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Global comparison of building energy use data within the context of climate change

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ABSTRACT

Building plays an important role in addressing climate change, with many studies on these topics having been conducted from a global perspective. However, building energy use is found to differ greatly among different countries, with the gaps yet to be fully considered or discussed. Thus, a picture of the overall situation in each country may be needed as a basis for global studies, and one of the first few steps to this end is to conduct a comparative study on energy use data. With these considerations, data related to building energy use are collected in this study from various resources. The energy use intensity, energy structure, and carbon emissions in different countries are compared using selected indicators and different projections were fitted presenting different development patterns. A new clustering of these countries is then proposed. Through the analysis, it could be found that countries with different phases of building energy development needs different patterns and the phase of each country based on global comparison could be some support for building energy policy and researches. Meanwhile, some suggestions on building energy data are discussed for a better understanding and evaluation of building energy use to better address climate change.

1. Introduction

Addressing climate change is a global challenge and requires responses from all sectors and on all aspects, including in terms of building energy use, which is an important contributor to the increase in CO_2 emissions. In 2017, the energy-related CO_2 emission of the buildings sector, including direct and indirect emissions, was 8671 million tCO_2, which accounts for approximately one quarter of the total value [21]. To achieve the targets in addressing climate change, the emissions of buildings will have to significantly decrease, with the main necessary actions on energy including the improvement of energy efficiency and the use of more renewable energy instead of fossil fuels [23,30].

Numerous studies focusing on climate change mitigation, with energy conservation as a main approach, in the fields of building design, construction, and management, have been conducted. One topic is the analysis of the status of building energy conservation, either in terms of a global perspective or in selected regions and countries, which will enhance the understanding of the energy use of buildings and provide support to policy making and development planning.

Through these studies in a global perspective, building energy use has been found to vary greatly in different countries and regions around the world. Through a regional analysis of carbon emissions, the emissions of countries that are members of the Organization for Economic Co-operation and Development (OECD) were found to be high, having grown moderately from 1970 to 2010, whereas those of the least developed countries were low with little growth, and those of Asia were determined to have grown quickly [29]. The International Energy Agency (IEA) also found that the building energy usage in OECD countries have been relatively stable in recent years, whereas those in non-OECD countries, especially in rapidly emerging economies, such as China and India [20], have significantly increased.

Many studies focusing on certain countries have also been conducted in the fields of energy use or carbon emissions history, characteristics, policies, etc., giving a better understanding of the building energy use situation in these countries or regions. Pérez-Lombard, Ortiz and Pout [45] found that buildings had become the largest energy consumers in the Europe Union (EU) and in the U.S., although available information was still lacking at that time; they found that related strategies are urgently needed for

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a sustainable energy future. Through the use of the ODYSSEE-MURE database, the situations in terms of energy use in the EU countries from 2000 to 2012 were analyzed, and the status quo and trends for these countries were found to be different [35]. Nejat et al. [42] analyzed the global CO_2 emission situations from 2000 to 2011 in the residential sectors of the top-10 emitter countries. Among those ten countries, developing countries were found to exhibit an increasing trend in emissions, whereas most developed countries, except for Japan and the U.S., exhibited reduction, with their energy structures having also been changed. Allouhi [1] determined the building energy-consumption trends around the world and in selected countries and regions (US, Australia, China, and EU) as a basis for evaluating energy policies. Cao, Dai and Liu [9] compared the building energy use of the U.S., China, and EU, and reported on the gaps in terms of energy use intensity (EUI), end-uses, and energy structures between these countries. Meanwhile, Berardi [4] compared the building energy use in the U.S., EU, and BRIC (Brazil, Russia, India, and China) countries and found that the energy usage in these countries has increased quickly, and that more energy conservation policies are urgently needed. Lu and Lai [38] noticed considerable differences between some developed countries and developing countries, and suggested that policy makers should propose related policies corresponding to the current and potential situations regarding building energy.

Meanwhile, there have been many studies analyzing the future development of the global building sector. These studies are always based on the results and framework of the status quo analysis. According to the latest energy outlook by the IEA, building energy use will increase by 20% in 2040 compared to that in 2018, assuming a started-policies scenario, or decrease by 13%, assuming a sustainable-development scenario, with half of the growth coming from developing Asian countries [25]. Wang et al. [56] found that under moderate development via Shared Socioeconomic Pathways (SSPs), building energy use will significantly grow in less developed countries, whereas it will stay constant or decrease in high-income countries. To achieve the 2 °C target, high-income countries will be the main contributors in reducing emissions, whereas for the 1.5 °C target, all regions will need to take action [57]. In Levesque et al. [36], it is found that with different SSPs, the energy consumption of buildings could range from being less than 5% to more than 2 times as high as that in 2010. The share of developing countries will significantly increase, with the climatic condition being one important reason for the change. The model by Levesque, Pietzcker and Luderer [37] has shown in a reference scenario that building energy use will be 126% that in 2015, mainly driven by population and income, whereas with strategies involving new technologies and behaviors, the energy use may decrease by 11%.

Through the existing studies, it could be seen that gaps in building energy use between different groups of countries have obviously been much discussed and have been considered in related policy and scenario analyses. On one hand, based on most studies, economic level could be seen as the main factor in grouping these countries, as well as the continent, which is used as one important classification basis in many studies. On the other hand, building energy use is a comprehensive result of technical and physical factors, such as climate, building envelope and equipment, and human-influenced factors [62], with these factors also being dependent on elements other than economic development. In other words, for studies on building energy status or scenarios on a global scale, discussions only on an economic level may not be enough. Thus, a picture of the overall situation in each country may be necessary, with one of the first few steps in creating this picture being a comparative study of data on energy use in different countries.

Through this study, one step further is expected to be made in understanding the global situation in terms of building energy use, especially regarding these three problems: 1) What is the status for all countries, i.e., not limited to selected countries or regions? 2) What relationships among different indicators can be found based on the current situation in each country? and 3) How will the countries be grouped according to building energy use? Then the supports for building low-carbon transformation policies and researches from the comparison analysis are discussed, as well as the potential improvements on national building energy use data and the limitations of this study.

Based on the aforementioned considerations, a worldwide comparative study focusing on building energy use will be conducted. Comparing with existing studies, this paper intends to supply a new viewpoint thinking of the building energy use and carbon emissions globally in following two aspects: firstly, the research object of this study is every country instead of selected regions, then the diversity of each country in one region will be released; secondly, this research put more focus on different indicators, such as the energy structure, which is not widely discussed for energy conservation but important for carbon emissions.

This paper is structured as follows. The next section introduces the method, including what indicators are used, how the data are collected, and how the curve fitting and clustering analysis are conducted. Section 3 introduces the results of a comparative research on the status quo in different countries, including the total amounts, intensities, energy structures, carbon emissions and how the countries will be clustered in the view of building energy use and the appreciative approach for each group. Section 4 discusses the comparative results, including supports to related policies, potential work on building energy data to address new trends in related studies, and limitations. Section 5 provides the conclusions of the study.

2. Method

In order to answer the questions mentioned above, the related data of different countries were collected. And before the data collection, different indicators related to building energy use and carbon emissions were reviewed to determine the data needed. Then curve fitting analysis were conduct to find the relationship between indicators and clustering analysis to group the countries in the view of building energy use.

2.1. Indicators

In a comparative analysis on energy use, the basis of the research would be data collection. However, before this part of the research, the previous step would be deciding what data are needed, namely the indicators that would be used in the analysis.

In the view of energy or emissions efficiency, the indicators in this study can be considered as a combination of inputs, such as energy and emissions, and activity output, to measure the services provided for a specific scope, namely the building sector [27]. The activity data include mainly the building stock and population from existing studies [27,11]. To fully compare different situations, these combinations will be used whenever possible.

The energy structure is also an important aspect of this research. The indicators employed include the shares of fossil fuel, renewable energy, and electricity [24,30]. In this study, the shares of electricity and biomass are chosen because of their strong links to climate-change mitigation actions. It is needed to note that biomass usage includes two ways, namely to burn the biomass directly in traditional way with low efficiency and to use densified biomass with high efficiency. In current statistic systems, these two kinds of usage were combined into one. Many households still use low-efficiency biomass in most developing countries and in some developed countries, bringing indoor and outdoor pollutions. The high-efficiency biomass is encouraged as a kind of zero-carbon fuel and is relatively clean.

