The evolution and future perspectives of energy intensity in the global building sector 1971–2060

Zhong, X.; Hu, M.; Deetman, S.P.; Dias Rodrigues, J.F.; Lin, H.; Tukker, A.; Behrens, P.A.

Journal of Cleaner Production 305 (2021) 127098

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

The evolution and future perspectives of energy intensity in the global building sector 1971–2060

Xiaoyang Zhong [a, *], Mingming Hu [a, b], Sebastiaan Deetman [a, c], João F.D. Rodrigues [a], Hai-Xiang Lin [a, d], Arnold Tukker [a, e], Paul Behrens [a, f]

[a] *Institute of Environmental Sciences (CML), Leiden University, 2333, CC, Leiden, the Netherlands*
[b] *School of Management Science and Real Estate, Chongqing University, Chongqing. 40045, China*
[c] *Copernicus Institute for Sustainable Development, Utrecht University, 3584, CB, Utrecht, the Netherlands*
[d] *Delft Institute of Applied Mathematics, Delft University of Technology, 2628, CD, Delft, the Netherlands*
[e] *Netherlands Organization for Applied Scientific Research TNO, 2595, DA, The Hague, Netherlands*
[f] *Leiden University College the Hague, Leiden University, 2595, DG, The Hague, the Netherlands*

A R T I C L E I N F O

Article history:
Received 9 November 2020
Received in revised form
6 April 2021
Accepted 9 April 2021
Available online 13 April 2021

Handling editor: M.T. Moreira.

Keywords:
Energy intensity
Global building sector
Integrated assessment model
LMDI
Decoupling
Scenario analysis

A B S T R A C T

Energy efficiency plays an essential role in energy conservation and emissions mitigation efforts in the building sector. This is especially important considering that the global building stock is expected to rapidly expand in the years to come. In this study, a global-scale modeling framework is developed to analyze the evolution of building energy intensity per floor area during 1971–2014, its relationship with economic development, and its future role in energy savings across 21 world regions by 2060. Results show that, for residential buildings, while most high-income and upper-middle-income regions see decreasing energy intensities and strong decoupling from economic development, the potential for further efficiency improvement is limited in the absence of significant socioeconomic and technological shifts. Lower-middle-income regions, often overlooked in analyses, will see large potential future residential energy savings from energy intensity reductions. Harnessing this potential will include, among other policies, stricter building efficiency standards in new construction. For the commercial sector, during 1971–2014, the energy intensity was reduced by 50% in high-income regions but increased by 193% and 44% in upper-middle and lower-middle-income regions, respectively. Given the large energy intensity reduction potential and rapid floor area growth, commercial buildings are increasingly important for energy saving in the future.

1. Introduction

Global development has long been associated with increasing resource and energy consumption (Schandl et al., 2018). Socioeconomic development raises living standards and has directly contributed to the increase in building energy consumption. In addition, the majority of people today spend almost 90% of their time indoors (Cao et al., 2016). These factors combine to make the building sector one of the largest energy consumers in the world (Cao et al., 2016) and comprise one-third of energy-related greenhouse gas emissions (International Energy Agency, 2018). Recent research noted that the expected emissions from existing and proposed infrastructures are probably inconsistent with the goal to keep global warming this century below 2 °C above pre-industrial levels, let alone the more ambitious 1.5 °C limit (Tong et al., 2019). As such, a rapid and deep transition towards efficient and sustainable building stocks plays a key role in attaining the 2050 climate targets (Svetozarevic et al., 2019).

An important variable in this dynamic is the global building floor area which continues to increase at an annual average rate of around 2.3%, driven by a growing population and increasing floor area per person (International Energy Agency, 2017). The fastest growth will be seen in lower-middle-income regions (especially in Asia and Africa) which are not yet fully covered by compulsory energy codes (Abergel et al., 2017). As a result, significant growth can be expected in building energy consumption, especially in

* Corresponding author.
E-mail addresses: x.zhong@cml.leidenuniv.nl (X. Zhong), hu@cml.leidenuniv.nl (M. Hu), deetman@cml.leidenuniv.nl (S. Deetman), j.f.dias.rodrigues@cml.leidenuniv.nl (J.F.D. Rodrigues), h.x.lin@cml.leidenuniv.nl (H.-X. Lin), tukker@cml.leidenuniv.nl (A. Tukker), p.a.behrens@luc.leidenuniv.nl (P. Behrens).

https://doi.org/10.1016/j.jclepro.2021.127098

rapidly developing regions such as India (Chaturvedi et al., 2014) and China (Zhou et al., 2018). Research using different methodologies and scenarios expect global building energy consumption to increase by 31%–95% between 2005 and 2050 (Levesque et al., 2018). Therefore, against the growing stock demand, energy efficiency improvement plays an increasingly important role in energy saving and emissions mitigation in the long run (Berardi, 2017).

Energy efficiency can be defined from either macroeconomic or physical perspectives (Ang et al., 2010). Energy-to-GDP is easy to compute but does not offer a good sectoral resolution. Energy consumption per unit of floor area is preferable since it is more relevant for understanding the driving forces of energy requirements in the building sector (Ang and Goh, 2018). As such, much of the literature uses energy consumption per unit of floor area as the proxy of building energy efficiency on the macro level (Gao et al., 2019). For example, Sandberg et al. (2016) investigated historical trends and driving factors of energy intensity per square meter in Norway's residential stocks since 1960, confirming the effect of large-scale efficiency improvement on energy savings. To understand how efficiency shapes building energy use, Huo et al. (2019) estimated China's building floor area and analyzed the evolution of residential energy intensity per square meter in urban China, which was observed to be much lower than in some high-income nations. However, due to different conceptual frameworks, these nation-specific studies are difficult to compare, and more importantly, such research mainly focuses on regions in China or Europe, leaving most lower-middle-income but rapidly growing regions unanalyzed. Moreover, energy intensity in non-residential buildings is rarely discussed on a regional or global level due to data limitations (Serrano et al., 2017). This has limited the understanding of how building energy intensity evolves with the economic development across regions and energy saving potentials may lie.

To address these research gaps, this study presents a novel integration of IEA's building energy databases (see Methods) with data from an integrated assessment model (IAM). Specifically, the IMAGE model (Stehfest et al., 2014), one of the most widely used IAMs, is selected for its global coverage, regional resolution, and broad time range. Under a series of scenarios, IMAGE provides consistent datasets required for multiregional building stock modeling such as the long-term socioeconomic parameters, urbanization rate, floor area per capita for 26 global regions (Stehfest et al., 2014). These data are combined to build a global-scale building energy intensity modeling framework that enables analyses of time series evolution, decoupling status, and decomposition under different scenarios. Note that, in this study, energy intensity is given by the regional average building energy consumption per square meter (see methods for detailed building types and energy end-users). This study brings in a historical perspective of energy intensity transformation, investigate whether building energy intensity has decoupled from economic development across different regions, and how large potential efficiency-driven energy savings may be to 2060.

