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Article

Path to Net Zero: Understanding the Building Energy Efficiency in Different Climates across Various Building Types

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Abstract This study analyses the determinants of building energy efficiency in different climate zones and user types. The energy consumption of buildings in different climate zones can be affected by well-known determinants in different ways. So do the buildings with different user types. The primary aim of this study is to investigate how building energy efficiency is determined in five major climate zones and four main property types. This study uses the global building data (Points Achieved dataset) from the Leadership in Energy and Environmental Design (LEED) rating system 2010 to conduct three cross-sectional tests with logit regression models. The results confirm that the determinants of building energy efficiency are the location of the building, adoption of Building Energy Codes (BECs), climate zones, building types, regional economic development level (namely Gross National Income—GNI, Purchasing Power Parity—PPP) and population density. However, the impact of the determinants varies considerably in different climate zones or for different building types. This is the first empirical study exploring building energy efficiency and how it is determined in different climate conditions and user types. The findings are helpful for the stakeholders, such as policymakers, developers, and local authorities, when they hope to implement measures to improve building energy efficiency and the policy/regulation to boost it. Each building requires specific measures that suit its different climate zones or building types to enhance energy efficiency.

Keywords energy efficiency; LEED; sustainability

Acronyms

- LEED—Leadership in Energy and Environmental Design
- GDP—Gross Domestic Product
- PPP—Purchasing Power Parity
- GNI—Gross National Income
- BECs—Building Energy Codes
- USGBC—U.S. Green Building Council
- HVAC—Heating, Ventilation, and Air Conditioning
- CO_2—Carbon Dioxide
- EUI—Energy Use Intensity
- UHI—Urban Heat Island
- REC—Residential Energy Consumption

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1. Introduction

The energy crisis and climate deterioration are among the hottest issues in the world today, and energy saving has become a common goal. Global energy consumption is estimated to increase by 32% from 2012 to 2035 [1]. Buildings consume around 40% of the total global energy yearly, which is expected to be further aggravated due to population growth [2,3]. Therefore, increasing the building's energy efficiency is crucial to solving energy crisis issues. A range of retrofit measures are found to help improve the energy efficiency of buildings, such as passive [4,5] and renewable energy systems [6]; however, the effectiveness of these measures is inconsistent due to the different features, locations and even uses of buildings. Various factors that impact building energy efficiency have been explored; however, the previous studies focus on one or some specific factor(s) and then investigate the interactive impacts of multiple factors. For example, it is widely agreed that the surrounding environment, such as the urban form [7] and the urban heat island effect [8], can affect building energy efficiency. Another study suggests that urban form can be expressed and measured not only in terms of the physical structure of a city in terms of land use or land cover but also of socioeconomic aspects, such as population size or density [9]. There can be fundamental differences in building energy efficiency between building types [10]. The climate is often seen as one of the factors affecting the energy consumption of a building in some previous research [11–14].

Moreover, the economic development level [15] and energy consumption policies, such as tax subsidies [16], innovation encouragement [17,18], and raising public awareness [19,20] are found to affect building energy efficiency globally. Building energy efficiency is complex and can be determined by many factors in various ways. It is essential to understand how each factor determines the building's energy efficiency while considering other factors. This study conducts a comprehensive analysis of the determinants influencing building energy efficiency across a diverse array of climates and building types globally, utilising a unique dataset from LEED-certified projects. By employing logit regression models, this research not only investigates traditional factors such as economic indicators and population density but also integrates these with climatic and building-specific characteristics in a novel empirical framework. The findings offer critical insights for tailoring energy efficiency strategies to diverse environmental and economic contexts, thereby supporting global sustainability goals. This approach marks a significant advancement over prior studies that have typically focused on narrower regional scopes or limited sets of determinants.

The global building data (Points Achieved dataset) from the LEED rating system from 2010 to 2020 is used, and three logit regression models are employed to test our hypothesis empirically. The results shed some light on the stakeholders, such as policymakers and property developers, in building renovation and development to achieve high energy efficiency.

The remainder of the paper is organised as follows. We review the relevant key literature focusing on the various factors impacting building energy efficiency. The theoretical framework and hypothesis development are provided in Section 3. Data and methodology are demonstrated in Section 4; Section 5 presents and discusses the results. The final section concludes this study.

2. Literature Review

Urban density can take many forms, such as building density, road network density, population density, etc. [21]. Urban density can be measured by building density; however, a fixed area or city limits are given where building density can be calculated with relative accuracy, whereas for larger cities, suburban areas and urban fringe may lead to significant errors in the calculation of overall city building density. Population density can also measure urban area density, especially in the study that includes more prominent cities, suburban areas, and urban fringe. Urban population density is often considered the reason for various urban environmental problems, such as aggravating UHI effect [22,23] and increasing urban pollutants [24]. In particular, UHI can indirectly increase building energy consumption by altering the temperature around the building. UHI is thought to be a phenomenon of heat accumulation due to buildings and human activities, with some urban areas experiencing higher temperatures compared to the nearest surrounding rural areas [25,26], which indirectly results in the necessity for buildings in cities to consume additional energy to maintain indoor thermal comfort [27]. Population density can also have a direct impact on a building's energy consumption. On the one hand, high population density means low per capita costs for transporting energy such as gas [28], which may lead to the better use of renewable energy systems [29]. On the other hand, study suggests that population density hurts the use of non-renewable energy sources [30]. Some research suggests that the relationship between urban density and building energy consumption may vary fundamentally from city to city [31] due to other factors influencing energy consumption, such as climate, building design, and resident behaviours [32].

Building type is also found to affect building energy efficiency. Most studies on building energy efficiency have been conducted on residential buildings. By 2030, it is predicted that around three-quarters of the population will be living in cities [33]. The residential property sector is responsible for approximately 25% of global energy consumption and 17% of global CO_2 emissions, making it essential for reducing energy consumption and carbon emissions [34]. Globally speaking, studies found that the energy consumption in residential buildings is high in some specific regions, such as the USA [35,36] and China [37,38]. Amongst a few studies, the relationship between a particular building type and building energy efficiency has been explored in non-residential buildings, such as commercial buildings [39–41], office buildings [42,43], and educational buildings [44,45]. Very few studies have included all building types. Some studied major building categories within the European region [10]; however, the global study can shed more light on this research question.

Buildings in different climate zones exhibit different energy efficiency patterns. Climate classification has been proposed since the early 20th century [46]. From 1949 to 1960, countries with extreme climates called for climate zoning to be used in programmes to reduce energy consumption in buildings [47]. There are some generic climate classification systems for building energy-related research and applications. The most typical one is the Köppen-Geiger system (Figure 1), which classifies climate into five main categories and is the most widely used climate classification system in many fields [48,49]. For example, some studies have selected major categories or subcategories of this climate classification system as specific climatic environments to explore strategies for optimising the envelope to improve building energy efficiency [50–52]. Several researchers have focused on improving the energy efficiency of buildings by optimising building materials in specific climatic zones of the system [52–55]. They all use the Köppen-Geiger system for the factors directly influencing building composition on energy efficiency [56,57]. However, the previous studies were conducted in only one specific climate zone, which cannot address building energy efficiency under different climates, which requires further research. Moreover, several strategies have been developed to boost energy efficiency across different climates, such as changing building orientation [58–60], changing materials [60–62], windows [58], increasing shading [63,64], improving ventilation systems [65], and utilising various renewable energy systems [66,67], etc. However, with the ongoing shifts in global climate, these strategies might require adaptations. For instance, passive energy-saving techniques effective in temperate zones for reducing winter energy use could inadvertently increase the risk of overheating and higher cooling energy consumption in summer. This could lead to these measures failing to deliver the anticipated benefits, such as when increasing the insulation of building envelopes [68].

