the residential sector of Russia according to end use (space heating, water heating, cooking, lighting and other). We have peeled off space cooling from ‘other’ as a separate category using data for 2010 in [12]. This relative breakdown is applied to the total residential energy use in Russia for 2010 as given in the IEA *Energy Balances*. Expert judgment is used to distribute the end use totals among the different energy types for those end uses that are not supplied solely by electricity. This is done in such a way that the sums over all end uses for each energy type match the IEA totals for the corresponding energy type. The energy totals for the non-Russian part of the FSU (as given by the IEA *Energy Balances*, and accounting for 35% of total FSU residential energy use) for each energy type are initially distributed among the various end uses in the same proportion as for Russia, then adjusted based on expert judgment to take into account, at least qualitatively, the known differences between Russia and other parts of the FSU. The Russian and non-Russian energy amounts are added to give the FSU energy amounts.

For FSU, Commercial: Evans et al. [13] provide estimates of the absolute energy use (heating, hot water, cooking, lighting and appliances) by end use and energy type for public-sector buildings in Russia in 2005. There is an inconsistency with the IEA *Energy Balances* for 2005, in that the natural gas use for public sector buildings given by [13] (0.478 EJ) is greater than the natural gas use for the entire commercial building sector (0.179 EJ) as given by the IEA. The other energy amounts are only slightly less in [13] than in the IEA *Energy Balances*. Nevertheless, lacking any other source of data, we have applied the relative breakdown among different end uses from [13] for each energy type to the FSU commercial sector energy totals for 2010 from the IEA *Energy Balances*. We have assumed that ‘appliances’ include space cooling equipment, and so have peeled off Stricker’s [12] estimate of commercial air conditioning use in Russia (but scaled to the FSU) from the FSU ‘appliances’ total.

For LAM: Energy consumption data by end use (water heating, space cooling, ventilation, lighting, and cooking in the residential and commercial sectors, along with appliances in the residential sector and ‘other’ uses in the commercial sector) for 2004 for oil, natural gas, biofuels and electricity were taken from [14] for residential and commercial buildings in Brazil. Commercial energy use by end use for Mexico was taken from [15] and split among energy types in a way thought to be plausible and such that the totals over all end uses for each energy type match the IEA *Energy Balances* totals for Mexico. The Brazilian proportions among the different end uses for each energy type were applied to the IEA *Energy Balances* 2010 totals for the rest of LAM. Similarly, data from [16, 17] for residential buildings in Argentina, from [18] for Chile and from [19] for residential buildings in Mexico were applied to the IEA totals by energy type in 2010 for Argentina, Chile and Mexico, respectively. As an indication of the uncertainty in the end use breakdown, and hence of the potential errors, we note that there are large disagreements in the relative proportions of residential electricity use in Mexico assigned to different end uses by [19] and by [20].[3] In any case, the overall proportions for this group of countries are then applied to the IEA *Energy Balances* totals for LAM (Argentina, Brazil, Chile and Mexico collectively accounted for 62% of total LAM residential energy use in 2010, while Brazil plus Mexico accounted for 51% of LAM commercial energy use).

For China (applied to CPA): Energy use by end use and energy type for commercial buildings and residential buildings is based on Eom et al. [21]. The Eom estimates are based on local expert judgment and various local estimates of the relative breakdown of each energy source among the various end uses, with the absolute energy uses obtained by multiplying the relative energy use fractions by the total for each energy type as given in the IEA *Energy Balances* report. Here, the relative distributions among different end uses for a given energy type are applied to the 2010 *Energy Balances* totals for each energy type summed over all the countries making up the CPA group (China accounted for 99.1% and 99.6% of overall CPA residential and commercial energy use, respectively, in 2010).

[3] In particular, RG and L assign the following percentages of electricity use: 0% and 37%, respectively, to cooking; 0% and 17% and to water heating; 31% and 7% to lighting; 12% and 7% to air conditioning; and 58% and 33% to appliances.

For India (applied to SPA): Energy use by end use for each energy type for commercial and residential buildings is taken from Chaturvedi et al. [22]. Energy use, for all end uses for a given energy type, is multiplied by the ratio of energy use for that energy type in SPA as given by the IEA *Energy Balances* to that in India as given by [22] (India accounted for 50% and 36% of overall SPA residential and commercial sector energy use, respectively, in 2010). In this way, the energy uses for each energy type are scaled up so as to make the total energy use for a given type match the IEA *Energy Balances* total.

3. Estimates of absolute and per capita building floor area

Figure OS.2 compares estimates of absolute floor area from various sources, while Fig. OS/3 gives the corresponding per capita floor areas.