Details of the modeling approach and data sources are described in the methods section. The results section first reports the energy intensity per floor area of residential and commercial sectors for 21 global regions during 1971–2014. Then the Tapio decoupling index is employed to identify the long-run decoupling between energy intensity and economic development. The Logarithmic Mean Divisia Index (LMDI) is then used to assess the potential energy savings attributed to energy intensity reduction by 2060 under the middle-of-the-road Shared Socioeconomic Pathway (SSP2) scenario. Policy implications specific to region groups are discussed in a subsequent section. Conclusions and future research prospects are also proposed.

2. Methods

2.1. Energy intensity in the residential and commercial building sectors

The residential energy intensity (per floor area) is defined as:

$$EI_R = \frac{E_R}{F_R} \tag{1}$$

where EI_R represents the residential energy intensity (MJ/m^2), E_R is the energy consumption in the residential sector (MJ), F_R is the floor area of residential buildings (m^2) as calculated by equation (2).

$$F_R = \sum_m \left(\sum_n \left(Pop_{m,n} * Fcap_{m,n} \right) \right) \tag{2}$$

where m and n denote the building type and area type, $Pop_{m,n}$ and $Fcap_{m,n}$ represent the population and floor area per capita in each type of residential building and area, respectively. The residential building types considered represent detached houses, semi-detached houses, apartments, and high-rise buildings. Area types are urban and rural. The hierarchy of residential building and area types is illustrated in Fig. S1. The commercial energy intensity is defined as:

$$EI_C = \frac{E_C}{F_C} \tag{3}$$

where EI_C represents the commercial energy intensity (MJ/m^2), E_C and F_C are the energy consumption (MJ) and floor area (m^2) in the commercial sector, respectively.

$$F_C = \sum_k (Pop_k * Fcap_k) \tag{4}$$

where k denote the commercial building type, Pop_k and $Fcap_k$ represent the population and floor area per capita in each type of commercial building. The hierarchy of commercial building types is illustrated in Fig. S1.

2.2. Decoupling analysis of energy intensity and economic growth

Decoupling of energy use from a growing economy is necessary if economic development is to continue while meeting sustainability goals across many rapidly-growing regions (Schandl et al., 2016). Decoupling is often characterized by relative or absolute decoupling (United Nations Environment Programme, 2011). Relative decoupling means that growth in an environmental indicator is lower than the economic indicator, while absolute decoupling indicates that the environmental indicator shows negative growth, i.e. reduces, regardless of the trend in economic growth. This decoupling framework is straightforward to calculate but fails to capture more diverse decoupling states (Wu et al., 2018). Tapio (2005) further refined the decoupling framework by distinguishing eight intermediate decoupling states, among which strong decoupling equates to absolute decoupling (see details in Fig. S4). The Tapio decoupling index is widely used in industrial sectors to depict decoupling trends between an environmental variable A and an economic variable B (Sanyé-Mengual et al., 2019). The index is defined as the percentage change of A divided by the percentage change of B over a specific period. Here GDP per capita is used as the economic indicator that influences energy use in residential buildings. According to previous studies (Ma et al., 2019), the economic output of the service industry mainly originates in commercial buildings. As such, the economic development of the commercial sector is represented by the economic output of the service sector, termed as Service Value Added (SVA).

The Decoupling Index (DI) of A from B during [t_1, t_2] can be calculated as follows:

$$DI_{A,B} = \frac{(A_{t_2} - A_{t1})/A_{t_1}}{(B_{t_2} - B_{t_1})/B_{t_1}} = \frac{\%\Delta A}{\%\Delta B} \tag{5}$$

Therefore the DI of residential energy intensity (EI_R) from GDP per capita (GDP_{cap}), denoted by DI_R , can be calculated as:

$$DI_R = \frac{\left(EI_R^{t_2} - EI_R^{t_1}\right)/EI_R^{t_1}}{\left(GDP_{cap}^{t_2} - GDP_{cap}^{t_1}\right)/GDP_{cap}^{t_1}} = \frac{\%\Delta EI_R}{\%\Delta GDP_{cap}} \tag{6}$$

The DI of commercial energy intensity (EI_c) from SVA per capita (SVA_{cap}), denoted by DI_C, can be calculated as:

$$DI_C = \frac{\left(EI_C^{t_2} - EI_C^{t_1}\right)/EI_C^{t_1}}{\left(SVA_{cap}^{t_2} - SVA_{cap}^{t_1}\right)/SVA_{cap}^{t_1}} = \frac{\%\Delta EI_C}{\%\Delta SVA_{cap}} \tag{7}$$

The decoupling status can be characterized in eight ways according to the triplet of values of ΔA, ΔB, and DI (Tapio, 2005), as shown in Fig. S4. Among these, strong decoupling (where $\Delta A<0$, $\Delta B>0$) followed by weak decoupling (where $\Delta A>0$, $\Delta B>0$,$0<\Delta A/\Delta B<0.8$) are most desirable from an environmental perspective. The former indicates a decrease in energy intensity with economy rising while the latter indicates that improvements in energy intensity go faster than growth in GDP.

2.3. Energy saving potential from energy efficiency improvement

The Logarithmic Mean Divisia Index (LMDI) is an index decomposition analysis (IDA) often used to assess the contribution of energy intensity to energy consumption in buildings (Ang, 2015). Following the existing literature, the trend in energy use in the building stock can be decomposed into three drivers: energy intensity, floor space use intensity, and activity, i.e., population (for residential energy) or SVA (for commercial energy) (Serrano et al., 2017). The residential energy consumption can be decomposed as follows.

$$E_R = \frac{E_R}{F_R} * \frac{F_R}{P} * P = \mathrm{EI_R EF_R EP_R} \tag{8}$$

where, $\mathrm{EI_R} = \frac{E_R}{F_R}$ is the energy intensity driver, $\mathrm{EF_R} = \frac{F_R}{P}$ represents building floor area per person (floor space use intensity driver), $\mathrm{EP_R} = P$ denotes population (activity driver).

The change in E_R (ΔE_R) between two given years t_2 and t_1 is decomposed by using LMDI method as follows.

$$\Delta E_R = \Delta \mathrm{EI_R} + \Delta \mathrm{EF_R} + \Delta \mathrm{EP_R} \tag{9}$$

where, $\Delta\mathrm{EI_R}$ shows the contribution of energy intensity to energy consumption in residential buildings, and $\Delta\mathrm{EX_R}$ (X=I, F, P) is calculated as follows.

$$\Delta \mathrm{EX_R} = \frac{E_R^{t_2} - E_R^{t_1}}{lnE_R^{t_2} - lnE_R^{t_1}} \ln\left(\frac{EX_R^{t_2}}{EX_R^{t_1}}\right) \tag{10}$$

The decomposition of energy consumption in the commercial sector is similarly:

$$E_C = \frac{E_C}{F_C} * \frac{F_C}{SVA} * SVA = \mathrm{EI_C} \mathrm{EF}_C \mathrm{ES_C} \tag{11}$$

where, $\mathrm{EI_C} = \frac{E_C}{F_C}$ is the energy intensity driver, $\mathrm{EF}_C = \frac{F_C}{SVA}$ represents building floor area per SVA (floor space use intensity driver), $\mathrm{ES_C} = SVA$ denotes the activity driver.