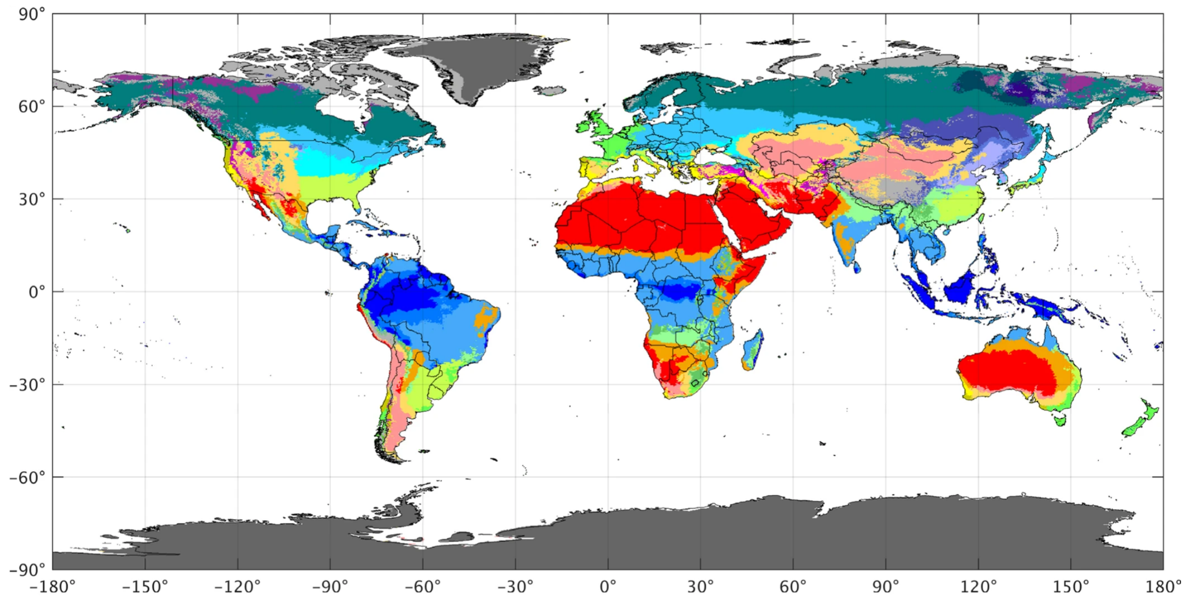

Figure 1. The Köppen-Geiger climate classification maps [49].

It is widely accepted that the economic development level impacts local building energy efficiency. PPP, GNI and GDP are often used as indicators to measure the level of regional economies, as they are all essential criteria for measuring and evaluating economic and social development [69–71]. Among them, GDP measures the goods (purchased by users) and services a country produces over time and counts all the output generated within a country [72]. Unlike GDP, GNI is an indicator of the value of the income generated by individual citizens of a country, regardless of where the income is generated [73]. PPP is used as a price indicator to compare the economic productivity and living standards of various countries and is an indicator of the strength of national currencies, usually expressed in U.S. dollars [74]. Most studies that have examined the relationship between economic factors and building energy consumption have been conducted in residential buildings. The amount of energy consumed by residential buildings is related to the economic level of the occupants [75]. In this regard, economic development levels are closely related to household purchasing power and affect residential energy consumption. Firstly, the economic development level determines the purchasing power of energy consumer goods, including energy. As the economy grows, households are likely to improve their amenities and purchase appliances, cars, etc., due to increased income. The manufacture and use of these items will primarily increase energy demand, and these durable goods will continue to consume energy for a long time [76,77]. Secondly, the economic development level also affects the purchasing power of energy. Higher-income levels give the citizens a higher elasticity of energy consumption response to changes in energy prices. At the same time, those with lower-income population groups are more vulnerable to changes in energy prices [78]. Low-income households face high energy prices and low levels of residential energy efficiency that leave occupants without access to heating, cooling, and lighting, defined as "energy poverty" [79–81]. Energy poverty can exacerbate the economic pressures on poor households. Thus, the economic development level indirectly affects the energy efficiency of residential buildings by influencing the level of purchasing power. It is worth noting that these studies are all about residential buildings in specific countries or regions, and PPP is more applicable for comparative studies involving countries or regions.

GNI often indicates economic-level studies on energy consumption in residential buildings. Researchers believe that GNI positively correlates with residential energy use [82]. In addition, per capita GNI has been used for research on energy consumption in residential buildings. Countries with high per capita GNI have high per capita total and per capita residential energy consumption [34]. However, almost all the above studies have focused on energy consumption in residential buildings and have not addressed non-residential buildings. GDP is also commonly examined in studies of building energy consumption. For example, a study of eleven cities in the Guangdong–Hong Kong–Macao Greater Bay Area showed a positive correlation between residential building energy consumption and GDP [83].

Some studies found that energy consumption-related policies and regulations can affect local building energy efficiency. The most important of the various energy strategies is the development of BECs, which is considered an effective strategy for improving the energy efficiency of buildings [84–87]. Therefore, using BECs can be considered the policy factor in this study. The emergence of BEC came after the oil crisis in the 1970s when European countries became aware of the need to conserve energy [88]. Some years later, all European Union member states were required to have building energy codes in place [89]. BECs exist in almost all developed countries to date [90], such as the United States [91] and Canada [92], etc. More and more developing countries are now introducing such regulations, such as India [93], China [94], and Thailand [95]. This shows that countries have a positive attitude towards implementing building energy codes. The worldwide implementation of BECs in 2013 is shown in Figure 2.

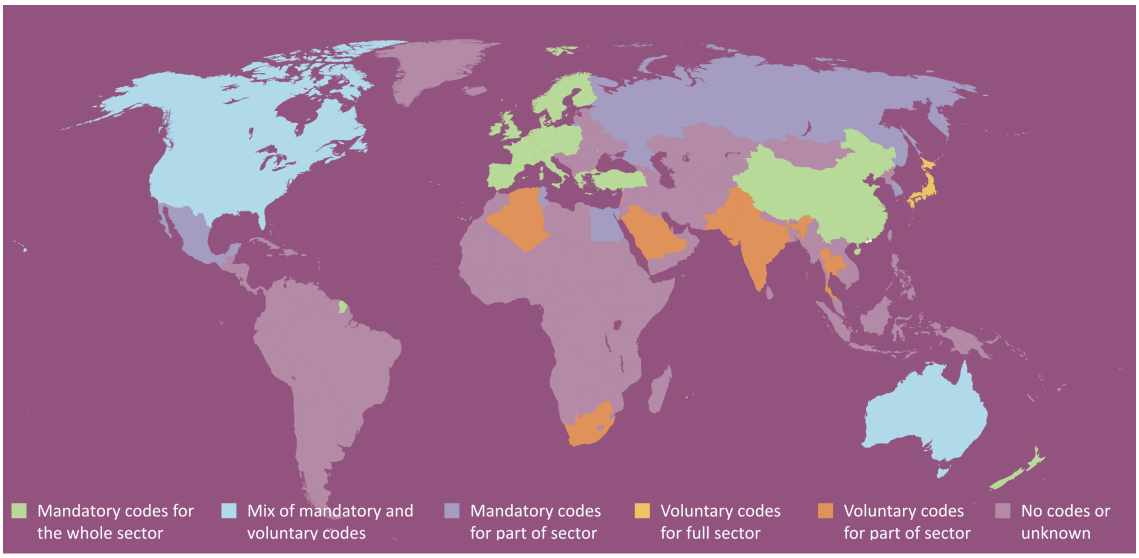

Figure 2. The worldwide implementation of building energy codes in 2013 [96].