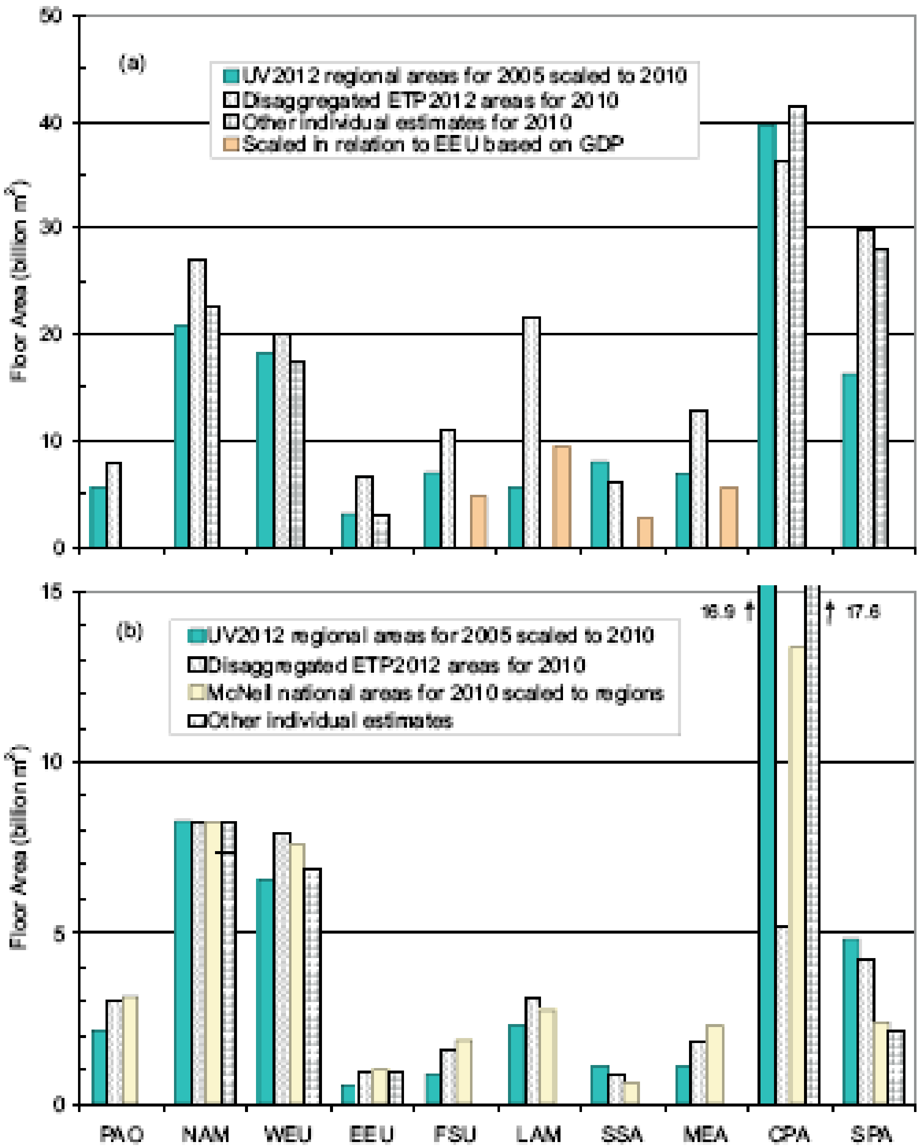

Figure OS.2. Residential (a) and commercial (b) building floor areas as given by different sources (described in the main text).