In a global comparative analysis, it is also necessary to reflect on the situation that, in some developing countries, there are still people without access to modern energy, which will affect the energy development target and energy inequality to some extent [47]. Thus, in this study, indicators about the shares of households or populations without electricity or commercial energy, or heavily dependent on non-commercial energy, which is listed in IAEA [18] to monitor progress in accessibility and affordability of modern energy, are planned to be included as a supplement.

The climatic condition also affects building energy use, especially heating and cooling demand, and thus its inclusion is necessary. It is necessary to note that for large countries with varied climatic zones, such as the U.S., China, and Australia, using one indicator to reflect the situation of the entire country may not be meaningful enough based on its meteorological definition, but may useful only in presenting a weighted situation. According to a review on climate zoning methods for building energy efficiency, degree days and temperature are found to be the most common variables for zoning [55]. These kinds of indicators will also be collected.

Finally, some indicators to reflect the economic and social development are also important because these can show the relationship between building energy use and the overall development of the country. Gross domestic product (GDP) data are always used as the most common indicator for evaluating the economic development and will be included in this study. Moreover, some other indicators that will reflect the living standards of people rather than only the overall economic level are also needed. These kinds of data can be considered as the "outputs" of the energy use, which reflect the service levels in buildings with different levels of energy use.

2.2. Data collection

Based on these indicators, the required data, including energy use (total amount, electricity, renewable energy, and biomass), carbon emissions, activity data, and access of modern energy, are collected for the following analysis.

In this study, the final energy consumption data, which include the energy consumption by fuel type of different sectors, are from the IEA database [22]. The residential sector, and commercial and public services are selected to compose the building sector [19]. The electricity is converted to a calorific value (1 Mtoe = 0.086 TWh) [24]. Meanwhile, the carbon emissions data, which include direct and indirect emissions, are from IEA [21].

The world development indicators (WDI) database is used to obtain population data from 1960 to 2018 [61]. The average number per household, released by the Department of Economic and Social Affairs of United Nations (UNDESA), is also used as a supplement to the demographic data [53].

Building stock is also an important parameter, but it seems that there is yet to be a database collecting these data globally. Thus, in this study, these data are collected by country, one by one. Furthermore, not all countries are found to have these data published, and thus the authors attempt to collect these data as much as possible. The sources include existing region datasets, statistic yearbooks, and related reports and papers. The details on the data used in the paper will be outlined together with illustrations. Because the definitions and boundaries in these different sources are different, the values are not well comparable. It is necessary to note that only the data on the overall situation may be useful, and that the individual values may not be very accurate. More research on this will be needed in the future.

For the indicator of access to modern energy, data on the shares of population access to clean fuels and technologies for cooking are collected from the WDI database. These indicators can also be used as a reference to evaluate how biomass is used in one country. If the shares of accessing to clean fuels and technologies are high, then it is believed that most biomass is used with high-efficiency. For the climatic condition, the heating degree days (HDD) and cooling degree days (CDD) from the global dataset by Atalla, Gualdi and Lanza [2] are used.

GDP data are obtained from the WDI database, whereas happiness scores, which are used to show how happy the citizens in each country perceive themselves to be, are sourced from the World Happiness Report and are taken as an indicator of living standards [16].

Through a combination of these databases, 135 countries and regions, which cover 95% of population, 98% of GDP, and 97% of building energy consumption globally, are included in this study, together with their respective main indicators (energy use by fuel type, carbon emissions, population, and GDP). For the study on the status quo, values from 2017 are used if available; otherwise, the latest values are used instead.

In terms of the relationships among these parameters, the indicators and data sources used in this study are shown in Fig. 1.

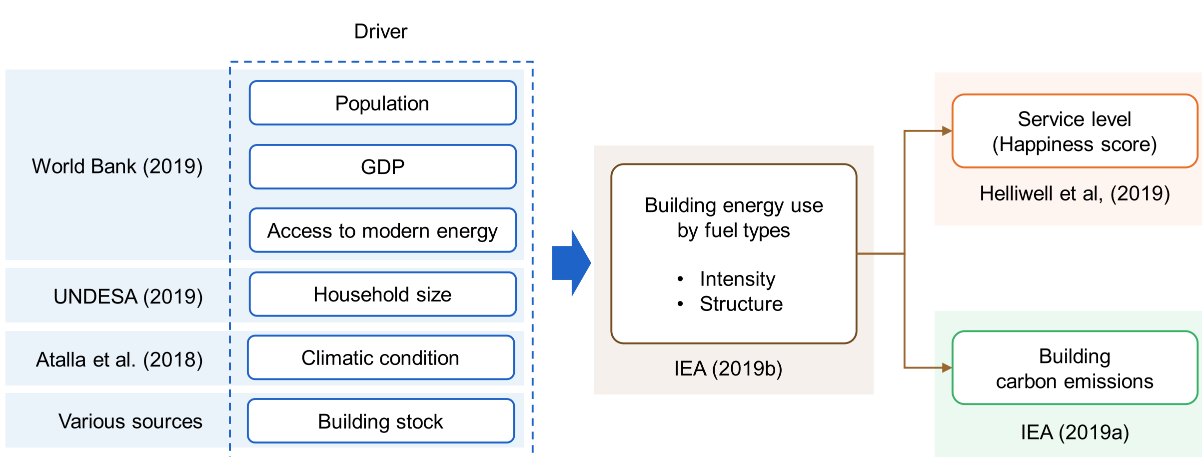


Fig. 1. Indicators data used in this study.

2.3. Curve fitting

To show the relationships among different indicators, curve fitting is used in the following parts of the research. According to some existing studies, a fitted curve on the international situation can be used as a basis for scenario setting[60]. In the global building model of the IEA energy technology perspective group, three lines (high, medium, low) were fitted according to available historic data from different countries to forecast the floor area and people per household following global trends [26]. In this study, the curves are also created to show global trends and boundaries, which can be used as a supplement to scenario setting or forecasting.

For each set of indicators, three curves are to be fitted: high, medium, and low. The high curve represents the 10% highest dots, and the low curve represents the 10% lowest, both covering extreme situations, whereas the medium curve represents the medium 80% or the average situation, as shown in Fig. 2.

Based on the studies on country comparison that have been mentioned previously, the linear shape and S-shape are found to possibly both exist. In this study, the basis function is selected according to the relationships among the indicators.

For the S-shape, Logistic and Gompertz curves are the most commonly used, but both of them have a relatively certain shape [17], which may not well reflect the real situation. Thus, in this study, the four-parameter model Richards function [48], as shown in formula 1, is used.

$$y = \alpha[1 + \beta e^{-\gamma x}]^{\delta} \quad (1)$$

2.4. Clustering analysis

To determine new groups according to building energy use, a clustering analysis is used. Based on the considerations mentioned previously, these new groups should be able to reflect the current overall situation of energy use. The specific indicator used for each field is chosen according to the results discussed in Section 3.

In this study, the k-means clustering approach is chosen because it is one of the most widely used clustering algorithms [31]. To create a better solution, the clustering work is repeated for several times [33] with different numbers of groups, with the final clustering results being selected based on a comparison of the results and using the measurement method by Pham, Dimov and Nguyen [46]. The clustering work is performed according to the following steps:

(1) Use min and max values to normalize all datasets according to formula 2:

$$I_{i,j}{}^{*} = \frac{I_{i,j} - I_{min,i}}{I_{max,i} - I_{min,i}}, \; i = 1, \ldots, N_d; \; j = 1, \ldots, N_c, \quad (2)$$

where $I_{i,j}{}^{*}$ is the normalized value of indicator i in country j, $I_{i,j}$ is the original value, $I_{max,i}$ and $I_{min,i}$ are the maximum and minimum of indicator i, and N_d and N_c are the numbers of indicators and countries, respectively.