It is worth noting that there may be some differences in BECs between regions or countries due to various factors, for example, climatic environment. A study implies that climate influences the implementation of building energy policies, as many standards, certification methods, and regulations rely on this approach [47]. In this regard, many studies on BECs in various regions are related to climate zones, for example, Greece [97], Brazil [98] and China [99]. Moreover, in some regions, the specific enforcement of BECs varies by building type, such as residential buildings [100], office buildings [101], hospitals and research institutes [102]. Studying the relationship between BECs and building energy efficiency in the same climate zone or building type can lead to a clearer picture of the effectiveness of using BECs.

3. Theoretical Framework

Based on the review of previous studies, we develop a theoretical framework (in Figure 3) to demonstrate how these factors determine building energy efficiency.

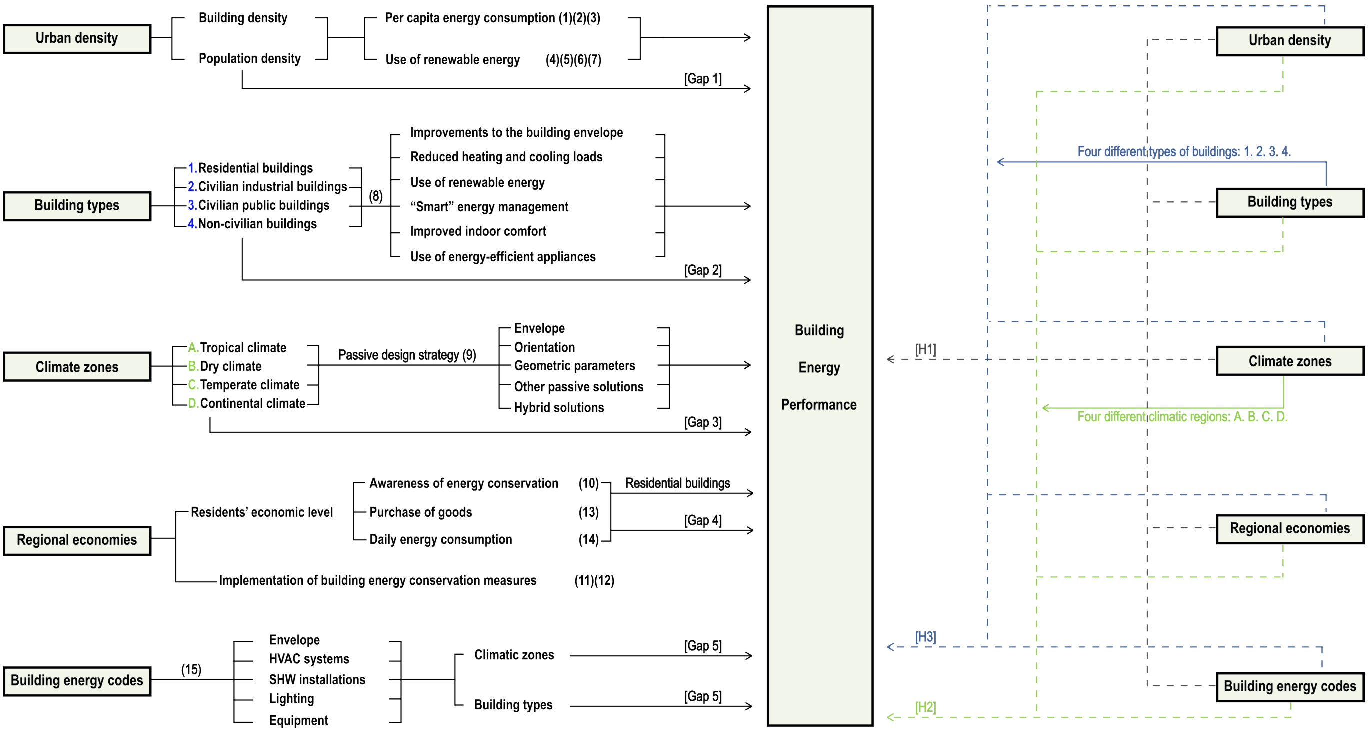

Figure 3. Theoretical framework and Hypothesis development.

Figure 3 shows five categories of factors investigated separately in previous studies. Firstly, according to previous research, population density is more appropriate to represent urban density in studies involving urban fringe and suburban areas than building density. Secondly, previous studies suggest that there is a range of measures that can improve building energy efficiency, including improving the building envelope (e.g., improving insulation, changing building shapes, etc.), reducing heating and cooling loads (e.g., controlling solar gain, incorporating passive technologies, etc.), using renewable energy sources (e.g., solar thermal systems, etc.), using intelligent energy management systems (e.g., monitoring systems, etc.), improving indoor comfort while reducing energy demand (e.g., increasing ventilation rates, etc.), and using energy-efficient appliances and compact fluorescent lamps [103]. However, for each specific building type, the energy efficiency improvement measures can be very different. Thirdly, passive strategies are often implemented in various schemes so buildings in different climates can adopt them [1,104]. Adaptation to climatic conditions has been demonstrated in studies in many different climatic zones [105–110]. The passive strategy analysis includes 1) building envelope, 2) orientation, 3) geometric parameters and other 4) passive, and 5) hybrid solutions [111]. Fourthly, the level of regional economic development tends to affect the energy efficiency of local buildings, especially residential buildings, due to the fact that the economic level of the inhabitants affects the energy consumption of residential buildings. The high probability that the difference in energy consumption is due to the economic level of the region determines the purchasing power of local residents, families with higher purchasing power are more willing to improve their living facilities and purchase more energy and energy-consuming products, but this does not mean that residential buildings in regions with higher economic levels consume more energy, the fact is that the residents of these higher economic levels tend to be more environmentally friendly, and will consciously reduce their energy consumption [112]. Moreover, regional economic development can directly affect the implementation of energy-saving measures. The relatively low economic level of the region may have a greater limiting effect on the financial potential of investment in building energy-saving renovation [113], and the adoption of these measures by residents may also be hindered by the cost of energy policies and other financial aspects [114]. Lastly, building energy codes enforce minimum building energy efficiency requirements [115] and can include HVAC systems, lighting, solar hot water (SHW) installations and equipment, and building envelopes [88]. Table 1 summarises the factors that impact building energy efficiency, which have been confirmed.

Table 1. The source in the diagram of the theoretical framework and Hypothesis development.