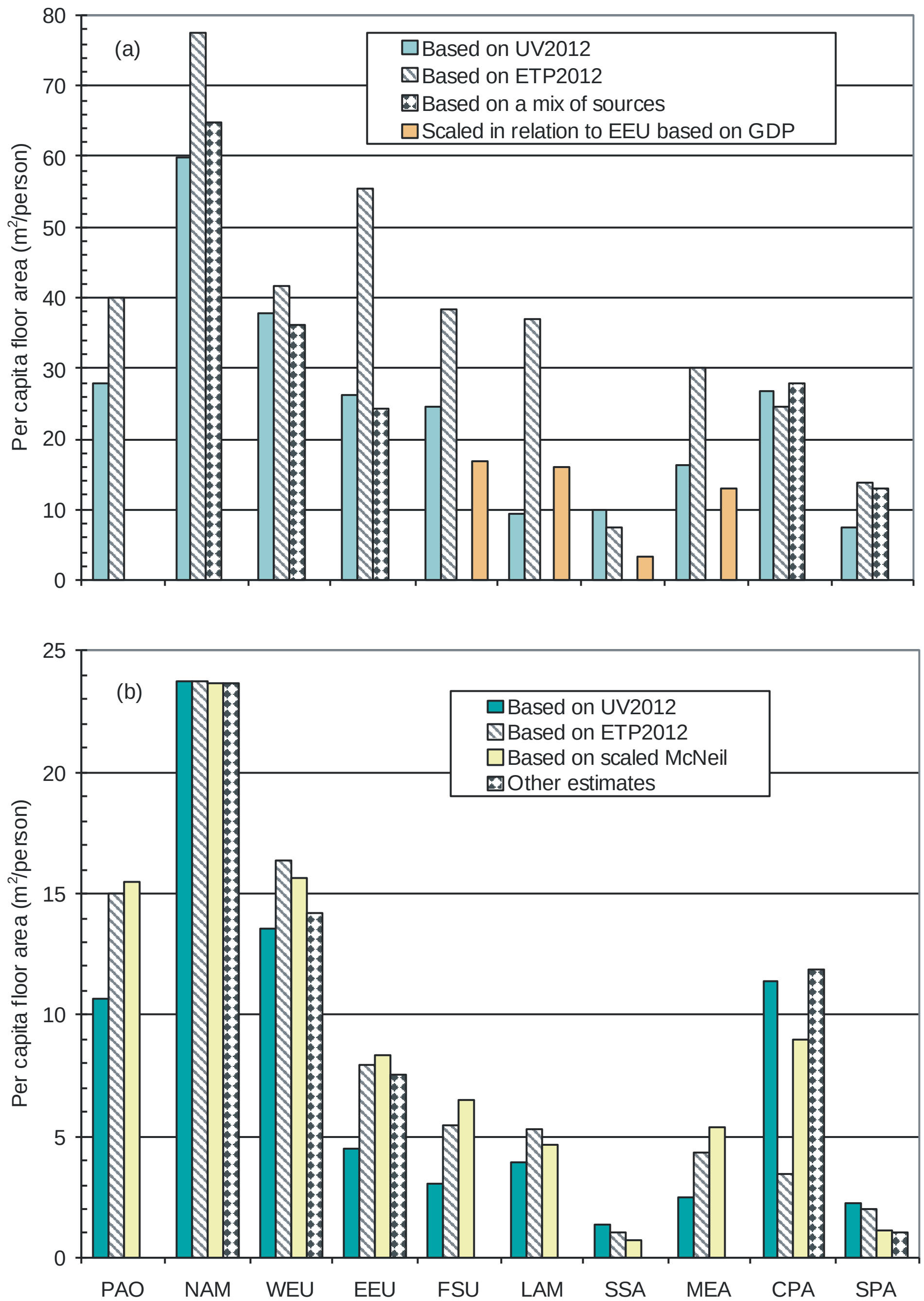

Figure OS.3. Residential (a) and commercial (b) building per capita floor areas based on the floor areas given in Fig. OS.2.

4. Derivation of mean commercial building energy intensity in China

Tables OS.5 and **OS.6** compile the data presented in Zhou et al. [23] that can be used to estimate the mean energy intensity of commercial buildings in China, and present the resulting estimate.

Table OS.5. Estimates of the proportions of different kinds of heating and cooling equipment in commercial buildings in China, the corresponding average efficiencies (or related parameter) and the weighted mean efficiency (or related parameter). All data are from Zhou et al. [23], except for the proportions of different kinds of equipment used for water heating, which are guesses. AC=air conditioner, GSHP=ground source heat pump, NG=natural gas, COP=coefficient of performance, PF=performance factor.

Space Heating			Space Cooling			Water Heating		
	Pro-portion	Effi-ciency		Pro-portion	COP		Pro-portion	PF
District heat	0.28	0.75	Central AC	0.64	1.91	Boiler	0.60	0.63
Boiler	0.59	0.63	Room AC	0.32	2.63	Gas Boiler	0.10	0.81
Gas Boiler	0.03	0.81	GSHP	0.01	3.15	Cogen	0.10	0.69
Small cogen	0.10	0.69	NG AC	0.03	1.26	Elect	0.10	0.94
Mean		0.68	Mean		2.13	Oil	0.10	0.81
						Mean		0.70

Table OS.6. Data from Zhou et al [23] used to compute the mean energy intensity of commercial buildings in China, and the resulting computed mean energy intensity.

	Building Type						**Mean**
	Office	Retail	Hospital	School	Hotel	Other	
Floor area fraction	0.33	0.14	0.04	0.17	0.14	0.18	
Penetrations (Table 8)							
Heating	0.35	0.35	0.35	0.35	0.35	0.35	
Cooling	0.20	0.31	0.20	0.07	0.31	0.20	
Lighting and other appl.	1.00	1.00	1.00	1.00	1.00	1.00	
Water Heating	1.00	1.00	1.00	1.00	1.00	1.00	
Useful Energy Intensity (kWh/m^{2}yr) (pp76-77)							
Heating	73.2	61.7	66.5	58.2	80.8	66.5	
Cooling	45.0	92.0	54.9	32.0	74.6	45.0	
Lighting and other appl.	26.8	47.2	30.0	7.7	44.7	26.8	
Water Heating	1.9	19.2	66.9	1.9	66.9	1.9	
Mean Equipment Efficiencies (from Table OS.5)							
Heating	0.68	0.68	0.68	0.68	0.68	0.68	
Cooling	2.13	2.13	2.13	2.13	2.13	2.13	
Lighting and other appl.	1.00	1.00	1.00	1.00	1.00	1.00	
Water Heating	0.70	0.70	0.70	0.70	0.70	0.70	
On-site-energy intensity (kWh/m^{2}yr) (calculated from the above)							
Heating	108.4	91.4	98.5	86.2	119.7	98.5	35.6
Cooling	21.1	43.1	25.7	15.0	35.0	21.1	5.9
Lighting and other appl.	26.8	47.2	30.0	7.7	44.7	26.8	29.0
Water Heating	2.7	27.3	95.2	2.7	95.2	2.7	22.8
Total	71.7	119.9	164.8	41.6	192.6	68.2	93.3