(2) Use k-means clustering approach to cluster the dataset, namely to find the cluster centers with the minimum value of sum of the squared error over all clusters, as shown in formula 3:

$$S_K = \sum_{k=1}^{K} \sum_{l=1}^{N_k} [d(C_{k,l}, w_k)]^2, \; C_n = [I_{1,n}*, \ldots, I_{N_d,n}*], \quad (3)$$

where S_K is the sum of the squared errors when K clusters are used, C is the vector of five indicators for each country, $C_{k,l}$ is the lth object belonging to cluster k, w_k is the center of cluster k, $d(C_{k,l}, w_k)$ is the Euclidean distance between $C_{k,l}$ and w_k, and N_k is the number of objects in cluster k. This work will be done using different numbers of clusters and repeated for 10 times.

(3) Choose the number of clusters K based on the results and evaluation function $f(K)$; a smaller $f(K)$ indicates a more concentrated cluster. $f(K)$ is calculated using formula 4.

$$f(K) = \begin{cases} 1 \text{ if } K = 1 \\ \frac{S_K}{\alpha_K S_{K-1}} \text{ if } S_{K-1} \neq 0, \forall K > 1 \\ 1 \text{ if } S_{K-1} = 0, \forall K > 1 \end{cases}, \; \alpha_K = \begin{cases} 1 - \frac{3}{4N_d} \text{ if } K = 2 \text{ and } N_d > 1 \\ \alpha_{K-1} + \frac{1-\alpha_{K-1}}{6} \text{ if } K > 2 \text{ and } N_d > 1 \end{cases} \quad (4)$$

Through the clustering calculation, new groups with respect to building energy use are to be proposed, and development approaches for different groups are to be discussed.

3. Results of global energy consumption comparison

3.1. Energy use total amounts and intensities

Fig. 3 shows the building energy use intensities and the populations in each of the countries, sorted by EUI. The area under the line equals the total amount of building energy use, whereas the colored squares indicate the ten countries with largest total building energy usages, which cover 60% of the global building energy use.

The energy use in different countries can be seen to differ greatly, from less than 50 kgoe/cap (14 kgoe/cap for South Sudan, and 33 kgoe/cap for Yemen) to more than 1600 kgoe/cap (1634 kgoe/cap for Luxembourg, and 1614 kgoe/cap for Canada). The EUI of more than 70% of the population is under the average level of the entire world.

The country with the largest building energy consumption was the U.S., following by China and India, but the structures of these three countries are not the same: the U.S. has a high EUI (1391 kgoe/cap) with a higher population, China has a relatively low EUI (302 kgoe/cap) with a large population, and the EUI of India (148 kgoe/cap) is quite low.

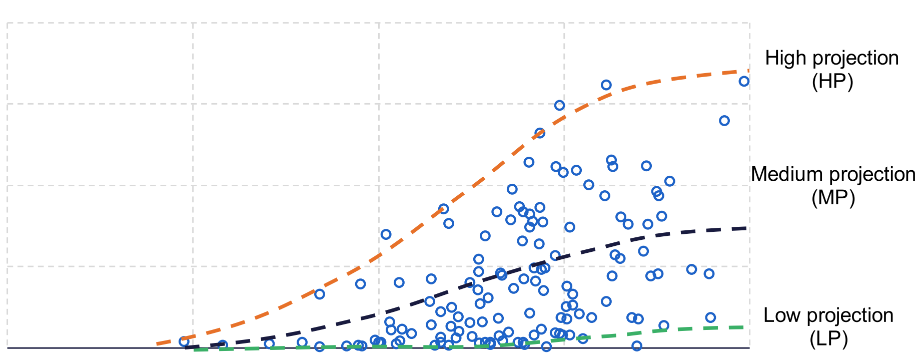


Fig. 2. Sketch of the fitted curves in this study.

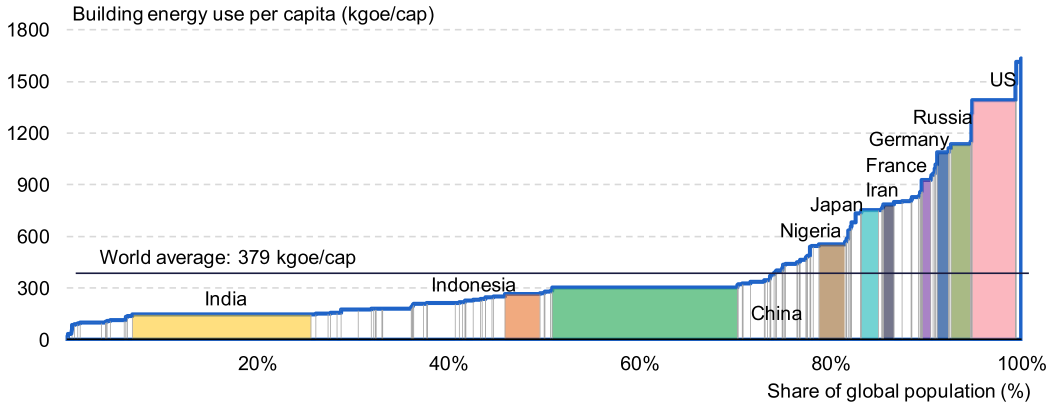


Fig. 3. Building energy use intensities and populations in countries (2017).

[Fig. 4](#) shows the energy use per capita and by unit of floor area in selected countries. These 12 countries account for around 60% of global building energy use. The countries with higher energy use per capita could be seen to have a relatively higher energy use per square meter (m^2).

Sources of floor area: US: EIA [12]; Canada: NRCAN [43], the value from 2016 is used because the handbook has not yet been updated; UK, France, Germany, and Spain: Enerdata [13]; Japan: MLIT [40]; Korea: KEEI and KEA [32]; China: BERC [6]; India: Kumar et al. [34] and NSO [44]; Russia: Bashmakov [3] and Rosstat [49]; Indonesia: Siagiana et al. [51], Nazer [41] and BPS [7].

The building energy usages by unit of floor area in India and Indonesia are relatively high. The building energy use data of these countries are found to include large shares of biomass, which is always non-commercial and of low efficiency. In these two countries, accesses to clean fuels for cooking are all below 60%. Furthermore, if non-commercial biomass is excluded from the data on the three developing countries in the figure (India, Indonesia and China), the intensities will be lower, as shown in Fig. 5. This topic will be discussed further in the energy structure part of this paper.

The floor area per m^2 in Russia could also be seen to be much higher. Based on depth analysis, one reason may be that the heat use was much higher, which in the residential sector was approximately 0.9 GJ/m^2 [39], whereas that in the Nordic countries was mainly around 0.4 GJ/m^2 [13].

Because the economic development level is considered as one of the important drivers in building energy use, the relationship of GDP per capita (GDPPC) and building EUI is also important, as shown in Fig. 6. Countries with higher GDPPC can be seen as having relatively higher building EUIs. For countries with similar economic levels, the differences in building EUI can be at least 5-fold, with the gaps being larger for higher GDPPCs. Analyzing energy use situations via grouping of countries by economic development is able to reflect overall trends, but in-group differences, which may also be large, will be ignored.

Meanwhile, different traces connecting the countries, as the curves in the figure, can also be considered as different approaches to building sector development. For developing countries, the selection of approaches will lead to big differences in building energy use in the future and would therefore require more focus, given the severe challenge of energy conservation and climate change.

Fig. 7 shows the relationship of building energy use intensity and happiness score. From a comparison with Fig. 6, the link of these two variables could be seen to be relatively, significantly weak. The overall trends, wherein countries with higher EUIs have higher happiness scores, still exist, but the gaps between countries with similar happiness indexes are even higher. Thus, to some extent, higher building energy use may not bring more happiness. The development approaches of countries with lower EUIs and higher happiness scores are worthy of further analysis to provide more insights on sufficiency development.