Factor that Has Impact on Building Energy Efficiency	Literature
Per capital energy consumption	[28,116,117]
Use of renewable energy	[30,118,119]
Measures to improve energy efficiency	[103]
Passive design strategy	[111]
Awareness of energy conservation	[112]
Purchasing power of energy-consuming goods	[76,77]
Daily energy consumption/demand	[78]
Implementation of building conservation measures	[113,114]
Building energy code content	[88]

This study addresses critical research gaps in the existing literature on building energy efficiency, advancing our understanding through a comprehensive global analysis. The gaps addressed are as follows:

Urban Density and Energy Efficiency: While there is ongoing debate on how urban density impacts building energy efficiency, previous studies have shown mixed results, often confounded by variables such as climate and building form. Our study integrates these factors—examining the influence of building types and climate zones on energy efficiency across urban densities to provide a clearer understanding of these relationships.

Inclusive Building Type Analysis: Historically, research has predominantly focused on residential buildings, with scant attention to non-residential structures. We extend this by including a diverse range of building types—residential, industrial, public, and others—thereby filling a significant gap in the literature on the energy efficiency of non-residential buildings.

Comprehensive Climate Zone Examination: Previous studies often limit their scope to specific climate zones. In contrast, our research encompasses all five major Köppen-Geiger climate classifications, offering a global perspective on how climate influences building energy efficiency.

Economic Factors Across Building Types: The impact of economic factors on energy efficiency is less studied in non-residential contexts. Our study addresses this by analysing how economic conditions influence energy efficiency across different types of buildings, including industrial and public buildings.

Global Scope of Building Energy Codes: While most investigations into the effectiveness of BECs have been confined to specific regions or countries, our analysis expands this examination globally. We assess the impact of BECs across different legal and economic frameworks, providing insight into their effectiveness and adaptability in various global contexts.

By addressing these gaps, our study contributes significantly to the field of sustainable building research. It offers novel insights that can aid policymakers, urban planners, and developers in implementing more effective energy efficiency strategies tailored to diverse urban, climatic, and economic conditions.

Three propositions are developed and will be empirically investigated in the next section.

Proposition 1: The five categories of factors can determine the building's energy efficiency together;
Proposition 2: In different climatic zones, the impact of each determinant on the building energy efficiency varies;
Proposition 3: Across different building types, the impact of each determinant on building energy efficiency varies.

4. Data and Methodology

4.1. Data Descriptions

The LEED rating system provides data that can be used to represent the energy efficiency of different buildings in this study. Developed by the USGBC, the LEED rating system is a globally recognised and comprehensive green building assessment rating system that examines building elements and assigns points accordingly and is now a model for the building industry [120,121]. In this study, the Points Achieved data of different buildings in each country measured by the LEED rating system for 2010–2020 was used as the dependent variable, and 56,203 buildings were collated.

Moreover, building type (T), climate zone (C), regional economic level (E), urban population density (P), building location whether located in the city centre (L) and the use of building energy codes (U) are the six independent variables in this study. Firstly, the building types are categorised by the Project Types dataset provided in the LEED rating system. Secondly, the climatic classification of the building surroundings is based on the five main climate categories of the Köppen-Geiger system, using the building locations provided by the LEED rating system to correspond to each climate zone. Third, for indicators measuring regional economic level, data on PPP and Per Capita Gross National Income (PGNI) for 2010–2012 are provided by The World Bank for each country. These data correspond one-to-one to the building certification year (CertDate dataset provided in LEED). Fourth, to improve accuracy, the population density, which was obtained from the Urban Centre Database of the European Commission, was used in this study to represent urban density. What matters is that the European Commission only provides data on population density in urban centres. At the same time, some buildings are in urban fringe areas or suburbs where the population density deviates somewhat from that of the city centre. As a result, this part also distinguishes whether the building is located in the central urban area, which is the fifth independent variable. Sixth, whether a building uses the BEC or not is classified according to the world map of BEC implementation provided by the IEA in 2013 [96].

Of these, the Points Achieved data, PPP, PGNI and the urban population density data are quantitative. In contrast, the rest of the data have been subjected to a process of categorisation which is qualitative, i.e., building type (T), climate zone (C), building location whether located in the city centre (L) and the use of building energy codes (U). Detailed information can be seen in Table 2.

Table 2. Data descriptions.

<table>
<tr><th colspan="2">Variable</th><th colspan="2">Description</th><th>Data Type</th><th>Data Source</th></tr>
<tr><td>Dependent Variable</td><td>PA</td><td colspan="2">Points Achieved (Indicates the energy efficiency of buildings)</td><td>numerical</td><td rowspan="5">LEED rating system: https://www.usgbc.org/projects</td></tr>
<tr><td rowspan="7">Independent Variables</td><td>T</td><td colspan="2">Building Type</td><td rowspan="5">categorical</td></tr>
<tr><td>C</td><td colspan="2">Climate Zone</td></tr>
<tr><td>E_y</td><td>PPP</td><td rowspan="2">Regional economic level</td></tr>
<tr><td>E_z</td><td>PGNI</td></tr>
<tr><td>P</td><td colspan="2">Urban Population Density</td><td rowspan="2">Urban Centre Database (European Commission): https://ghsl.jrc.ec.europa.eu/index.php</td></tr>
<tr><td>L</td><td colspan="2">Whether the building is located in the urban central area</td><td rowspan="2">categorical</td></tr>
<tr><td>U</td><td colspan="2">Whether building energy codes are used in the region</td><td>Based on Nejat et al. [84]</td></tr>
</table>

Table 3 describes the information for the data sets of Points Achieved, Urban Population Density, and Regional Economic Level (including PGNI and PPP).

Table 3. Summery statistics of data.

Data Sets	Mean	Median	Std. dev.	Max	Min
Points Achieved	59.16	57.00	16.03	127.00	12.0
Urban Population Density (inhabitants/km2)	2709.42	1770.00	2551.96	24,117.00	546.00
PGNI (current US$)	50,544.46	55,800	16,914.04	104,370	400
PPP (constant 2017 billion US$)	16,259.94	18,243.73	6139.09	229,963.85	4.10

The two dummy variables used in our empirical tests are summarised in Table 4.

Table 4. Summary of dummy variables.

Variable	Value	No. of Obs
Located in the city Centre (*L*)		
	1 (yes)	40853
	0 (no)	15350
Use of building energy codes (*U*)		
	1 (yes)	53660
	0 (no)	2543

The classification of building types produces four primary categories, with the quantity and details of each category shown in Table 5. The correlation matrix of the variables in our empirical tests is provided in Appendix A. The interaction among variables is presented in Appendix B.

Table 5. Distribution of numbers and details of the four types of buildings.

Building Type (*T*)	No. of Obs	Details
1. Residential buildings	25,961	Multi-unit Residence, Single-family Home, Attached Single-family, Low-rise Multi-family, etc.
2. Civilian industrial buildings	1926	Industrial, Industrial Manufacturing
3. Civilian public buildings	21,328	Higher Education, Library, Campus, Commercial Office, Retail, Health Care, Hotel/Resort, etc.
4. Non-civilian buildings	6988	Public Order/Safety, Military Base, Office: Government, etc.