5. Other estimates of building energy intensity

Table OS.7 presents various estimates of the average energy intensity of different kinds of commercial buildings in China or in southern China. Table OS.8 compares estimates of national average energy intensity with Japan with that in PAO, while Table OS.9 presents case study estimates of energy intensity of residential buildings in Saudi Arabia, Bahrain and the United Arab Emirates

Table OS.7. Recent estimates of the average overall energy intensity of commercial buildings in China.		
Description	**Result**	**Reference**
Bottom-up estimate of mean energy intensity in 2005 based on data in the indicated reference	82.5 kWh/m^2yr	[23]
Bottom-up estimate of mean energy intensity in 2010 based on data in the indicated reference	93.4 kWh/m^2yr	[23]
First national estimate of mean energy intensity for Offices and government buildings Hospitals Hotels Supermarkets Department stores	 80 kWh/m^2yr 95 kWh/m^2yr 135 kWh/m^2yr 155 kWh/m^2yr 220 kWh/m^2yr	 [24]
Retail stores in 11 widely-distributed Chinese cities	250-350 kWh/m^2yr	[25]
Shopping mall in Guangzhou	201 kWh/m^2yr total 90 HVAC 30 lighting	[26]
Survey results from 6 cities in southern China: Government buildings Offices Hotels	 66 kWh/m^2yr 95 kWh/m^2yr 146 kWh/m^2yr	 [27]

Table OS.8. Comparison of energy intensities **(**kWh/m^2yr) for different end uses in Japanese buildings as given by Murakami et al. [28], as obtained here, as given by ETP2012-2 for the OECD-Pacific region (which is dominated by Japan), and as calculated from M2013 for commercial buildings in Japan. Commercial data in [28] were originally given in terms of primary energy intensity, but are converted to approximate on-site energy intensities here by dividing by an assumed conversion factor of 1.1 for heating+cooling and 3.0 for ventilation, lighting+plug and other. Hot water is assumed to be largely supplied by fuels, so no adjustment is made here.

Residential						
	Heating	Cooling	Hot Water	Lighting+ Plug	Cooking	Total
Murakami	36	3	42	36	9	126
Here (PAO)	40	2	26	40	9	117
ETP2012 (PAO)	41	3	27	41	9	122
Commercial						
	Heating+ Cooling	Ventilation	Hot Water	Lighting+ Plug	Other	
Office	109	46	13	59	25	251
Hospital	180	12	322	37	37	587
Hotel	170	71	270	39	27	577
Dept Store	117	55	75	80	36	362
Here (PAO)	143	33	41	97	19	357
ETP2012 (PAO)						374
M2013 (Japan)						403

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Table OS.9. Reported energy intensity of buildings in Saudi Arabia (SA), the United Arab Emirates (UAE) and Bahrain. ADC=Abu Dhabi City (Emirate of Abu Dhabi), AAC=Al-Ain City (Emirate of Abu Dhabi), WWR = window:wall ratio.

Building type	**Location**	**Energy Intensity** (kWh/m^{2}yr)	**Reference**
Multi-story residence	Jeddah, SA	350	[29]
1991 villa (no insulation, WWR=0.115)	UAE	334 cooling energy	[30]
2011 villa (same as above but with insulation as required in 2011)	UAE	210 cooling energy	[30]
Traditional residential average	UAE	55	[31]
Contemporary residential average	UAE	268	
Multi-unit residential (two cases studies, 2 and 3 stories, WWR=0.11)	UAE	150-180 cooling 15 heating 25-30 fans 62-64 lighting 270-306 total	[32]
Multi-unit residential, north rooms south rooms	UAE	120 cooling 150 cooling	[33]
Various residential building forms	ADC & AAC	50-65 cooling	[34, Fig. 5]
Average residential	AAC	170 cooling 265 total	[34, Fig. 7]
Educational building	Rabigh City, SA	266 total	[35]
Five shopping malls	SA	250-275	[36]
2-story office, WWR=0.19, 18-23°C indoor temperature, 13-25 W/m^2 LPD, 3-11 W/m^2 EPD	SA	268	[37]
Six office buildings	Bahrain	65-460 HVAC 100-805 total	[38]
12-story office building, WWR=0.8 on north and south facades, single glazing	Bahrain	446 cooling, 69 heating 120 fans, 22 pumps 55 lighting, 163 equip 878 total	[39]
Office building	Bahrain	315-410, range represents 4 years of measured total	[40]
Office buildings	Kuwait	300-600	[41]

6. Detailed results

Figures OS.4 and **OS.5** give a detailed breakdown of the estimated building energy sue by end use, energy type and region for the residential and commercial sectors, respectively. **Figure OS.6** gives estimates of per capita energy use for residential service hot water (SHW), regional energy factors by energy source, and the estimated per capita delivery of hot water.