In many studies, the share of building energy use in total final energy consumption is reported as an indicator that reflects the importance of building energy conservation. Fig. 8 shows the relationship of this indicator with building EUI and economic level. Dots with different colors symbolize different groups classified by GDPPC. It could be seen that in the countries with lower GDPPC,

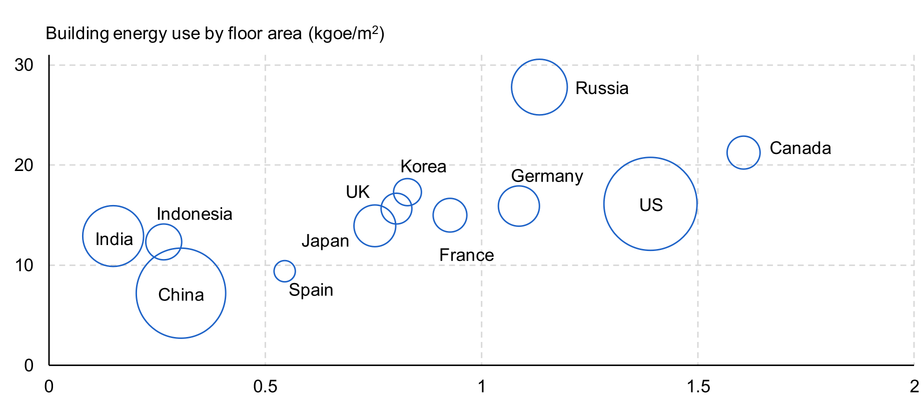


Fig. 4. Building energy intensities in selected countries (2017).

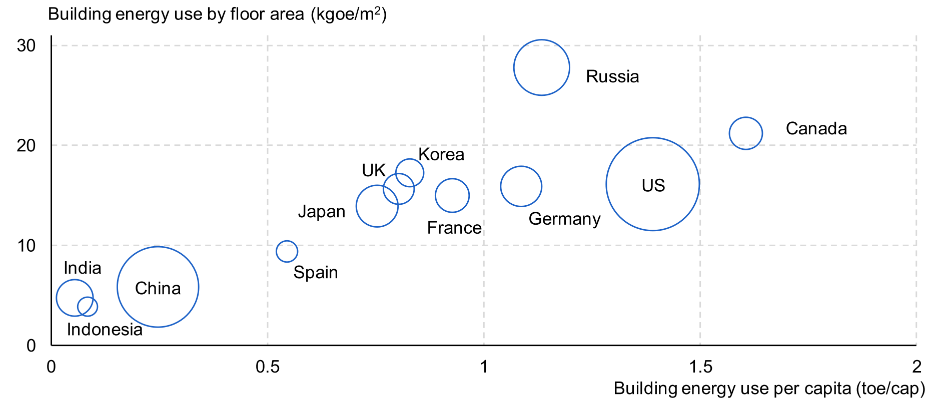


Fig. 5. Building commercial energy intensities in selected countries (2017).

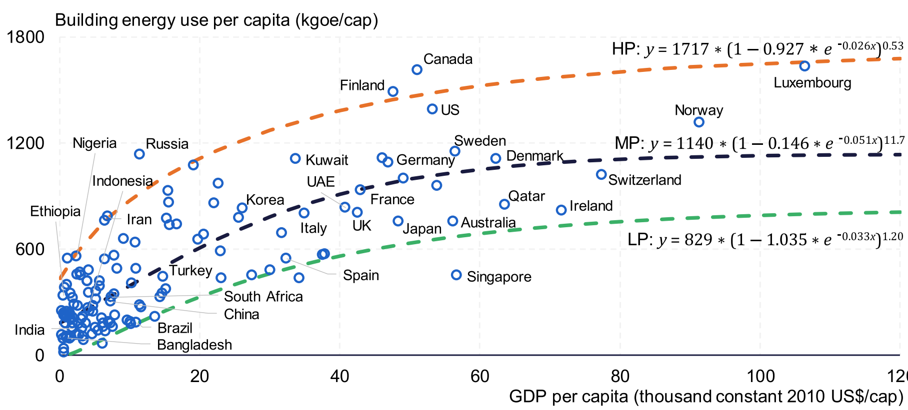


Fig. 6. Building EUI and GDP per capita (2017).

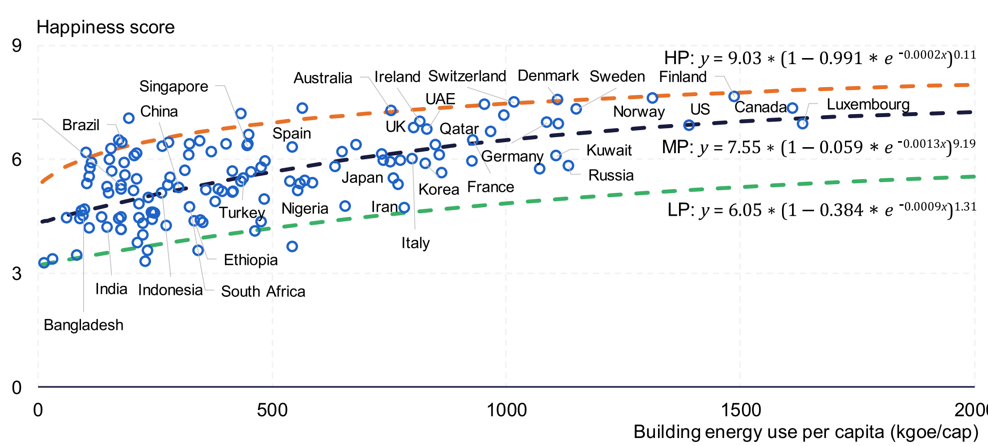


Fig. 7. Building EUI and happiness score (2017).

when the building EUI grows, the share of building energy use will also grow. However, this trend does not apply to developed countries.

For countries in group 1 to group 3 (the least to medium wealthy, namely the blue and green dots in the figure) with similar EUIs, the share of building energy use in the wealthier countries will be lower. One main reason for this phenomenon is that for the least developed countries, industry or transport demands are not high. In other words, for these countries, the higher share is not due to the high building energy use, but rather is due to the relatively low energy use in other sectors. Meanwhile, for the developed countries (groups 4 and 5, i.e., the orange and red dots), the share is approximately 20% to 40%, and the link between EUI and the share of building energy use is quite weak. Thus, using the share of building energy use to evaluate the necessity of building energy conservation work in one country may not be very appropriate.

3.2. Energy structure

In this section, the building energy structure is to be discussed. For the entire world, electricity accounts for the biggest share (ap-

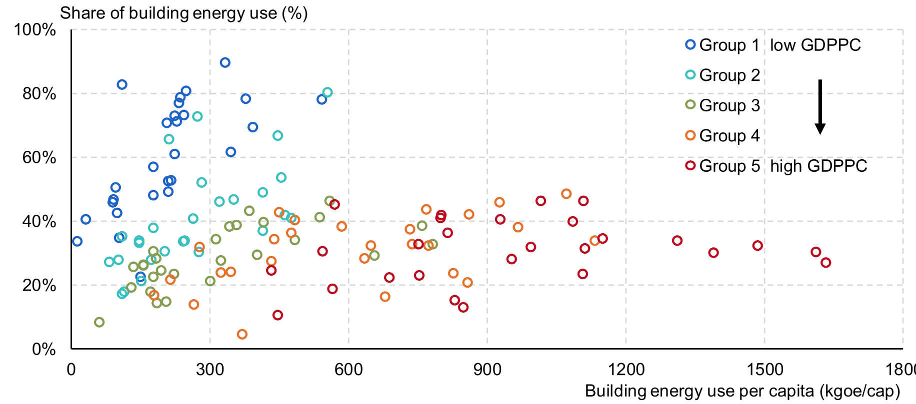


Fig. 8. Building EUI and the share of building sector in total energy use (2017).