In addition, the climate of the area where the building is located is one of the independent variables based on the Köppen-Geiger system. However, due to the small number of buildings in the Polar climates (Climate Zone E) climate zone and the fact that almost all of them are far away from the city centre, the use of population density data from the city centre is more inaccurate, so the data from this zone was chosen to be discarded. The data is therefore divided into four climate zones, Tropical climates (Climate Zone A), Dry climates (Climate Zone B), Temperate climates (Climate Zone C) and Continental climates (Climate Zone D), and the number of buildings in each climatic zone is shown in Table 6. Most buildings are in the C climate zone, while the buildings in the A climate zone are the least. In addition, the characteristics of each climate zone are also explained in Table 6 [122].

Table 6. Distribution of building numbers and climatic characteristics in the four climate zones.

Climate Zone (*C*)	No. of Obs	Climate Characteristics
A. Tropical climate	2610	The monthly average temperature is above 18 °C, and the annual precipitation is significant.
B. Dry climate	6898	The annual precipitation is minimal and the climate is dry. The location of this area has longer summers and shorter winters.
C. Temperate climate	32,855	The average temperature of the coldest month ranges from 0 °C to 18 °C, with at least one month's average temperature above 10 °C.
D. Continental climate	13,840	The temperature in the coldest month is below 0 °C and the temperature in the hottest month is greater than 10 °C.

4.2. Empirical Methods

In our study, we employ logit regression models to analyse the impact of various factors on building energy efficiency, a method widely used and validated in the field for handling binary outcome variables. This choice is supported by the work [123], which used similar econometric techniques to analyse the financial performance of green-certified buildings compared to non-green buildings, demonstrating the economic benefits of sustainable building features. Ideally, our hypothesis could have been tested by a panel regression model. Unfortunately, the dataset doesn't support the panel regression. Future studies with a more comprehensive dataset can improve the study in this aspect.

Three logit regression models were developed to explore the relationship between various factors and building energy efficiency: Model 1, Model 2, and Model 3.

The first model explores how the six independent variables mentioned above affect building energy efficiency and is shown in Formula 1.

$$PA_i = b_0 + b_1 LnP_i + b_2 T_i + b_3 C_i + b_4 LnE_{yi} + b_5 LnE_{zi} + b_6 U_i + b_7 L_i + e \quad (1)$$

where PA refers to the Points Achieved of the building according to the LEED rating system. The independent variables are set to P for population density, T for building type, C for climate zone, E for regional economy, U for the use of building energy codes and L is whether the building is located in the central area of the city. In addition, the regional economy E includes PPP and PGNI, which are respectively represented by E_y and E_z in this study. b_0 is the intercept, LnP, LnE_y *and* LnE_z are logarithm forms of explanatory variable P, E_y *and* E_z respectively, i (i = 1,2…,56203) is the number of buildings, and e stands for error.

Moreover, the second model of this study examines the relationship between building energy efficiency of buildings and factors such as building types, population density, etc., in each climate zone (the four different climatic zones mentioned above). Thus, buildings in each climate zone are tested with Model 2 as follows:

$$PA_i = b_0 + b_1 LnP_i + b_2 T_i + b_4 LnE_{yi} + b_5 LnE_{zi} + b_6 U_i + b_7 L_i + e \quad (2)$$

In addition, the third model of this study addresses the relationship between factors such as climate zones, population density, etc., and building energy efficiency for a fixed building type (selected from the four different building types mentioned above). Thus, four different building types are tested with Model 3 as follows:

$$PA_i = b_0 + b_1 LnP_i + b_3 C_i + b_4 LnE_{yi} + b_5 LnE_{zi} + b_6 U_i + b_7 L_i + e \quad (3)$$

5. Empirical Results and Discussion

5.1. The Determinants of Building Energy Efficiency

The empirical estimation results of Model 1 are presented in Table 7. It shows that the determinants of building energy efficiency are the location of the building, adoption of BECs, climate zones, building types, regional economic development level (namely GNI, PPP) and population density.

Previous studies have explored a range of determinants that impact building energy efficiency, whilst the climate factor and the usage type of the building have yet to be discussed regarding building energy efficiency. In this study, the generic buildings with LEED ratings in the dataset are included, and five significant climates and the usage type of each building are considered together with all the other determinants of building energy efficiency discovered in the previous research.

The booming economy can have two impacts on building energy efficiency. Economic expansion requires massive energy consumption, while the great awareness of energy conservation in well-developed economies may contribute to promoting energy efficiency. The two sides of economic development have been discussed in previous studies (i.e., [124]). However, the results in Table 7 show that globally, both the regional PGNI level and the regional PPP level show only a significant negative correlation with building energy efficiency, i.e., the higher the economic level of the region, the lower the energy efficiency of the building, which is due to the increase in energy demand caused by the increase in economic level. Therefore, it is important to implement building energy efficiency strategies globally, especially in those countries or regions with higher economic levels.

Table 7. Estimation results of regression Model 1.

Dep. var. = PA	**Model 1**	
constant	94.998 (3.965)	***
Independent Variables		
Whether the building is located in the urban centre	2.653 (0.143)	***
Use of building energy codes	6.409 (0.395)	***
Climate Zone A	0.000 (0.000)	***
Climate Zone B	3.265 (0.375)	***
Climate Zone C	−3.031 (0.333)	***
Climate Zone D	0.097 (0.350)	
Residential buildings	0.000 (0.000)	***
Civilian industrial buildings	−13.352 (0.283)	***
Civilian public buildings	−14.392 (0.147)	***
Non-civilian buildings	−7.474 (0.188)	***
Ln(PGNI)	−2.034 (0.150)	***
Ln(PPP)	−1.262 (0.860)	***
Ln(Population density)	3.144 (0.174)	***
Number of obs	56199	
R-squared	0.190	
F-test	1294.404	
Prob > F	0.000	

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Note: *** indicates significance at the 1% level; ** indicates significance at the 5% level; * indicates significance at the 10% level.

We also find that the location of the building and the population density of the location have positive impacts on building energy efficiency. Similar to a previous study [28], our results show that buildings located in urban centres tend to exhibit higher levels of energy efficiency than those situated in non-urban areas, which can be attributed to the warmer spaces between buildings, increased cooling load in summer, decreased heating load in winter, reduced lighting energy consumption, higher living costs in the urban area and so on. In line with previous findings [125], higher urban population density promotes building energy efficiency in this study, which can be explained by compact cities' minimising building energy consumption for space heating/cooling. This may be due to the buildings' surface-to-volume ratios (S/V), with a low S/V minimising heat exchange with the atmosphere (gains in summer and losses in winter), resulting in lower energy consumption for heating or cooling. The empirical sample in our study covers the generic buildings globally. It thus includes low-latitudes (e.g., Egypt, etc.) and high-latitudes (e.g., Norway, etc.), which indicates that, from a global perspective, cities with higher population densities can effectively reduce energy consumption compared to cities with lower population densities. Policy and regulations, proxied by adopting BECs, are also found helpful in improving building energy efficiency.