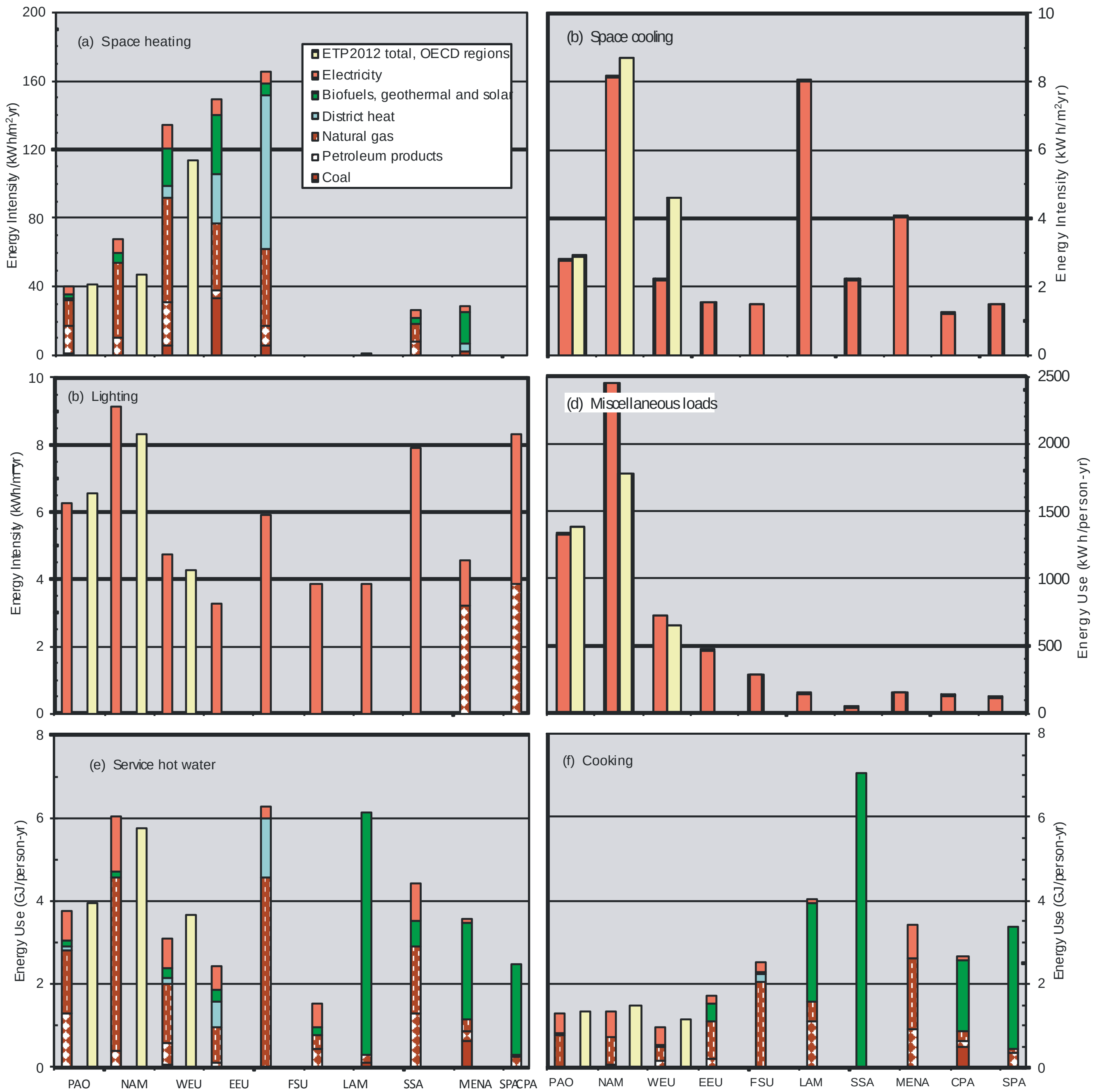

Figure OS.4. Residential energy intensities (kWh/m^{2}yr) or per capita energy use for different end uses, further broken down by energy type, in each of the 10 regions. (a) space heating, (b) space cooling, (c) lighting, (d) miscellaneous (plug) loads, (e) service hot water, and (f) cooking.