This transformed equation (9) into:

$$\Delta E_C = \Delta \mathrm{EI_C} + \Delta \mathrm{EF}_C + \Delta \mathrm{ES_C} \tag{12}$$

where, $\Delta\mathrm{EI_C}$ shows the contribution of energy intensity to energy consumption in commercial buildings, and $\Delta\mathrm{EX_C}$ (X=I, F, S) is calculated as follows.

$$\Delta \mathrm{EX_C} = \frac{E_C^{t_2} - E_C^{t_1}}{lnE_C^{t_2} - lnE_C^{t_1}} \ln\left(\frac{EX_C^{t_2}}{EX_C^{t_1}}\right) \tag{13}$$

This is used to quantify building energy savings from energy intensity change between 1971 and 2014, and 2014–2060, respectively (Section 4.1).

2.4. Data sources

For variables during 1971–2014, GDP (in 2010 constant US dollars), SVA (Service Value Added, in 2010 constant US dollars), and population are derived from The National Accounts Section of the United Nations (United Nations Statistics Division, 2019). Energy consumption data for residential and commercial sectors during 1971–2014 are obtained from the IEA energy balances (International Energy Agency, 2015).

For consistency among future variables, the population growth, economic development, and residential energy consumption by 2060 are all based on the IMAGE model (Stehfest et al., 2014), under the Shared Socioeconomic Pathways (SSP). Specifically, the SSP2 is used to represent the middle-of-the-road scenario in which "social, economic, and technological trends do not shift markedly from historical patterns" (Riahi et al., 2017). For energy consumption in commercial buildings, this study uses data from the IEA's Reference Technology Scenario (RTS) (International Energy Agency, 2018) that reflects the world's current ambitions with existing energy related commitments by countries. The energy consumption data here mainly refers to the energy used by space heating, water heating, space cooling, lighting, appliances, and cooking.

The residential floor area per person during 1971–2060 is derived from IMAGE (under SSP2) (Daioglou et al., 2012). Commercial floor area per person during 1971–2050 is derived from Deetman et al. (2019) and then extended to 2060 using the regression approach developed in the same study. Deetman et al. (2019) assumed a time-independent Gompertz-type relationship between the per capita Service Value Added and per capita commercial floor area. Such Gompertz curves are widely used for housing floor space estimates (Daioglou et al., 2012). The calculation of residential and commercial building floor area is based on the python codes developed by Deetman et al. (2019). See detailed floor area data in the Supplementary data.

The number of building energy efficiency policies in different groups is estimated based on IEA's Energy Efficiency Policies and Measures Database (International Energy Agency, 2020). As listed in Table 1, the 21 global regions include 7 high-income regions, 8 upper-middle-income regions, and 6 lower-middle-income regions according to the World Bank Atlas classification (Fantom and Serajuddin, 2016).

3. Results

3.1. The evolution of energy intensity in global building sectors during 1971–2014

On the global level, residential energy intensity exhibited a clear downward trend from 897 to 476 MJ/m^2 between 1971 and 2014 (with some small fluctuations). However, diverging trends were observed across regions and income groups, with most high-income regions continuously decreasing their energy intensity (see solid lines in Fig. 1), most lower-and upper-middle-income regions experienced an increase during the beginning decades (dashed lines) or even the whole study period (dotted lines). In the high-income group, Canada (CA), the United States (US), Oceania (OC), and Western Europe (WE) reduced their residential energy intensity by 60%, 53%, 39%, and 29%, respectively over the period. One exception is Japan (JP), where residential energy intensity increased during 1971–2005 and decreased slightly after. This can be partially explained by the already low energy intensity compared to other high-income regions. Similar patterns of first increasing then decreasing intensities were observed in most lower- and upper-middle-income regions including Mexico (MEX), Other America (OA), Western & Eastern Africa (WEA), Middle East (ME), Southeast Asia (SAS), Indonesia region (ID). It is noteworthy that the China region (CN), India (IN), and Brazil (BR), as three of the largest emerging economies, also continuously decreased their residential energy intensity, showing the positive impact of their energy efficiency policies. In comparison, in poorer regions such as Western & Eastern Africa (WEA) and Rest of Southern Africa (RSA), the per floor area residential energy intensity was very high, which was likely due to insufficient energy efficiency policies (International Energy Agency, 2020). Similarly, Northern Africa (NA) and Rest of South Asia (RSAS), the other two lower-middle-income regions, saw no peak by the end of the period.

Commercial building energy intensity, while significantly higher than the residential sector, also demonstrated dramatic declines globally (in spite of a slight initial increase). The differences among regions and income groups were more significant than those in the residential sector. On average, the high-income group reduced energy intensities by 50%, while upper-middle and lower-middle groups increased intensities by 193% and 44%, respectively. Most high-income regions saw continuously decreasing commercial energy intensities from 1971 to 2014, with Canada, the United States, Western Europe, and Oceania having more than halved their intensity values. On the contrary, the increasing trend continued in many lower-and upper-middle-income regions, led mainly by Asian regions such as the Indonesia region, Turkey, Southeast Asia, and China region, where commercial energy intensities more than tripled over the period 1971–2014.

Further analysis here examines the intensity change by fuel types (Fig. 2), which is generally characterized by an increase in electricity and a decrease in coal, oil, and biofuel products. The decline of residential energy intensity was mainly driven by fossil fuels (especially oil and coal products) in high-income regions and biofuels in lower- and upper-middle-income regions. This is likely due to the switch from oil and coal to renewables in high-income regions (Michelsen and Madlener, 2016) and rapid urbanization in lower-and upper-middle-income regions, with biomass being the principal fuel form for developing rural communities (Smith, 2013).

As for the commercial sector, electricity intensity increased for all regions excluding Canada, which already had the highest intensity at the start of the period. However, in high-income regions, the intensity increase of electricity was compensated by the intensity decrease in fossil fuels. The Korea region saw the only exception, with a marked increase in the intensity of electricity, gas, and biofuels. This increase was mainly seen during the first half of the study period, which then shifted into a long decrease (Fig. 1). In the lower-and upper-middle-income regions, increases in electricity intensity were not offset by decrease in other fuels. Instead, increases in gas and oil intensity were also commons. Overall, the largest increase in commercial energy intensities was seen in upper-middle-income regions, mostly in Asian regions such as the Middle East, Turkey, and Southeast Asia.