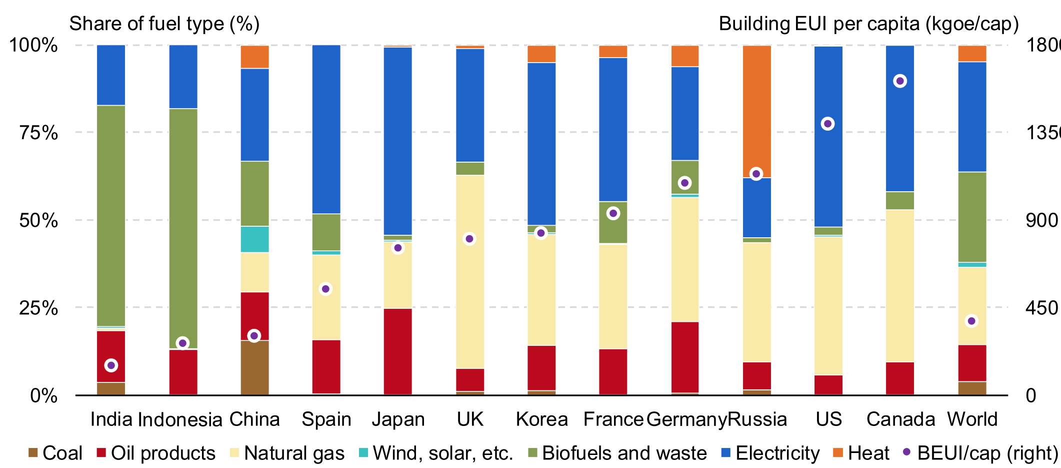


Fig. 9. Energy structures of selected countries (2017).

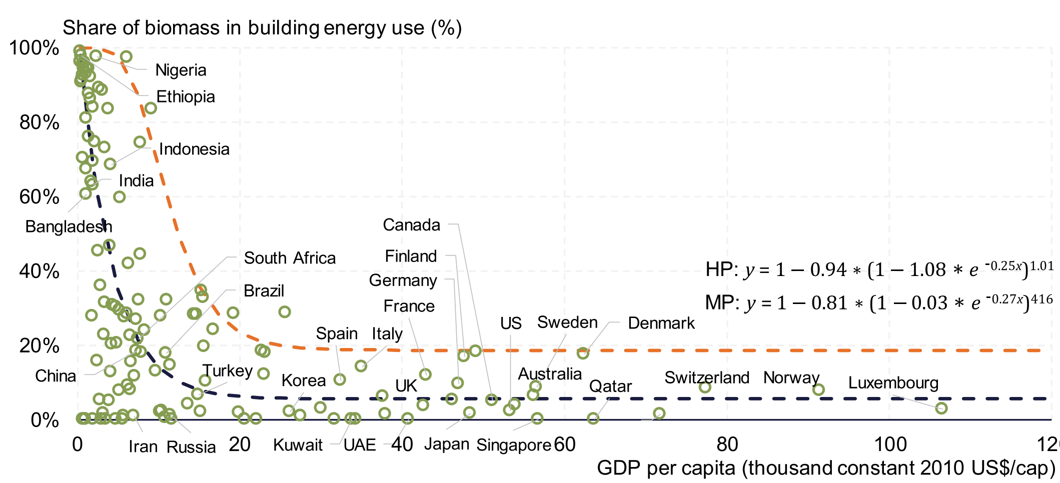


Fig. 10. Share of biomass in building energy use and GDP per capita (2017).

proximately one third), followed by biomass (one quarter). Fig. 9 shows the energy structure of the entire world and in selected countries. The energy structures in different countries could be seen to vary greatly. Electricity and natural gas are the main fuel types for developed countries, whereas relatively higher building EUIs and use of biomass apply in developing countries, whose EUIs are lower.

Fig. 10 shows the relationship of the share of biomass and GDPPC. The shares of biomass in countries with lower GDPPCs are obviously higher. In these countries, people use traditional biomass for cooking and heating. For the developed countries, the share of biomass could also be seen to vary, and in some countries, the share is close to 20%. In these countries, biomass is used in a highly efficient way, which is quite different from what is done in developed countries. Actually, with the higher pressure on carbon reduction, the use of high-efficiency biomass has been proposed in many countries and regions, such as Europe [14], as an important approach. It might be foreseeable that in the future, the relationship of the share of biomass and GDPPC will change from the current *L* shape to a *U* shape with more usage of biomass in developing countries, but with the efficiency, cleanliness, and cost of the fuel being absolutely different.

The share of electricity in final energy consumption is also much discussed with the promotion of electrification. Fig. 11 shows the relationship of the share of electricity and GDPPC. When the GDPPC is relatively low, the share of electrification could be seen to increase significantly with economic development, but the link becomes weak in developed countries. On the other hand, to increase the electrification ratio in the building sector, the main task is to improve the ratios of space heating, water heating, and cooking demand, and the heat demand is largely affected by the climate condition.

Through further analysis, the electrification ratio is found to not have a strong link to the climatic condition in the developing phase, but the trend changes for countries whose GDPs per capita are higher than US$ 10 thousand, constant 2010, as shown in Fig. 12. One reason of this phenomenon might be that countries with higher HDD have larger heating demands. Heating is one of the main end-use for direct fossil-fuel usage [59] and the electrification rate for heating is relatively low. For the developing countries, the share of cooking is high while appliances relatively low, then the impacts of heating structure are weakened. For the developed countries, the share of cooking is relatively low, and heating becomes the largest end-use with lower electrification ratio. Then the impacts of heating structure emerge. However, for a death explanation, more data and analysis, such as case studies, are still needed.

3.3. Carbon emissions

Fig. 13 shows the building carbon emissions intensities in selected countries. Similar to in the energy use situation, the intensity varies among the countries, except the trends for these countries are different. Contrasting Fig. 9, the energy usages and structures in France and Germany are found to not vary greatly, with the carbon emissions in France being much lower, as a result of a high proportion of nuclear electricity production. The direct emissions mean the emissions from fossil fuels used in buildings directly and the indirect emissions from electricity and heat supply. It could also be found that US has extremely high indirect emissions. It is because that the electricity use intensity there is much higher than other countries (as shown in Fig. 9) and the carbon intensity of electricity is in middle level.

Fig. 14 shows the building carbon emissions and energy use per capita in each country, exhibiting the strong link between carbon intensity and EUI and also the considerable gaps in carbon intensity in the same sector of building energy use. These data also

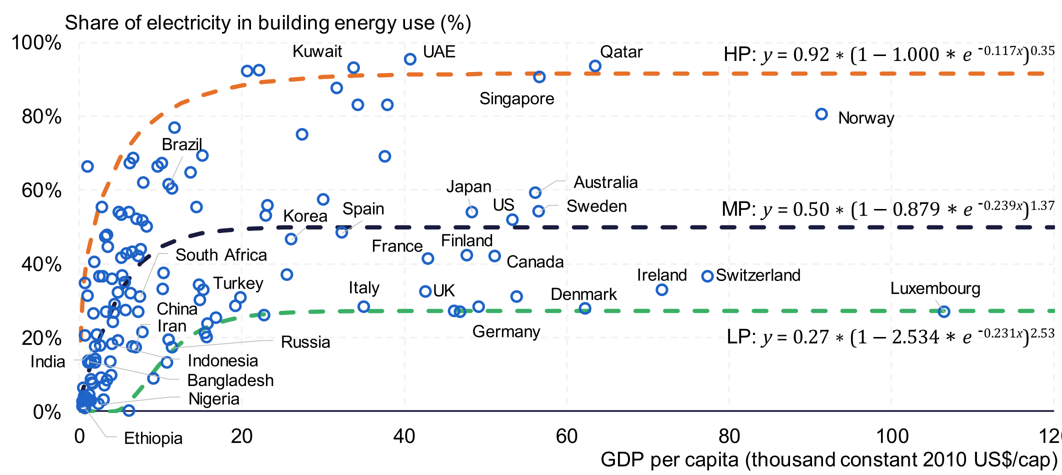
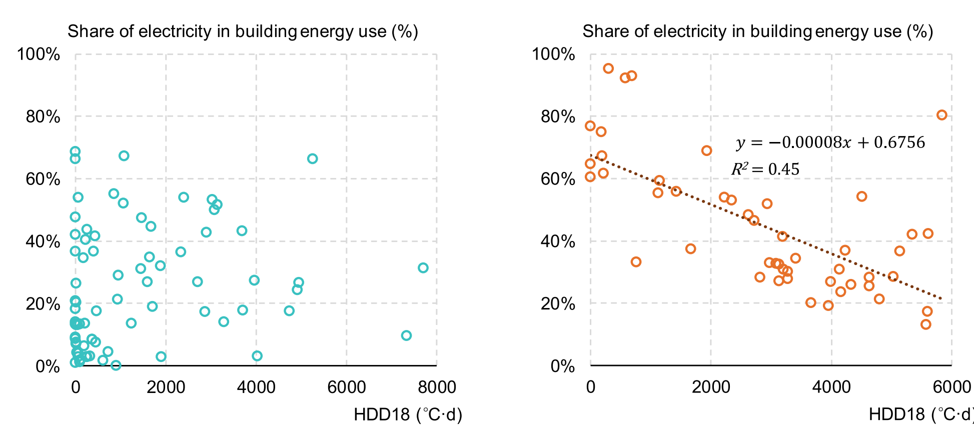


Fig. 11. Share of electricity in building energy use and GDP per capita (2017).