Our empirical results show that the climate factor plays a significant role in building energy efficiency. It shows that buildings in Climate Zone C have the lowest energy efficiency while those in Climate Zone B have the highest; it also some difference between the buildings in Climate Zones B, C, and D and those in Climate Zone A regarding energy efficiency. The difference in building energy efficiency between B and C may be caused by the variations in heating or cooling energy used to maintain indoor comfort across different climate zones. Some previous studies suggested that a large proportion of building energy consumption is related to thermal comfort [12]. Some found that more heating loads are consumed in colder climates [126], whereas, in hotter climates, more cooling loads are consumed. In temperate climates, heating and cooling energy consumption can be minimised. To maintain indoor comfort, buildings in different climate zones have different energy consumption demands: in Climate Zone A, trivial heating energy is consumed for cooling loads; in Climate Zone B, it primarily requires cooling loads; Climate Zone C demands both heating and cooling loads, with cooling needs being substantially more significant than those in Climate Zone D; and finally, Climate Zone D focuses primarily on heating, with a small amount of cooling load required (similar in [122]). Given the enormous different features among the climate zones, we break buildings into different climate groups for further investigation.

Building energy efficiency shows very different patterns among various building types as well. Residential buildings exhibit the highest energy efficiency, while civilian public buildings have the lowest. Previous findings noted that buildings open to the public consume 40% more energy than residential buildings, possibly due to the higher EUI of non-residential buildings across all building types [127]. Commercial buildings also exhibit higher EUIs than residential buildings. This is similar to the previous finding, which shows that the EUI of commercial buildings was approximately twice that of residential buildings [128]. Therefore, we break buildings into different usage type groups for further investigation.

5.2. Does Climate Matter? The Climate Zone Level Analysis

In Model 2, we divide the buildings into four sub-groups, representing the four climate zones, and empirically examine the determinants of building energy efficiency in each climate zone. The results are shown in Table 8.

Table 8. Estimation results of regression Model 2.

Dep. var. = PA	**Climate Zone A**		**Climate Zone B**		**Climate Zone C**		**Climate Zone D**	
constant	11.870 (12.872)	***	165.859 (15.613)	***	90.642 (6.498)	***	113.069 (6.932)	***
Independent Variables								
Whether the building is located in the urban centre	−2.395 (0.776)	***	−6.226 (0.484)	***	6.180 (0.185)	***	−0.562 (0.265)	**
Use of building energy codes	−3.648 (1.331)	***	5.899 (0.985)	***	5.881 (0.551)	***	−4.692 (1.516)	***
Residential buildings	0.000 (0.000)	***	0.000 (0.000)	***	0.000 (0.000)	***	0.000 (0.000)	***
Civilian industrial buildings	−14.634 (1.229)	***	−21.391 (0.841)	***	−10.452 (0.362)	***	−17.233 (0.580)	***
Civilian public buildings	−16.670 (0.926)	***	−19.615 (0.490)	***	−11.708 (0.191)	***	−18.036 (0.281)	***
Non-civilian buildings	−12.894 (1.039)	***	−14.565 (0.688)	***	−4.987 (0.235)	***	−10.487 (0.374)	***
Ln(PGNI)	−3.187 (0.428)	***	−5.107 (0. 482)	***	−0.991 (0.224)	***	−1.914 (0.357)	***
Ln(PPP)	2.123 (0.374)	***	−1.038 (0.300)	***	−1.568 (0.141)	***	−1.214 (0.137)	***
Ln(Population density)	4.243 (0.681)	***	−1.158 (0.750)		2.625 (0.255)	***	2.504 (0.306)	***
Number of obs	2610		6898		32852		13839	
R-squared	0.217		0.311		0.132		0.261	
F-test	100.395		815.413		650.346		557.534	
Prob > F	0.000		0.000		0.000		0.000	

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Note: *** indicates significance at the 1% level; ** indicates significance at the 5% level; * indicates significance at the 10% level.

Due to the widely varying features across different climate zones, this study aims to investigate the impact of determining factors on building energy efficiency in each climate zone. Although the location of a building within an urban centre can affect its energy efficiency, the nature of this relationship varies among climate zones. Specifically, urban-centre locations are negatively associated with building energy efficiency in Climate Zones A, B, and D, whereas the opposite holds for Climate Zone C.

The UHI effect can help explain the negative relationship in Climate Zones A and B. Buildings primarily consume cooling loads to maintain indoor comfort. The UHI raises the temperature in urban areas, causing buildings to consume more cooling loads. Some note that UHI reduces the demand for heating but increases the demand for cooling, ultimately increasing energy consumption for buildings in hot climates (i.e., Climate Zones A and B) with low demand for heating loads [129]. This effect is amplified in urban centres. In this sense, buildings in Climate Zone D are expected to benefit from the UHI; however, the results show the opposite. In Climate Zone D, where cold weather prevails in winter, more solar gain helps to reduce heating energy consumption. As a previous study [122] argues, buildings in continental climates should be exposed to the sun to increase solar gain. Non-urban areas have relatively low building density, which gives buildings more solar gain, resulting in higher energy efficiency. It is essential to make stakeholders aware that minimising the solar gain of buildings can reduce cooling energy consumption in Climate Zones A and B. In contrast, maximising solar gain can reduce heating energy consumption in Climate Zone D, particularly in urban areas.

In contrast, as explained in previous research [130], buildings in Climate Zone C tend to have more compact layouts in urban centres. Adjacent buildings often share walls, reducing energy losses for cooling or heating.

Using building energy codes helps improve energy efficiency in Climate Zones B and C. However, their impact could be more present in Climate Zone D and negative in Climate Zone A. The efficacy of building energy codes varies widely across countries and regions, and they are often ineffective or fall far short of expectations in developing countries, as some [90] found in this study's sample, where most developing countries were in Climate Zone A. Furthermore, non-compliance with building energy code practices and lack of implementation knowledge is evident in some developed countries in Climate Zone D, such as the USA and Norway [131]. Therefore, adopting building energy codes might only be adequate to improve building energy efficiency if regulations and implementations are strengthened.

For the regional economic level, the regional PGNI level shows a negative correlation with building energy efficiency in all four climate zones. Moreover, the regional PPP level is negatively correlated with building energy efficiency in Climatic Zones B, C, and D, but positively correlated with building energy efficiency in Climate Zone A. Thus, other developing countries or cities in Climate Zone A can learn from the strategies of more developed and economically advanced regions to improve building energy efficiency, and the study [132] directly points out that Singapore's experience in improving energy efficiency is highly relevant. Notably, in some countries in the other three climate zones, the consumption of petroleum fuels discourages the use of renewable energy, thus affecting the energy efficiency of buildings, e.g., Middle Eastern and North African (MENA) countries, Australia, and the USA [34,133,134]. Furthermore, due to high government subsidies, the MENA region offers the cheapest energy prices globally [135]. The abundance of primary energy resources and low energy prices lead to a higher purchasing power for energy, which, according to the study [136], hampers the energy efficiency of buildings in Saudi Arabia due to lavish lifestyles, increasing annual per capita income, and the availability of cheap energy. Consequently, economic growth in the MENA region will likely lead to increased energy consumption and a continued decline in building energy efficiency.

The increase in urban population density in Climate Zones A, C, and D benefits the energy efficiency of buildings. In contrast, increasing population density does not impact building energy efficiency in Climate Zone B. This can be attributed to the differences among countries.