Note that electricity, as a form of secondary energy, is generated from primary energy. Despite regional divergence, over 60% of global electricity was produced by fossil fuels, of which coal's share was roughly constant between 1974 and 2014, oil decreased and natural gas increased (Fig. S2). The change in electricity use intensity is further translated into the change in coal, oil, gas, and biofuels (Fig. S3). The patterns examined in the residential sector remain largely unchanged because the electricity intensity changes in residential buildings were insignificant. However, the increase in electricity intensity in commercial buildings can indirectly increase fossil fuel intensities (depending on the generation mix), which could offset reductions in the direct use of fossil fuels on-site. For example, the direct decrease in coal intensity across commercial buildings in Korea, Japan, South Africa, and India was converted into a net increase after accounting for electrification and associated upstream/indirect fossil fuel use. Along with increasing efficiencies and further electrification, a transition towards greener electricity is also critical to primary energy savings.

3.2. Energy intensity and economic growth decoupling

Regional decoupling indexes for energy intensity are presented in Fig. 3 (full details are available in Table S2). For ease of inspection, three decoupling categories, i.e., strong decoupling, weak decoupling, and other decoupling states (see full states in Fig. S4), are illustrated. Here three main findings are highlighted.

Firstly, decoupling status has improved over the period for most regions. In the first period (1971–1981), strong decoupling was observed in only a few regions, mainly in the high-income group (especially in commercial sectors). Several regions saw weak decoupling, mainly due to rapidly growing economies with energy intensity increasing more slowly. Regions fitting this characteristic include Other America, Central Europe, Southeast Asia, and Japan. In the final period (2004–2014), most regions strongly decoupled their energy intensity in both residential and commercial sectors. This is likely due to the gradual effects of increasingly deploying energy efficiency strategies.

Second, the decoupling status in residential buildings is generally deeper than that in commercial buildings. During the final years of

Table 1
Region classification and regional abbreviations.

Income group	Regions
High-income (HI)	Canada, United States, Western Europe, Central Europe, Korea region, Japan, Oceania (CA, US, WE, CE, KR, JP, OC)
Upper-middle-income (UMI)	Mexico, Brazil, Other America, South Africa, Turkey, Middle East, China region, Southeast Asia (MEX, BR, OA, SA, TU, ME, CN, SA)
Lower-middle-income (LMI)	Northern Africa, Rest of Southern Africa, Western & Eastern Africa, India, Rest of South Asia, Indonesia region (NA, RSA, WEA, IN, RSAS, ID)

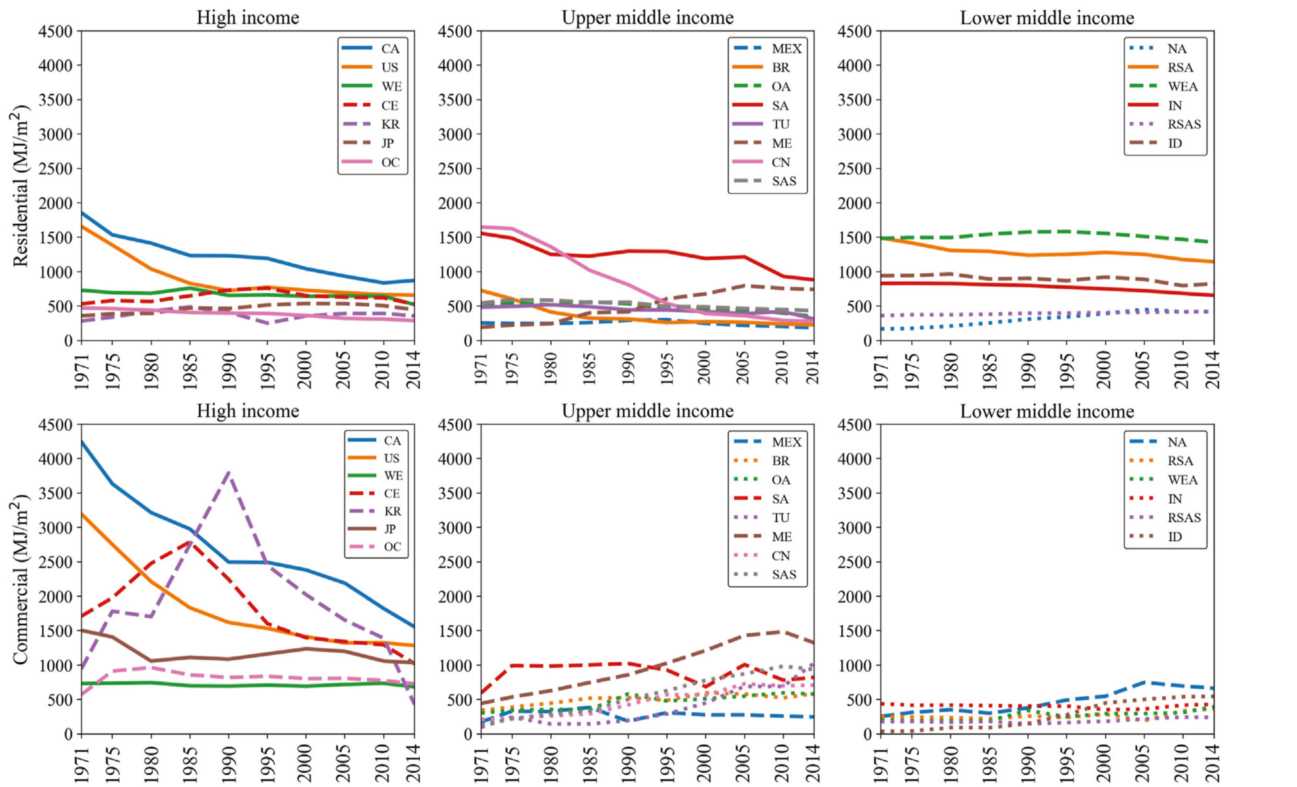

Fig. 1. The evolution of regional building energy intensity per floor area during 1971–2014. The solid lines represent regions where energy intensities continuously decreased during the study period. The dashed lines represent regions where energy intensity peaked after a long increase. Finally, the dotted lines represent regions whose energy intensity did not peak by the end of the period. Full region names and countries in each region are listed in Table 1 and Table S1 in the Supplementary Information.

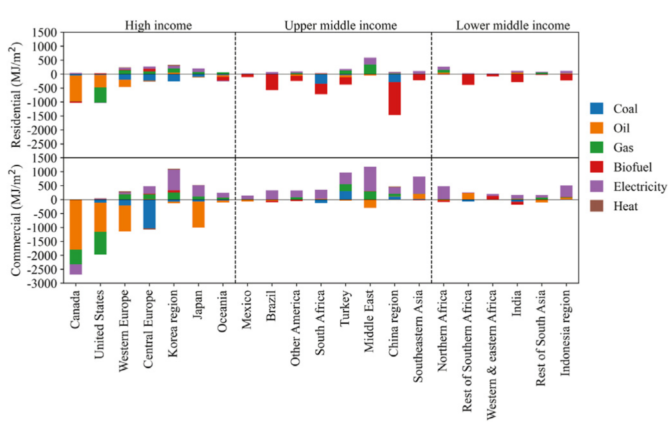

Fig. 2. Change in energy intensity per floor area by different energy resources in residential and commercial sectors during 1971–2014.

the investigation (2004–2014), residential energy intensity in 20 out of 21 regions had strongly decoupled from economic growth, the remaining region from the lower-middle-income group also weakly decoupled. By contrast, only 13 regions achieved strong decoupling in their commercial sectors and 2 regions failed to weakly decouple. This might be due to industrial development patterns, i.e., some countries transition to service industries much later and only after the economy has passed through an industrializing process. This development pattern is especially applicable to China, India, and Brazil, the largest emerging economies in the world.