(a) GDPPC < 10,000 constant 2010 US$* *(b) GDPPC > 10,000 constant 2010 US$

Fig. 12. Share of electricity in building energy use and HDD (2017).

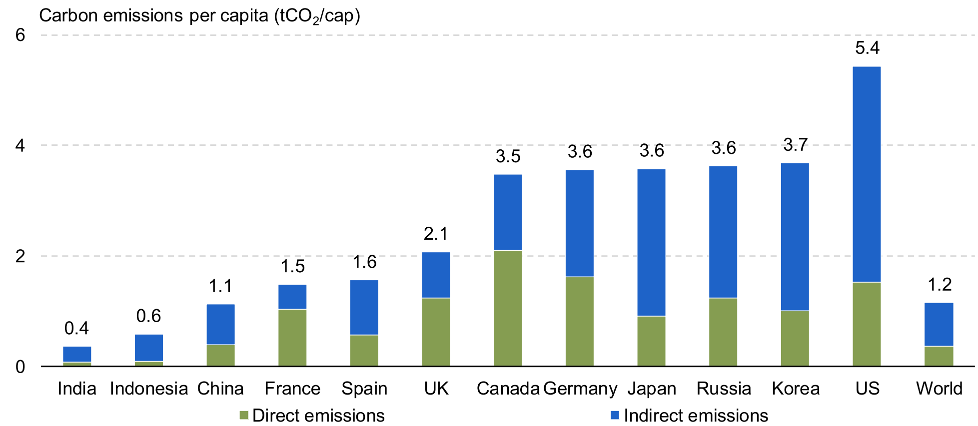


Fig. 13. Energy-related carbon emissions per capita in selected countries (2017).

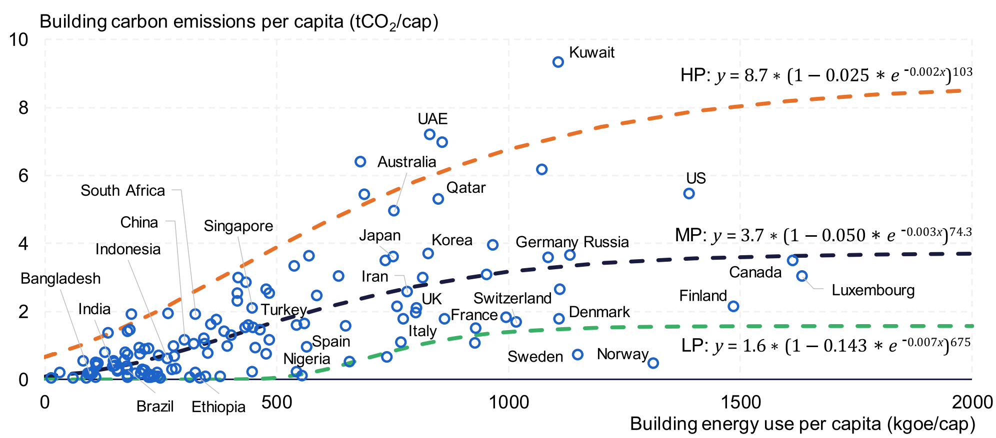


Fig. 14. Carbon emissions intensity and energy use intensity (2017).

Table 1
Country groups with respect to building energy use characteristics.

	Center of each group (GDPPC, HDD, EUI, biomass share, electricity share)	Example countries
Group a	1897 US$/cap, 206 °C·d, 189 kgoe/cap, 82%, 11%	India, Indonesia
Group b	3356 US$/cap, 601 °C·d, 452 kgoe/cap, 90%, 7%	Ethiopia, Nigeria
Group c	7035 US$/cap, 912 °C·d, 190 kgoe/cap, 15%, 49%,	Brazil, South Africa
Group d	8831 US$/cap, 3836 °C·d, 439 kgoe/cap, 17%, 31%,	China, Turkey, Spain
Group e	30,020 US$/cap, 3063 °C·d, 786 kgoe/cap, 11%, 40%,	UK, Japan, Iran
Group f	49,771 US$/cap, 4295 °C·d, 1120 kgoe/cap, 10%, 43%,	Canada, US, Russia

indicate that energy conservation or efficiency work alone may not solve the problem of climate change, which is the same as the conclusion of Urge-Vorsatz et al. [54].

This difference is in the comprehensive result of the study on the energy structure and electricity structure. Some countries have low energy intensities and extremely low carbon emissions, which are mainly due to the main fuel type being biomass, which, in most cases, is non-commercial biomass used with low efficiency, such as in Nigeria. Some countries have relatively higher EUIs but low carbon emissions, such as Norway and Sweden, in which the shares of renewable electricity are always higher. Moreover, the carbon intensity in Kuwait is much higher than those in other countries with similar EUIs, and the electricity ratio there is found to be above 90%, and the share of renewable electricity is determined to be less than 1%. In summary, the situation of each country can vary greatly, and from the point of view of building management, both energy use intensity and energy structure are important in reducing carbon emissions.

3.4. Clustering countries based on building energy use

Based on the results in Section 3, the GDP per capita (I1), HDD (I2), building energy use per capita (I3), and shares of electricity and renewable energy (I4 and I5) are selected for the clustering. The first two indicators are to describe the driver, whereas the latter three describe the energy use situation. In this part of the research, 123 countries are included based on the data assessment.

Through clustering work, the countries were classified into six groups, as shown in Table 1, and the results for all countries can be seen in Fig. 15.

The countries in "Group a" have the least building energy use and the least income, with high shares of biomass, low shares of