The results highlight the significant influence of building type on building energy efficiency across different climate zones. The findings indicate that residential buildings are generally the most energy-efficient across all climate zones. In contrast, civilian public buildings' energy efficiency is comparable to civilian industrial buildings across all four climate zones. The results further reveal that the energy efficiency of civilian public buildings is marginally lower than that of civilian industrial buildings in Climate Zones A, C, and D. However, civilian industrial buildings' energy efficiency is lower than that of civilian public buildings in Climate Zone B.

The observed differences in building-type energy efficiency across climate zones may be attributed to variations in different regions' primary industries and economic structures. For instance, developed countries tend to have a higher proportion of energy consumption in the commercial sector due to the dominance of the tertiary sector in their economies. However, in some countries in Climate Zone B, the industrial sector is likely to account for a larger share of energy consumption than other sectors, particularly in the Middle East. This trend may lead to higher energy losses in industrial buildings than in commercial buildings. The Middle East is also considered one of the least energy-efficient economies globally, with industrial consumption accounting for a substantial proportion of the total energy consumed in the region. These factors may account for the lower energy efficiency of civilian industrial buildings in Climate Zone B than civilian public buildings.

5.3. Does the Building Type Matter? The Building Type Level Analysis

Similarly, in Model 3, we divide the buildings into four sub-groups representing the four building types and empirically examine each user type's determinants of building energy efficiency. The results are shown in Table 9.

Table 9. Estimation results of regression Model 3.

Dep. var. = PA	Residential Buildings		Civilian Industrial Buildings		Civilian Public Buildings		Non-civilian Buildings	
constant	166.242 (8.515)	***	61.088 (11.771)	***	48.954 (5.849)	***	25.709 (7.591)	***
Independent Variables								
Whether the building is located in the urban centre	2.607 (0.195)	***	−0.556 (0.522)		1.697 (0.241)	***	4.714 (0.469)	***
Use of building energy codes	6.854 (1.707)	***	0.645 (1.020)		6.123 (0.577)	***	6.247 (0.685)	***
Climate Zone A	0.000 (0.000)	***	0.000 (0.000)	***	0.000 (0.000)	***	0.000 (0.000)	***
Climate Zone B	6.671 (0.802)	***	−5.399 (1.198)	***	−1.360 (0.555)	**	−0.731 (0.810)	
Climate Zone C	−5.234 (0.761)	***	−4.211 (1.064)	***	−1.81 (0.470)	***	0.570 (0.654)	
Climate Zone D	2.468 (0.781)	***	−2.956 (1.167)	**	−1.669 (0.490)	***	1.276 (0.701)	*
Ln(PGNI)	−12.391 (0.935)	***	−0.217 (0.414)	***	−0.336 (0.211)		0.553 (0.311)	*
Ln(PPP)	1.397 (0.397)	***	0.086 (0.273)		−1.392 (0.122)	***	−1.038 (0.158)	***
Ln(Population density)	−2.091 (0.339)	***	2.684 (0.588)	***	5.587 (0.256)	***	6.204 (0.375)	***
Number of obs	25960		1926		21322		6988	
R-squared	0.119		0.186		0.114		0.140	
F-test	495.105		52.751		340.265		144.609	
Prob > F	0.000		0.000		0.000		0.000	

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Note: *** indicates significance at the 1% level; ** indicates significance at the 5% level; * indicates significance at the 10% level.

Across all building types, including residential, civilian public, and non-civilian buildings, higher building energy efficiency is observed in urban centres except for the civilian industrial buildings. The differences in energy use between urban and non-urban areas are influenced by various factors, which are usually related to the energy needs of urban residents. Thus, for industrial buildings, the energy requirements of the production process overwhelmingly determine energy consumption, and the impact of the factors related to building location on the energy efficiency of industrial buildings is almost negligible. We find that residential buildings exhibit the highest building energy efficiency in Climate Zone B and the lowest energy efficiency in Climate Zone C. This may be attributed to the fact that residential buildings in Climate Zone B require the least energy to maintain indoor thermal comfort, while those in Climate Zone C require the most energy compared to the other climate zones.

The result shows that civilian industrial buildings demonstrate the highest energy efficiency in Climate Zone A and the lowest in Climate Zone B. The difference between developed and developing countries can explain this. Worrell et al. [137] suggest that most of the world's energy-intensive industries are currently located in developing countries, and many of these facilities in developing countries are new and use the latest technologies that can improve energy efficiency and reduce carbon emissions in the industrial sector. These findings highlight the importance of considering regional climate conditions and the industrial landscape when developing and implementing energy efficiency policies for different types of buildings.

It is essential to address that the relationship between the regional economic level and building energy efficiency is complex and depends on various factors such as the economic structure, energy policies, and technological advancement of the region. While the results of this study suggest a correlation between the economic level and building energy efficiency, further research is needed to fully understand the underlying mechanisms and potential solutions for improving energy efficiency in buildings.

For civilian public buildings, as shown in a study on commercial buildings [138], the main factors of energy consumption in buildings are space heating, cooling, ventilation and lighting. The results in Table 9 show that whether the building is located in an urban centre, the climate, and the population density all show a strong correlation with the energy efficiency of the building, as they all affect the space heating, cooling, ventilation and lighting of the building, either directly or indirectly by influencing the built environment. This suggests that strategies to improve the energy efficiency of public buildings should not ignore the optimisation of the surrounding environment, and should take into account all of these factors in order to achieve the best possible energy efficiency of the building, not just the operational practices and design elements.

It is worth considering the potential role of government policies and regulations in improving building energy efficiency. For example, building energy codes and standards can set minimum energy performance requirements for new and existing buildings, which can help reduce energy consumption and greenhouse gas emissions. Incentives such as tax credits and subsidies can also encourage building owners and operators to invest in energy-efficient technologies and practices.

Regarding urban population density, only the energy efficiency of residential buildings exhibits a negative correlation. In contrast, non-residential buildings (i.e., civilian industrial buildings, civilian public buildings, and non-civilian buildings) all demonstrate a positive correlation. A previous study argued that without accounting for regional variations in geographical and socio-economic conditions, an increase in the proportion of the urban population will lead to a decrease in the total REC (which represents the energy consumed for various needs within residential buildings, such as heating, cooling, lighting, cooking, etc., but excludes energy consumption by commercial enterprises and public service spaces within residential buildings) [139]. However, this contradicts the results of the present study. The same study [139] also noted that when considering regional differences in geographical and socio-economic conditions, REC positively correlates with population density. Urbanisation has a more pronounced effect on the total REC in relatively less urbanised regions, particularly in developing Asia, the Middle East, and North Africa. In these regions, an increase in the proportion of the urban population leads to a greater total REC. This suggests that an increase in population density is linked to higher energy consumption in residential buildings, thus lowering their energy efficiency.

In order to further explore and analyse the effects of the variables on energy efficiency in residential buildings under different climate types, we divided all residential buildings according to four climate zones and conducted regression analyses. The results are shown in Table 10.

In Table 10, the results of the correlation between residential building energy efficiency and the use of building energy codes in Climate Zone D are not shown because almost all the residential buildings tested in Climate Zone D were required to refer to building energy codes (these buildings were mainly located in several countries from the USA, Canada, China and Northern Europe), and there were only a very small number of residential buildings that did not use building energy codes, so they are ignored in the calculation process. It is clear that the use of energy codes in Climate Zones A, B, and C will greatly improve the energy efficiency of residential buildings.