Third, building energy intensities of high-income regions decoupled earlier and more strongly from economic development. Some of the highest-income regions, i.e., the United States and Canada, succeeded in achieving strong decoupling after 1971. Strong decoupling was also observed, but only later in Western Europe, Oceania, and Japan. Many lower-and upper-middle-income regions achieved strong decoupling only recently and several saw no strong decoupling over the period. This could be due to two reasons: firstly, high-income economies invested more to improve the energy use performance of buildings via technological improvements and house renovation, while lower-and upper-middle-income regions were still building a large amount of less efficient buildings; and, secondly, many lower-and upper-middle-income regions were still increasing energy use in pursuit of higher indoor living quality, which was probably accomplished in advanced countries previously.

Turning to energy types, significant differences are observed between electricity and non-electricity resources (as shown in Fig. 4 and Fig. S5). Electricity use intensity was tightly coupled with economic growth in most regions before 2000, for both residential and commercial buildings. By the final period 2000–2014, only high-income regions saw strong decoupling. Most lower- and middle-income regions saw consistent rising electricity intensity in building sectors, with rapidly developing Asian regions seeing the largest increases. For example, the Indonesia region experienced a more than twenty-fold increase in electricity consumption per floor area, with a roughly ten-fold growth of economic output. This might be attributed to the increase in household appliances (especially air-conditioning) demand, as well as increasing electrification (Cabeza et al., 2014). By comparison, almost all regions strongly decoupled their non-electricity energy intensity from their economic development during the whole study period. The only exception is the commercial energy intensity in the upper-middle-

Strong decoupling | Weak decoupling | Other states

Income group	Region \ Period	Residential $DI_R=\Delta EI_R\% / \Delta GDP_{cap}\%$ 1971-1981	1982-1992	1993-2003	2004-2014	Commercial $DIc=\Delta EIc\% / \Delta SVA_{cap}\%$ 1971-1981	1982-1992	1993-2003	2004-2014
HI	Canada	-1.38	-0.86	-0.82	-0.79	-0.92	-1.67	-0.32	-2.06
	United States	-2.34	-1.16	-0.48	-0.88	-1.36	-1.22	-0.49	-0.64
	Western Europe	-0.36	0.18	-0.17	-4.23	-0.61	-0.63	-0.41	-1.18
	Central Europe	0.19	-3.32	-0.52	-0.48	1.08	-21.98	-0.71	-0.80
	Korea region	0.75	-0.28	0.94	-0.16	6.34	0.57	-0.79	-0.94
	Japan	0.31	0.25	0.47	-2.98	-0.47	-0.15	0.57	-2.86
	Oceania	-0.49	-0.22	-0.61	-1.10	2.69	-0.23	-0.04	-0.85
UMI	Mexico	-0.10	-4.89	-1.72	-3.28	1.75	45.49	-0.68	-1.14
	Brazil	-0.69	-4.39	-1.08	-0.63	0.51	1.09	0.40	0.01
	Other America	0.20	-38.57	-0.59	-1.00	0.88	24.23	2.37	-0.02
	South Africa	-7.79	-1.52	-0.79	-1.58	5.00	2.21	-0.35	-0.60
	Turkey	0.10	-0.47	-0.87	-0.41	1.96	2.25	11.80	1.39
	Middle East	5.12	-5.58	3.83	-0.04	0.73	-2.28	1.88	-0.06
	China region	-0.49	-0.40	-0.36	-0.17	0.20	0.51	0.06	-0.02
LMI	Southeastern Asia	0.17	-0.18	-0.23	-0.21	2.18	2.26	1.13	0.17
	Northern Africa	0.88	8.41	0.92	-0.09	0.66	0.71	1.07	-0.17
	Rest of Southern Africa	0.70	1.37	0.05	-0.21	0.52	-17.53	-0.78	1.30
	Western & eastern Africa	0.74	-0.55	-0.21	-0.17	-0.30	-7.66	1.14	0.62
	India	-0.05	-0.11	-0.15	-0.16	0.05	0.01	-0.08	0.25
	Rest of South Asia	0.28	0.22	0.17	0.06	-0.17	-0.28	0.88	0.44
	Indonesia region	0.00	-0.06	0.15	-0.17	1.85	1.88	6.32	0.14

Fig. 3. Decoupling indexes (DI) of energy intensity and economic growth in the residential and commercial sectors.

income regions, presently experiencing weakly decoupling in a trend that became stronger over the period. The continuous reduction of non-electricity energy intensity is broadly due to the decreasing consumption of traditional fuels for heating and cooking purposes (Duan et al., 2014), which is also an achievement of the expansion in electrification (Ürge-Vorsatz et al., 2015).

In sum, most regions managed to decouple their building energy intensity by varying degrees. However, electricity and non-electricity energy resources show very different decoupling trends. This can be explained by two reasons. From the consumption side, there was an increase in cooling and digital needs, mainly satisfied by electricity, and a decrease in heating demand related to other fuels. From the supply side, decarbonization efforts and phasing out of traditional biofuels drove electrification and energy efficiency improvements.

4. Discussion

4.1. The potential contribution of energy intensity changes to energy savings by 2060

Globally, around 28 EJ (EJ; 1 EJ = 10^{18} J) of residential energy (equal to 30% of the total in 2014) can be saved during 2014–2060 as a result of efficiency improvements, which is slightly smaller than during 1971–2014 (32 EJ), as shown in Fig. 5. The role of energy intensity in residential energy savings varies significantly across regions and income-groups (Fig. 6, and Fig. S6–S9 in the Supplementary Information). The high-income group has limited energy saving potential during 2014–2060, perhaps due to limited options for further efficiency improvement in the SSP2 scenario with no marked shift expected in socioeconomic and technological systems. Most of the efficiency-driven energy savings are to be gained in the lower-middle-income regions, especially in the rapidly growing African and Asia regions, with Western & Eastern Africa and India being the top two hotspots. This is mainly due to the large room for energy efficiency improvements in the fast-expanding residential stocks to shelter a rising population and bigger houses. Unlike other emerging middle-income regions (which expect a decline in energy intensity), China is likely to witness a significant increase in the residential energy intensity during 2014–2060 (from 278 to 370 MJ/m^2). This is likely due to the fact that the energy intensity in the China region is very low at present, so it could still climb (driven by the desire for increased indoor living quality) faster than any technological improvements. Therefore, more investment and strict policies are needed to improve energy-saving performance, especially in the efficiency of cooling systems (Karali et al., 2020) and digital appliances (Zhou et al., 2018) in residential buildings.