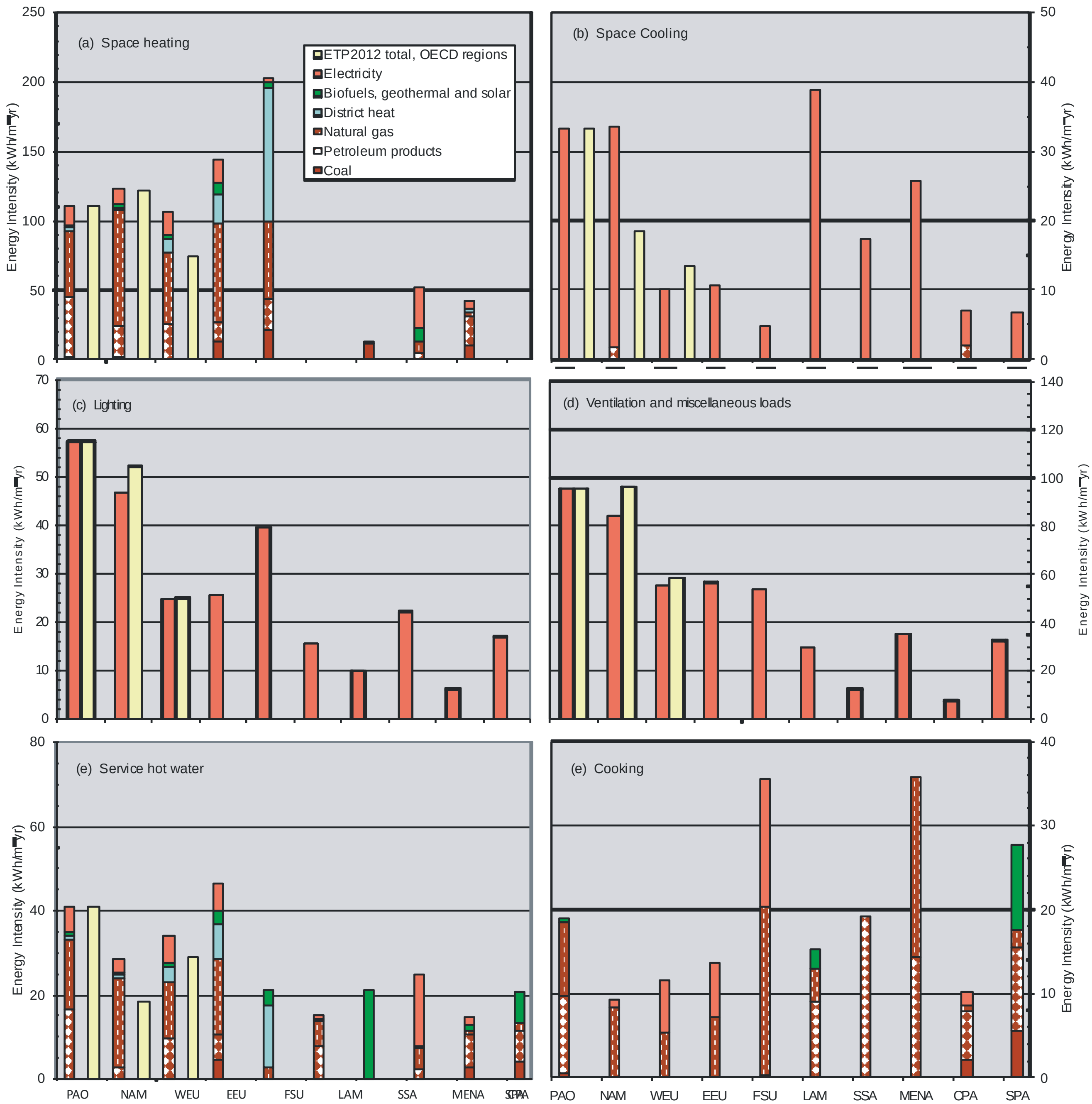

Figure OS.5. Same as Fig. OS.4, except for commercial buildings.