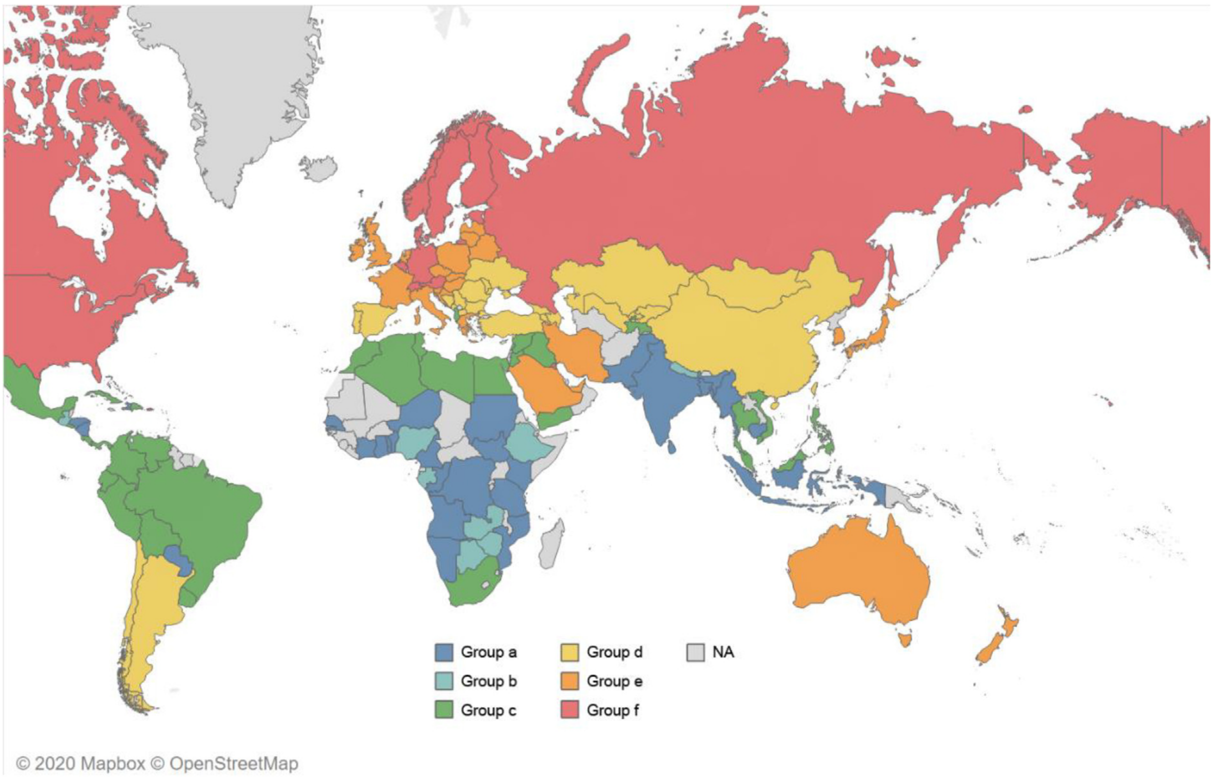


Fig. 15. Results of clustering countries based on building energy use.

electricity, and low demands for heating. "Group b" countries have higher EUIs and economic levels, with higher heating demands and biomass usages. In these countries, the biomass is usually non-commercial and used in low efficiency for cooking and heating. If only commercial energy use is considered, then the energy consumptions of these countries will be much lower. The GDPs per capita of "Group c" and "Group d" countries are similar and about twice those of "Group b" countries. The EUI of "Group c" is similar to that of "Group a," whereas that of "Group d" is similar to that of "Group b", but with the biomass share being much lower. The HDD of "Group d" is nearly four times that of "Group c," and the electrification ratio of "Group d" is lower. The EUIs of "Group e" countries are about twice that of "Group d," but with much higher incomes and slightly lower heat demands. "Group f" countries are the countries having highest energy intensities and economic levels; the heat demands are also relatively high, and the electrification ratios are at medium level.

Compared with existing groups, this new classification method refined the countries with similar economic levels based on energy consumption and demand. Thus, approaches for different groups could be proposed more specifically.

For "Group a" and "Group b," the requirement on building energy consumption is probably not energy efficiency, but rather, the desire to ensure the requirement of basic living standards and improve indoor air quality. Energy use will keep increasing, and thus the use of non-commercial biomass in low efficiency should be reduced. For these countries, the main task will be to select an appreciative developing approach, which is able to increase the service level but not following the approach with high intensity. Furthermore, modifying the energy structure, including reducing traditional biomass and increasing electrification ratio, is still necessary. For "Group c" and "Group d," the EUI is relatively higher, but the improvement of service level is also necessary in most countries. These countries need to avoid obvious increases in energy use and, at the same time, ensure sufficient service levels. In terms of energy structure, reducing the traditional biomass used in some countries and improving the electrification ratio are both necessary. For "Group d" and "Group e" countries, the reduction of EUI through effective energy conservation and increase in electrification ratio is urgently needed. Meanwhile, for "Groups d," "e," and "f" countries with high heating demands, decarbonization on heating will be important.

In summary, the suggested main development targets as well as the characteristics for each group are outlined in Table 2.

4. Discussions

4.1. Support for building energy policies and researches

Through above analysis, it could be found that with various building energy use and carbon emissions, different countries have different bottle-necks on low-carbon transformation and needs different development patterns. The global comparison of building energy use data could help to show which phase of the country is in, and give supports for policy making and related researches on development patterns.

In terms of energy use intensity, there are mainly three kinds of countries: countries with quite low EUI (like group a and b in 3.4), with EUI at medium level (group c and group d) and with high EUI (group e and group f). For the first kind of countries, the energy use intensity will increase because of the excessively low service level; the second kind of countries are at the crossroad and they need to be quite careful to choose how their building sector will develop; and for the last kind of countries, their EUIs need to decrease, as shown in Fig. 16.

In terms of energy structure, the countries with quite low EUI used to have a high percentage of traditional biomass and low share of electricity and other renewable energy (group a and b). For these countries, one approach is to follow the path of other developed countries, namely to change traditional biomass to fossil

Table 2
Main development target on building energy use of each country group.

	Characteristics			Target	
	Economic level and climatic condition	Energy use intensity	Energy structure	EUI	Energy structure
Group a	Least income with lowest demands for heating	Least building EUI, lower commercial EUI	High shares of low-efficiency biomass, low shares of electricity	Keep increasing to meet the basic living standards	Reduce the use of low-efficiency biomass sharply
Group b	Low economic level with low heating demands	Relatively low building EUI and lower commercial EUI	Highest shares of low-efficiency biomass, lowest shares of electricity	Keep increasing to meet the basic living standards	Reduce the use of low-efficiency biomass sharply
Group c	Medium economic level with low heating demands	Least building EUI	Low shares of biomass, highest shares of electricity	Avoid big increase on EUI for development	Increase electrification ratio and reduce the use of low-efficiency biomass
Group d	Medium economic level with high heating demands	Relatively low building EUI	Low shares of biomass, medium shares of electricity	Avoid big increase on EUI for development	Increase electrification ratio sharply and reduce the use of low-efficiency biomass
Group e	High economic level with high heating demands	Relatively high building EUI	Low shares of biomass, relatively high shares of electricity	Reduce EUI by energy conservation effectively	Increase electrification ratio
Group f	Highest economic level with highest heating demands	Highest building EUI	Low shares of biomass, relatively high shares of electricity	Reduce EUI by energy conservation effectively	Increase electrification ratio

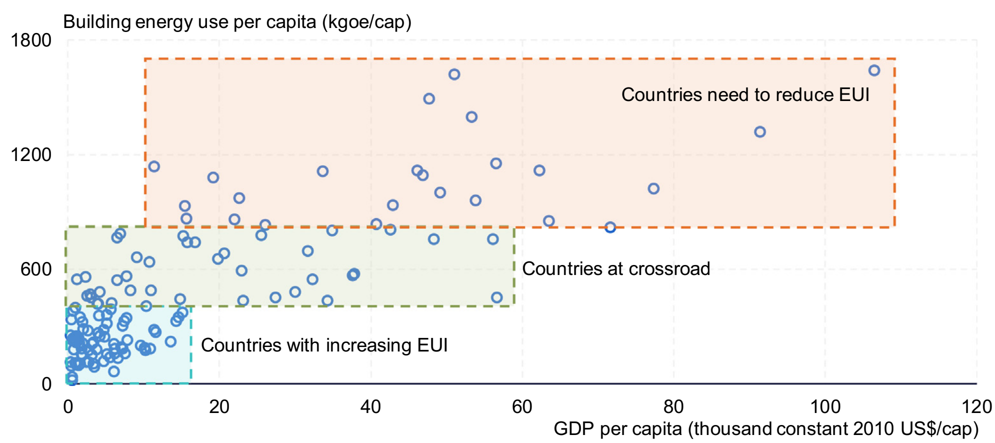


Fig. 16. Sketch of the countries with different kinds of EUI.

fuels, and then fossil fuels to electricity or other renewable energy; the other is to skip the fossil fuel phase, namely to change from traditional biomass to electricity or renewable energy directly. In terms of climate change, the latter one seems more appreciate. For the countries with low percentages of traditional biomass, the main challenge is to change fossil fuel to electricity or other renewable energy. Some countries are on a transition phase, namely they should reduce the usage of fossil fuels and traditional biomass at the same time. The three kinds of countries are shown in Fig. 17 sketchy. The countries with higher heating demands should put more focus on the decarbonization of heating systems.

4.2. Potential suggestions for data on building energy use

Through the previous analysis, opportunities to improve the involved data have been found for future studies on building energy use.