By comparison, potential energy savings from efficiency improvements in commercial buildings (28.9 EJ) overtakes those in residential buildings between 2014 and 2060 (Fig. 5). This is mainly because commercial energy intensity could significantly decrease by 467 MJ/m^2 (from 911 to 444 MJ/m^2), while the residential energy intensity may only slightly decrease from 498 to 383 MJ/m^2. Also note that the commercial building sector may triple the floor area from 33970 to 114834 km^2 during 2014–2060, which makes commercial energy savings increasingly important.

4.2. Policy implications

This study analyses historical trend, decoupling status, and the future potential of energy intensity per floor area for 21 global regions categorized into 3 income groups. In the residential sector, most regions already saw a peak in energy intensity and decoupling

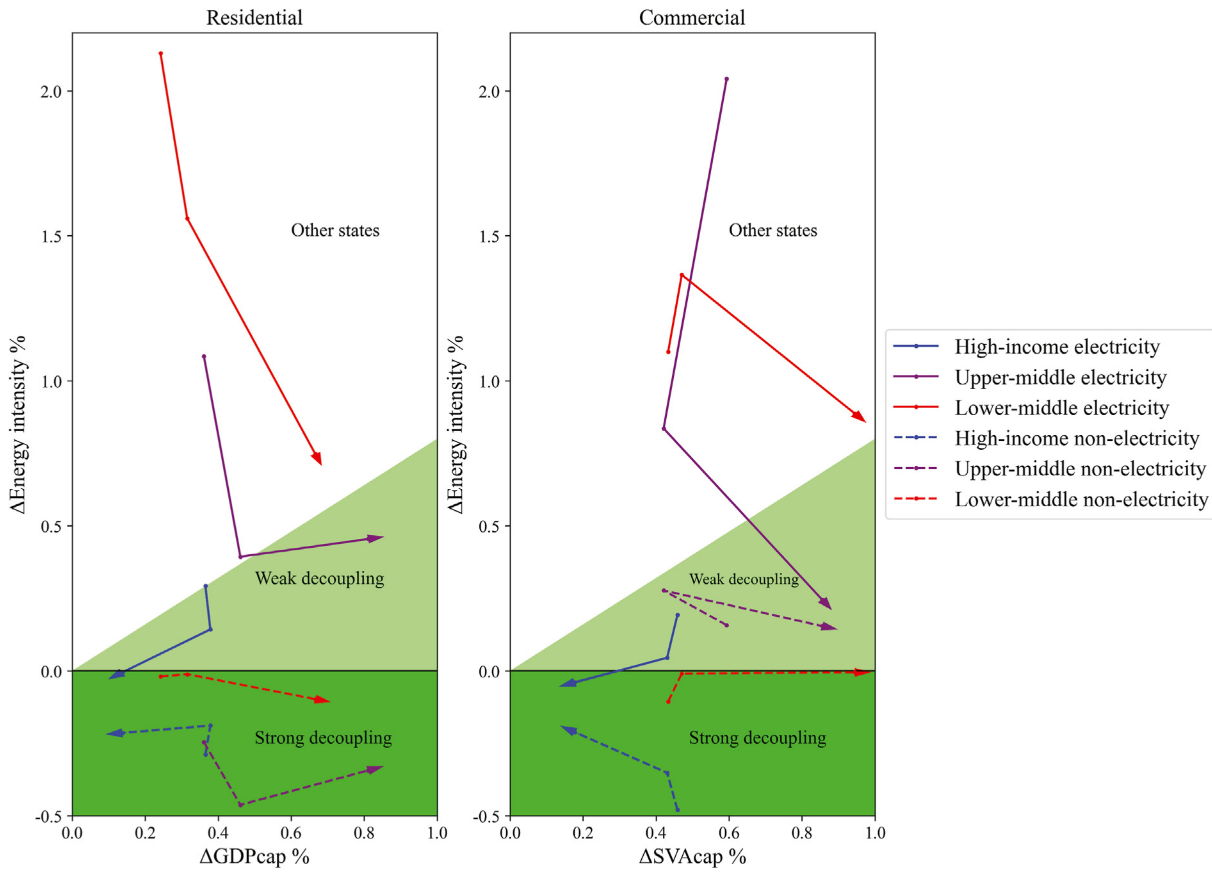

Fig. 4. The state map of decoupling between energy intensity and economic development. Left: the change of the decoupling index (DI) of residential energy intensity (ΔEr/Fr) from GDP growth (ΔGDP_{cap}); Right: the change of DI between commercial energy intensity (ΔEc/Fc) and Service Value Added growth (ΔSVA_{cap}). Each line shows three data points representing the time periods of 1971–1985, 1985–2000, 2000–2014, respectively. The changing directions in all groups (blue for high-income, purple for upper-middle-income, red for lower-middle-income) are shown by the arrows. The solid lines represent the electricity intensity and the dashed lines represent the non-electricity energy.

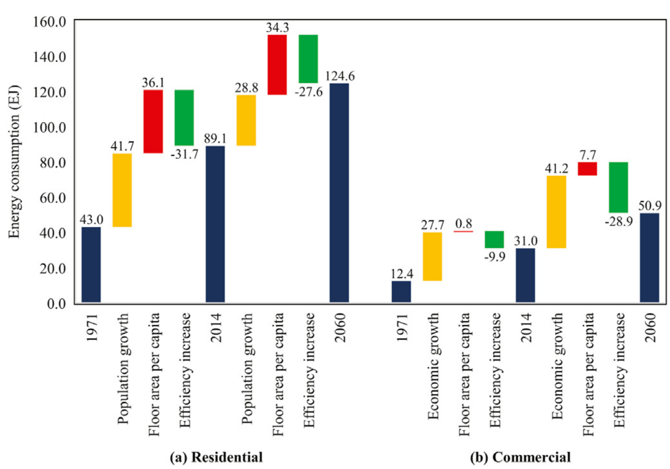

Fig. 5. Decomposition of change in residential (a) and commercial (b) energy consumption.