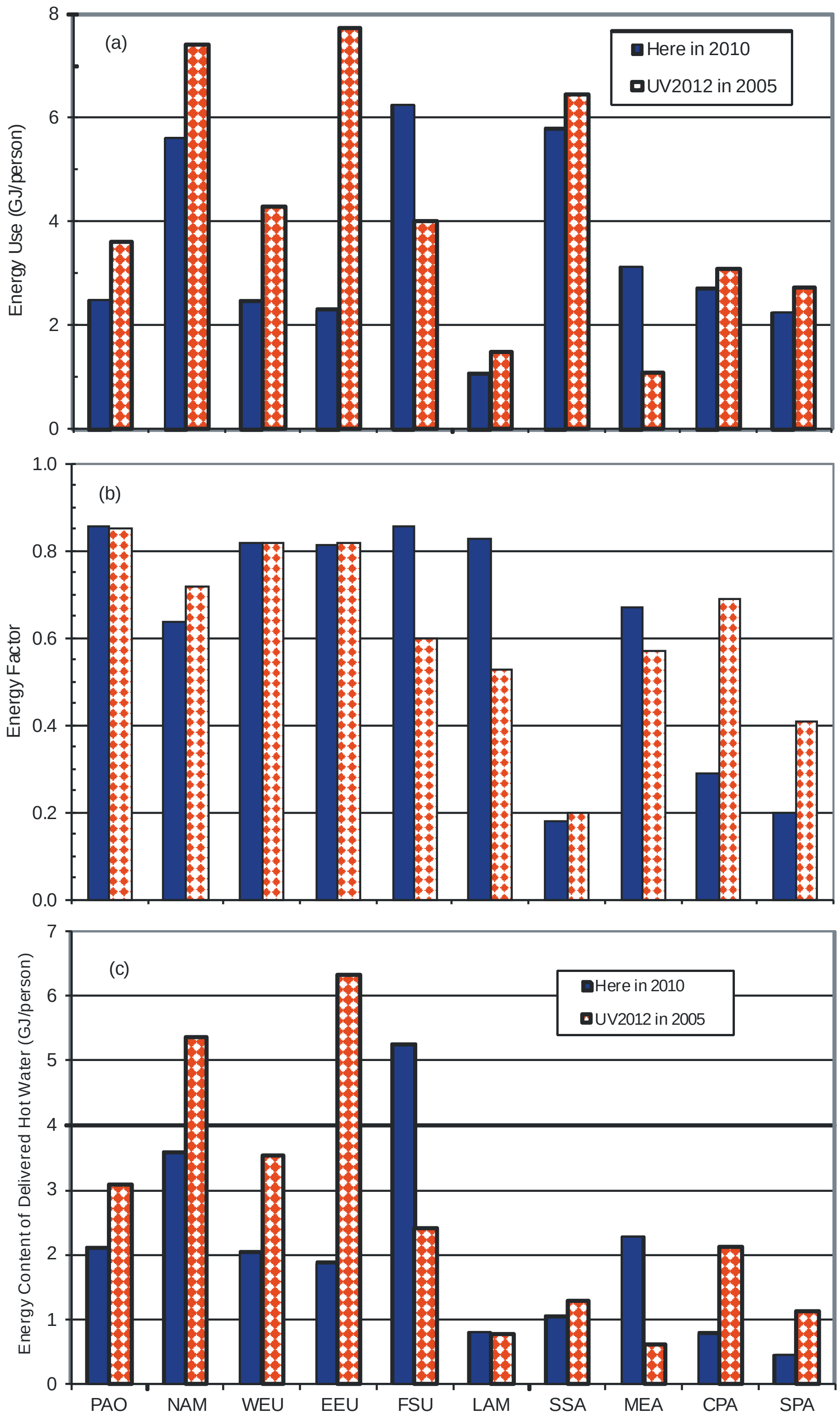

Figure OS.6. Average per capita energy use in producing residential SHW as estimated here and by UV2012. (b) Regional average energy factors used here and in UV2012 to convert energy use for SHW to the energy content delivered hot water. (c) Average per capita energy content of delivered residential hot water.

7. Overall proportions

Figures OS.7 and **OS.8** give the global proportions of various end uses supplied by various types of energy, and proportions of various types of energy summed of all end uses, respectively.