Although many studies on energy use data have been conducted, and many indicators have been proposed, finding a global indicator is still difficult, and the definitions of some indicators need to be further clarified. As already mentioned, building stock is one of the most important activity data, but some global datasets are still lacking, and thus the only method presently available is to collect data through related materials, one by one. However, many countries are still without related statistics or studies, with the boundaries for each material differing among countries. Thus, some studies on this topic may still be needed. Another indicator that requires more attention is the share of biomass. In existing studies, these data include both traditional and modern biomass use, where the former should be reduced, and the latter should be encouraged. Combining these two kinds of biomass may cause some confusion in related analyses, and thus clarifying the fuel types for this indicator will be necessary.

With the new trends in the building energy field, some indicators would require more focus. On building energy use intensity, the total energy use is employed. However, in many developing countries, traditional biomass is found to still be largely used; this proportion of energy use should be reduced, whereas other forms of energy use need to be increased. For these countries, the use of commercial energy, namely, energy use excluding non-commercial biomass used in low efficiency, will be an improvement. These data will be available if it is possible to obtain the shares of traditional biomass for each country. With regard to energy structure, as electrification plays a big role, the electrification ratio will also be of importance in evaluating the carbon reduction work in the building sector. Aside from the aforementioned, energy poverty is another topic much discussed in recent years in the building energy sector; it is found to have strong and comprehensive links to energy use and climate change [50]. No global or regional database seems to be focusing on this issue,

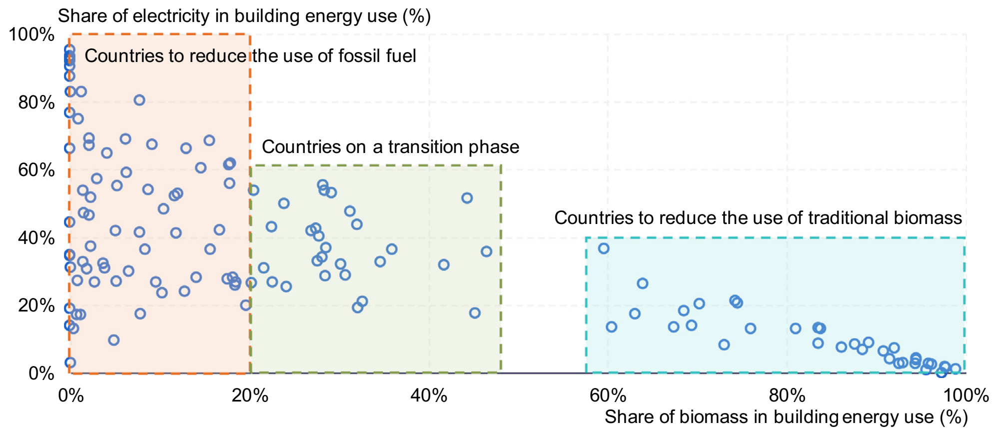


Fig. 17. Sketch of the countries with different kinds of energy structure.

but many studies on this phenomenon have been conducted, and some indicators for evaluating this situation have been proposed [10]. In future studies, some related indicators will also be needed.

Meanwhile, with regard to building energy, some relative fields are still missing in most studies, despite being of great importance in addressing climate change. Including these indicators in future research will bring better and more comprehensive understanding on climate change, and will bridge gaps in studies regarding the link of energy and climate change in buildings, which is found through analysis of literature [8]. Adaptation is also important in the face of climate change, including global warming and more extreme events [28], both of which will affect building energy consumption. For example, more extreme heat will lead to more cooling demand and risks of indoor overheating, and some different indicators for evaluating the risks will be necessary [15]. In addition, the total emissions in the building sector greatly depend on the electricity carbon intensity. Buildings can possibly contribute to electricity carbon intensity through demand response, energy storage, etc. [23], but these measures cannot be included in the existing indicators system for evaluating if a building is low-carbon or not. To encourage the building owners to do more on this issue, some other indicators also need to be included.

Furthermore, based on various perspectives, buildings are not only an important contributor to energy use and carbon emissions, but are also the places in which people spend more than 90% of their time [52]. Thus, issues like health, productivity, and wellbeing all need to be considered in building development [58]. These perspectives also have approximate links to climate change. In future studies, some indicators in these fields may also be considered.

4.3. Limitations

This research has several limitations, mainly in four aspects: the explanation of the data, the processing of bias, data collection and research method.

Firstly, in this study, the difference of energy consumption and carbon emissions in countries were discussed, but many phenomena are still worthy of further analysis. And some relationships of different indicators are not explained clearly enough. Based on more depth explanations, improved suggestions on building energy use policy and researches could be put forward, which might be helpful for the low-carbon transformation.

Secondly, it could be seen that there are many significant omitted variable bias in the curves. These bias show that there are still many factors influencing the building energy use but not considered fully yet, like climatic condition, occupancy behavior, etc. In this study, this problem has not been discussed because information collected were insufficient, as a result of the difficulty of data collection and the quantitative description in some fields. However, it is quite important for a better understanding of the data and will bias the results. And it is needed to be analyzed in following studies with more data and methods.

Thirdly, as mentioned above, more data is needed for further analysis. In this study, many databases have been collected but the data is still largely insufficient for depth researches. One important bottle neck of data collection is that the building energy use data system needs improvement, as discussed in 4.2. And some other data sources may also be needed except for statistical data. For example, large-scale surveys on residential building energy use and case studies on campus buildings in the U.S. and China have been used to understand the difference of building energy consumption in these two countries [5]. In future studies, data form more surveys, investigations or other sources could be used as the supplement of the statistical data. These data from other sources may also supply more information on the relationship of the macro situation and the specific strategies on technologies and building design.

Fourthly and lastly, in this study, more analysis used descriptive statistics methods. These analyses could release and explain some phenomenon but were not enough. In economic and social science fields, there are many methodologies for data analyze. These methods can be used for further researches.

Above all, this study is only some initial work on this topic. In following works, these limitations will be take into considerations.

5. Conclusions

In this study, data related to building energy use, including building energy use, energy structure, carbon emissions, activity data, climatic condition, and access to modern energy, were collected, covering more than 95% of the world. With the use of these data, a global comparison study on building energy use, including on energy use intensity, energy structure, and carbon emissions, was conducted. A new clustering of the countries was then proposed based on the energy use characteristics, and the approach for each group was discussed. Finally, some potential suggestions on building energy use data were proposed.

The novelty of this research is that this study offers some new viewpoints on looking at global building energy use and carbon emissions. Data from various sources on different fields related to building energy use were collected. The difference between countries instead of regions were released in the view point of low-carbon transformation, including energy use intensity, energy structure and other influence factors.

Through the analysis, it could be found that large gaps in terms of both building energy use intensity and energy structure still exist in many countries. Building energy use is linked to the economic level but is also affected by many other aspects, especially for developed countries. The different situations in terms of energy use in developed countries can also show different development approaches for the building field. For developing countries, selecting a suitable approach is of great importance.

Although energy conservation is much discussed globally, many countries still have demands to increase energy use to meet their basic living standards. In other words, for different groups of countries, the targets for building energy usage are different. Improving electrification ratio and reducing the usage of low-efficiency biomass is needed in most countries, and the key fields in modifying energy structure are different depending on the heating demands.

Meanwhile, through this study, it could be found that through global comparison, the phases of each country on building energy consumption and carbon emissions could be shown, and this information could be helpful on policy making and related researches. Meanwhile, to have a better understanding of building energy use and addressing climate change, data on building energy use probably need to be modified further. Some potential work includes collecting building stock data, separating traditional biomass and modern biomass for energy statistics, using commercial energy consumption and electrification ratios, and adding indicators regarding adaptation and links to grid.

This research is only some initial work on global comparison of building energy use, and much further work is still needed to better explain the differences between countries in terms of building energy use and variable bias. More data will have to be collected from different sources and through some other methods like surveys and investigations. And some other methodologies in economic and social science may also be used.

CRediT authorship contribution statement

Siyue Guo: Conceptualization, Methodology, Visualization. **Da Yan:** Conceptualization, Methodology. **Shan Hu:** Conceptualization, Methodology. **Jingjing An:** Methodology, Visualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2020.110362.

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