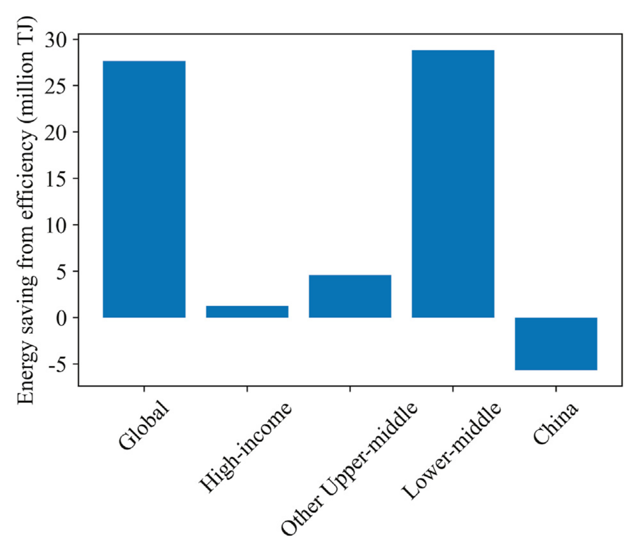

Fig. 6. Energy savings via improved energy efficiency for residential buildings between 2014 and 2060. Regions included in each group are shown in Table 1.

between energy intensity and economic growth before 2014, indicating the decreasing trends were likely to continue. However, results also show that there is limited room for energy efficiency improvement in residential buildings under the SSP2 scenario without dramatic social, economic, and technological shifts. Most of the future potential for efficiency-driven residential energy saving lies in lower-middle-income regions, especially in rapidly urbanizing African and Asian regions. One often-overlooked reason is that the current residential energy consumption per floor area in the lower-middle-income regions is as high as that in the high-income regions, probably due to the wide usage of low-efficiency appliances and buildings, and therefore has larger reduction potentials (Figs. 1 and 6). In terms of the commercial sector, energy intensity across many regions did not exhibit a peak and achieved only weaker decoupling. As expected, potential efficiency-driven energy savings in the commercial sector are slightly higher than in residential due to the larger reduction potential of energy intensity and a sharp increase in the floor area.

Fig. 7 illustrates a wide variation in the number of policies concerning building energy efficiency in different income groups. There seems to be a direct correlation between energy intensity change and the number of building energy efficiency policies, indicating the significant payoff of the in-force efforts. To curb energy demand growth in the building sector, locally customized policies are required according to the region and type of development.

In general, for high-income regions, energy efficiency policies have effectively reduced the energy intensity in the past decades, but their further potentials seem to be limited under the current strength. More ambitious energy reduction goals require stronger actions to achieve a drastic shift in socio-economic and technological systems. Further efficiency gains could be obtained by greener lifestyles (Rouleau et al., 2019) and ongoing zero-energy initiatives (Laski and Burrows, 2017). At the same time, deep renovations of existing buildings are especially important in highly urbanized regions where most buildings that will be still standing in 2060 have already been built.

In middle-income regions, current policy efforts to improve building energy efficiency are not sufficient to offset the demand growth. As such, there are large potentials in energy savings through policy enhancement. In particular, in most emerging African and Asian regions, where building infrastructure is predicted to increase rapidly, strict building efficiency standards for new buildings should be implemented as soon as possible, to avoid costly retrofits (and lock-in). By adopting modern construction technologies and principles, emerging regions have the opportunity to avoid accumulating a stock of inefficient buildings (Müller et al., 2013). Concerning the high level of coupling between electricity use and economic growth in lower-middle-income regions, special attention should be paid to more efficient air-conditioners and other electricity-use appliances which may see high demand in the coming decades (Zhou et al., 2018).

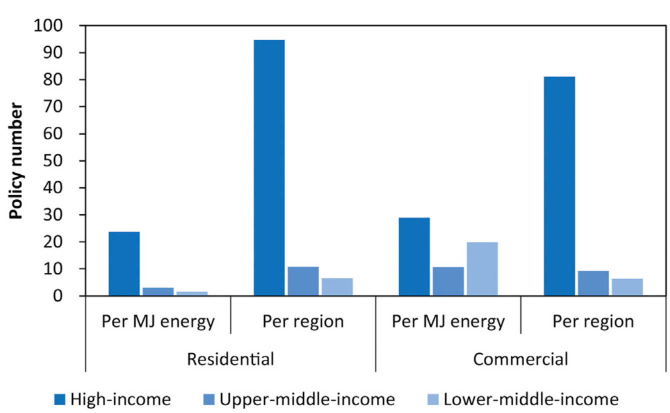

Fig. 7. The average number of building energy efficiency policies per MJ energy and per region in each income group. Source: Own estimation from IEA's Energy efficiency Policies and Measures Database (International Energy Agency, 2020). For policy number counting, only in-force policies are considered. The building energy efficiency policies and those multi-sectoral energy efficiency policies related to the buildings are all included. Regions included in each group are shown in Table 1.

5. Conclusions and prospects

This study provides a comprehensive investigation of the historical trends in building energy intensity, its relationship with economic development, and the future role of energy intensity improvements regionally. Energy efficiency has been significantly improved over the past decades in both residential and commercial buildings and has generally decoupled from economic growth. However, the study shows that future gains in efficiency will require more aggressive policies. In the context of addressing climate change, an ambitious improvement of the energy intensity of buildings is required in parallel with an energy transition towards emission-free electrification.

Further extensions to this work could integrate the influence of urbanization trends on energy use per unit of floor area. In some rapidly developing regions, the energy use of some appliances (e.g., lighting and electronic equipment) has not increased as fast as the expanding floor area per household. In other words, larger homes with the same appliances. This leads to a 'dilution effect', i.e., a decline in energy use per floor area even in the absence of technological improvements in energy-saving (Gao et al., 2019). This dilution effect should be quantified so that energy use per square meter can be more reliable as an efficiency measurement.

Another area for future investigations is the impact of climate change on energy use per unit of floor area. Global warming generally increases cooling and decreases heating demand in buildings. While the increment of cooling may overtake the decrease in heating in most regions, there are exceptions in heating-dominated regions like Canada and Russia (Clarke et al., 2018). That is, even with no energy efficiency change in buildings, the energy intensity changes over time in different directions and by varying extents.

A final suggestion for future work is the investigation of potential trade-offs between operational and embodied energy intensity. Previous studies have explored the trade-off between the embodied and operational emissions in specific buildings regarding different material choices and construction methods. This could be expanded more broadly to larger-scale analyses.

CRediT authorship contribution statement

Xiaoyang Zhong: Conceptualization, Methodology, Writing – original draft. **Mingming Hu:** Supervision, Writing – review & editing. **Sebastiaan Deetman:** Resources, Writing – review & editing. **João F.D. Rodrigues:** Writing – review & editing. **Hai-Xiang Lin:** Writing – review & editing. **Arnold Tukker:** Writing – review & editing. **Paul Behrens:** Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127098.

References

Abergel, T., Dean, B., Dulac, J., 2017. Towards a Zero-Emission, Efficient, and Resilient Buildings and Construction Sector: Global Status Report 2017. UN Environment and International Energy Agency, Paris, France.