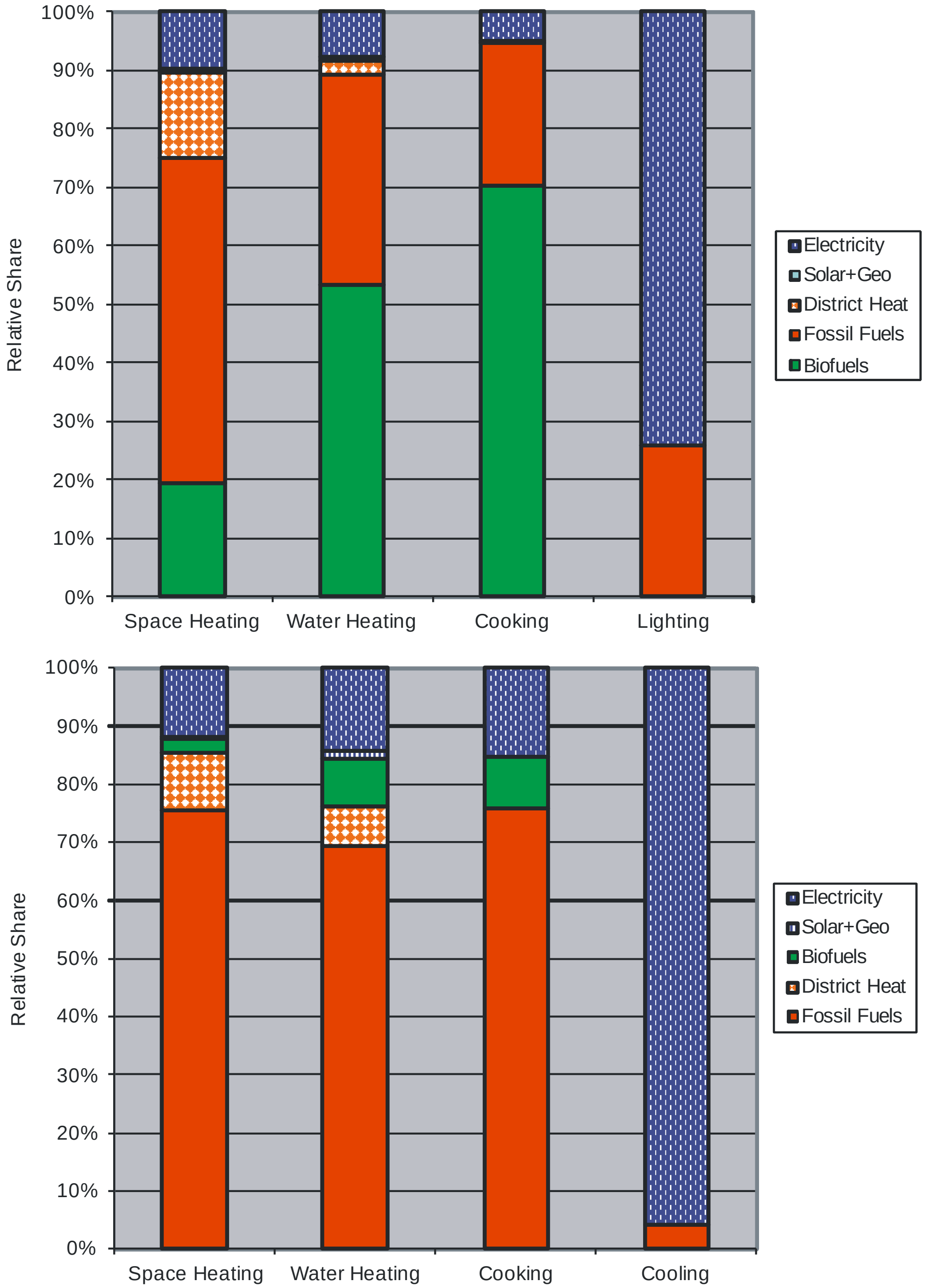

Figure OS.7. Global proportions of various end uses that are supplied by various types of energy. (a) residential buildings, and (b) commercial buildings.

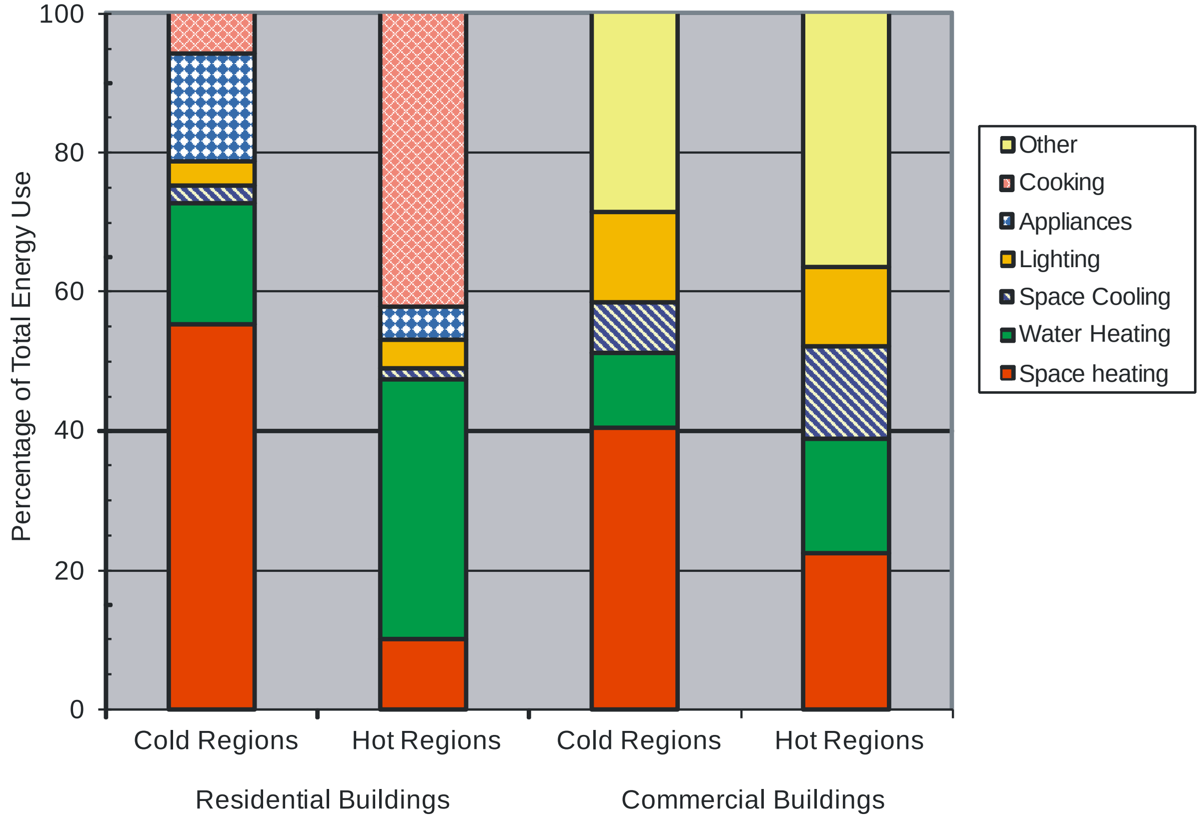

Figure OS.8. Proportions of total energy use by different end uses, for residential and commercial buildings in cold (PAO+NAM+WEU+EEU+FSU) and hot (LAM+SSA+MENA+CPA+SPA) regions.

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