Ang, B.W., 2015. LMDI decomposition approach: a guide for implementation. Energy Pol. 86, 233–238.
Ang, B.W., Goh, T., 2018. Bridging the gap between energy-to-GDP ratio and composite energy intensity index. Energy Pol. 119, 105–112.
Ang, B.W., Mu, A.R., Zhou, P., 2010. Accounting frameworks for tracking energy efficiency trends. Energy Econ. 32 (5), 1209–1219.
Berardi, U., 2017. A cross-country comparison of the building energy consumptions and their trends. Resour. Conserv. Recycl. 123, 230–241.
Cabeza, L.F., Urge-Vorsatz, D., McNeil, M.A., Barreneche, C., Serrano, S., 2014. Investigating greenhouse challenge from growing trends of electricity consumption through home appliances in buildings. Renew. Sustain. Energy Rev. 36, 188–193.
Cao, X., Dai, X., Liu, J., 2016. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. Energy Build. 128, 198–213.
Chaturvedi, V., Eom, J., Clarke, L.E., Shukla, P.R., 2014. Long term building energy demand for India: disaggregating end use energy services in an integrated assessment modeling framework. Energy Pol. 64, 226–242.
Clarke, L., Eom, J., Marten, E.H., Horowitz, R., Kyle, P., Link, R., Mignone, B.K., Mundra, A., Zhou, Y., 2018. Effects of long-term climate change on global building energy expenditures. Energy Econ. 72, 667–677.
Daioglou, V., van Ruijven, B.J., van Vuuren, D.P., 2012. Model projections for household energy use in developing countries. Energy 37 (1), 601–615.
Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D.P., Edelenbosch, O., Heijungs, R., 2019. Modelling global material stocks and flows for residential and service sector buildings towards 2050. J. Clean. Prod., 118658
Duan, X., Jiang, Y., Wang, B., Zhao, X., Shen, G., Cao, S., Huang, N., Qian, Y., Chen, Y., Wang, L., 2014. Household fuel use for cooking and heating in China: results from the first Chinese environmental exposure-related human activity patterns survey (CEERHAPS). Appl. Energy 136, 692–703.
Fantom, N., Serajuddin, U., 2016. The World Bank's Classification of Countries by Income. The World Bank.
Gao, J., Zhong, X., Cai, W., Ren, H., Huo, T., Wang, X., Mi, Z., 2019. Dilution effect of the building area on energy intensity in urban residential buildings. Nat. Commun. 10 (1), 4944.
Huo, T., Ren, H., Cai, W., 2019. Estimating urban residential building-related energy consumption and energy intensity in China based on improved building stock turnover model. Sci. Total Environ. 650, 427–437.
International Energy Agency, 2015. World Energy Balances: Overview. IEA, Paris.
International Energy Agency, 2017. Tracking Clean Energy Progress 2017. International Energy Agency (IEA), Paris.
International Energy Agency, 2018. Energy Technology Perspectives 2017. International Energy Agency (IEA).
International Energy Agency, 2020. Energy efficiency policies and Measures database. Avaliable from. https://www.iea.org/policiesandmeasures.
Karali, N., Shah, N., Park, W.Y., Khanna, N., Ding, C., Lin, J., Zhou, N., 2020. Improving the energy efficiency of room air conditioners in China: costs and benefits. Appl. Energy 258, 114023.
Laski, J., Burrows, V., 2017. From Thousands to Billions: Co-ordinated Action towards 100% Net Zero Carbon Buildings by 2050. World Green Building Council.
Levesque, A., Pietzcker, R.C., Baumstark, L., De Stercke, S., Grübler, A., Luderer, G., 2018. How much energy will buildings consume in 2100? A global perspective within a scenario framework. Energy 148, 514–527.
Ma, M., Cai, W., Cai, W., Dong, L., 2019. Whether carbon intensity in the commercial building sector decouples from economic development in the service industry? Empirical evidence from the top five urban agglomerations in China. J. Clean. Prod. 222, 193–205.
Michelsen, C.C., Madlener, R., 2016. Switching from fossil fuel to renewables in residential heating systems: an empirical study of homeowners' decisions in Germany. Energy Pol. 89, 95–105.
Müller, D.B., Liu, G., Løvik, A.N., Modaresi, R., Pauliuk, S., Steinhoff, F.S., Brattebø, H., 2013. Carbon emissions of infrastructure development. Environ. Sci. Technol. 47 (20), 11739–11746.
Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ. Change 42, 153–168.
Rouleau, J., Gosselin, L., Blanchet, P., 2019. Robustness of energy consumption and comfort in high-performance residential building with respect to occupant behavior. Energy 188, 115978.
Sandberg, N.H., Sartori, I., Vestrum, M.I., Brattebø, H., 2016. Explaining the historical energy use in dwelling stocks with a segmented dynamic model: case study of Norway 1960–2015. Energy Build. 132, 141–153.
Sanyé-Mengual, E., Secchi, M., Corrado, S., Beylot, A., Sala, S., 2019. Assessing the decoupling of economic growth from environmental impacts in the European Union: a consumption-based approach. J. Clean. Prod. 236, 117535.
Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Schaffartzik, A., Krausmann, F., Gierlinger, S., Hosking, K., Lenzen, M., Tanikawa, H., Miatto, A., Fishman, T., 2018. Global material flows and resource productivity: forty years of evidence. J. Ind. Ecol. 22 (4), 827–838.
Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M., Owen, A., 2016. Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. J. Clean. Prod. 132, 45–56.
Serrano, S., Ürge-Vorsatz, D., Barreneche, C., Palacios, A., Cabeza, L.F., 2017. Heating and cooling energy trends and drivers in Europe. Energy 119, 425–434.
Smith, K.R., 2013. Biofuels, Air Pollution, and Health: a Global Review. Springer Science & Business Media.
Stehfest, E., van Vuuren, D., Bouwman, L., Kram, T., 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model Description and Policy Applications. Netherlands Environmental Assessment Agency (PBL).
Svetozarevic, B., Begle, M., Jayathissa, P., Caranovic, S., Shepherd, R.F., Nagy, Z., Hischier, I., Hofer, J., Schlueter, A., 201. Dynamic photovoltaic building envelopes for adaptive energy and comfort management. Nature Energy 4, 671–682.
Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transport Pol. 12 (2), 137–151.
Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., Davis, S.J., 2019. Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature 572, 373–377.
United Nations Environment Programme, 2011. Decoupling Natural Resource Use and Environmental Impacts from Economic Growth. UNEP/Earthprint.
United Nations Statistics Division, 2019. National Accounts Section of the United Nations, Statistics. Avaliable from. https://unstats.un.org/unsd/snaama/Index.
Ürge-Vorsatz, D., Cabeza, L.F., Serrano, S., Barreneche, C., Petrichenko, K., 2015. Heating and cooling energy trends and drivers in buildings. Renew. Sustain. Energy Rev. 41, 85–98.
Wu, Y., Zhu, Q., Zhu, B., 2018. Comparisons of decoupling trends of global economic growth and energy consumption between developed and developing countries. Energy Pol. 116, 30–38.
Zhou, N., Khanna, N., Feng, W., Ke, J., Levine, M., 2018. Scenarios of energy efficiency and CO 2 emissions reduction potential in the buildings sector in China to year 2050. Nature Energy 3 (11), 978.