Table 10. Impact of variables on energy efficiency of residential buildings under different climate types.

Dep. var. = PA	**Climate Zone A**		**Climate Zone B**		**Climate Zone C**		**Climate Zone D**	
constant	145.769 (75.505)	*	286.261 (20.916)	***	171.653 (15.163)	***	−0.946 (18.226)	
Independent Variables								
Whether the building is located in the urban centre	7.473 (2.233)	***	−9.799 (0.619)	***	7.905 (0.238)	***	−4.505 (0.378)	***
Use of building energy codes	1.297 (9.356)		5.736 (4.056)		16.470 (2.906)	***	.	
Ln(PGNI)	−11.661 (3.967)	***	−16.340 (3.688)	***	−3.911 (0.973)	***	−8.496 (1.777)	***
Ln(PPP)	4.132 (2.778)		1.032 (1.625)		−2.470 (0.537)	***	6.391 (0.353)	***
Ln(Population density)	−11.355 (4.138)	***	−8.857 (1.027)	***	−1.838 (0.456)	***	−3.864 (0.538)	***
Number of obs	487		4487		16456		4531	
R-squared	0.037		0.156		0.071		0.116	
F-test	3.494		332.267		277.237		210.716	
Prob > F	0.004		0.000		0.000		0.000	

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Note: *** indicates significance at the 1% level; ** indicates significance at the 5% level; * indicates significance at the 10% level.

Residential buildings located in urban centres in Climate Zones A and C show higher energy efficiency, while buildings located in non-urban centres in Climate Zones B and D are more energy efficient. This is due to changes in energy consumption to maintain indoor thermal comfort, as described above, buildings located in urban centres will be more susceptible to UHI, which will further increase temperatures in urban centres, leading to an increase in cooling energy consumption for residential buildings located in urban centres in Climate Zone B, and for residential buildings located in urban centres in Climate Zone D, due to the dense building layout in the urban centres, the buildings will receive less solar radiation, which will increase the heating energy consumption of the buildings.

Among the four climate zones, higher regional PGNI is associated with lower energy efficiency of residential buildings. Increased incomes have made people happy to improve their amenities and purchase durable items such as household appliances, which will continue to consume energy for a long time [76,77]. Moreover, the level of regional PPP is not correlated with the energy efficiency of residential buildings in Climatic Zones A and B. In contrast, there is a strong correlation in Climate Zones C and D, with a negative correlation in Climate Zone C and a positive correlation in Climate Zone D. For the completely opposite trend of correlation between regional PPP level and building energy efficiency in Climate Zones C and D, Shi et al. [112] mention that the relationship between building energy consumption of urban residents and the level of regional economic development has two opposing effects: the higher the level of the regional economy, the higher the energy demand of the residents for comfort, and at the same time, the increased awareness of environmental protection of the residents, which can lead the residents to reduce their energy consumption.

Furthermore, the results of the tests in all climate types show that the higher the population density, the lower the energy efficiency of residential buildings will be. Firstly, as higher population densities will exacerbate UHI [22,23], this will indirectly result in residential buildings having to consume additional energy to maintain indoor thermal comfort [27], and secondly, population densities will impair the use of non-renewable energy sources [30], which will make residential buildings even more dependent on non-renewable energy sources.

6. Conclusions and Implications

In recent years, the factors that affect building energy efficiency have received much attention from researchers, while very few studies have empirically examined them together. This study employs three logit regression models to investigate the determinants of building energy efficiency using the LEED rating system data from 2010 to 2012. The determinants of building energy efficiency are empirically investigated in general (Model 1), in various climate zones (Model 2) and different building types (Model 3).

Firstly, we find that buildings in urban centres exhibit higher levels of energy efficiency globally than those in non-urban areas. This conclusion applies equally to residential, civilian public and non-civilian buildings. Still, the impact of building location on energy efficiency in industrial buildings is minimal as they are usually away from urban centres [140]. In hot climates (i.e., Climate Zones A and B), the heat island effect in the city centre increases the energy consumption of buildings for cooling. In Climate Zone D, due to the lower building density in the suburban or peripheral areas of the city, buildings can gain more solar gain and thus use less energy for heating. This suggests that buildings in non-urban centres will maintain higher building energy efficiency in Climate Zones A, B and D. Therefore, urban cooling strategies (i.e., increasing urban greenery and urban ventilation) are essential for buildings in urban centres that hope to achieve high energy efficiency.

Secondly, using BECs is positively associated with building energy efficiency for most building types, except industrial buildings. This suggests that current BECs may not be improving the energy efficiency of industrial buildings and that updating energy codes for industrial buildings needs to be in place.

Thirdly, the regional economic development level, which Ln(PPP) and Ln(PGNI) measure, is found to have twofold impacts on building energy efficiency. On the one hand, as the economy expands, much energy consumption is required, which may lead to low building energy efficiency. On the other hand, as the economy grows, people become more conscious about energy efficiency; the government has more funds to implement government energy efficiency policies and have greater access to energy-efficient housing and products, which may lead to high building energy efficiency. Luxury lifestyles and the availability of cheap energy are more evident due to the many excessive uses of petroleum fuels, especially in the Middle East. Therefore, buildings in the Middle East should make more use of renewable energy sources in order to reduce dependence on non-renewable energy sources [141].

Fourthly, we find that climate is an important factor which affects building energy efficiency. Due to the differences in heating or cooling energy consumption used to maintain indoor comfort in different climate zones, buildings in Climate Zone C are the least energy efficient, and buildings in Climate Zone B are the most energy efficient. In addition, the same situation occurs for residential buildings (i.e., residential buildings in Climate Zone B require the least energy to maintain indoor thermal comfort, while those in Climate Zone C require the most energy). For civilian industrial buildings, buildings in Climate Zone A have the highest energy efficiency due to the new facilities and technologies used in developing countries. This suggests that other measures, such as controlling solar gain and ventilation rates to enable buildings to reduce heating/cooling loads, smart management systems, energy-efficient equipment, and lights, etc., may improve energy efficiency in non-residential buildings.

Fifthly, building type is also found to have a determined impact on building energy efficiency. Residential buildings are the most energy-efficient building type in all the different climate zones, and the energy efficiency of civilian public buildings is very similar to that of civilian industrial buildings. In Climate Zones A, C and D, the energy efficiency of civilian public buildings is slightly lower than civilian industrial buildings. Still, the opposite situation occurs in Climate Zone B due to differences in the different regions' main industrial and economic structures. This reflects the continued development and energy input of those countries located in Climate Zone B, which will increase industrial energy losses, making it imperative to improve the energy efficiency of industrial buildings in these countries.

Lastly, high-density cities are found to be more effective in reducing energy consumption compared to low-density cities. Compact cities tend to reduce the energy consumption of buildings in terms of space heating/cooling. However, for residential buildings, the increase in population density leads to lower building energy efficiency, especially in less urbanised regions such as Asia, the Middle East and North Africa. It implies that the developing regions which have rapid urbanisation and high population growth need to prioritise the agenda of improving energy efficiency for residential buildings.

This study is limited by the data set: a large proportion of the buildings in this sample are in the USA, which may lead to some bias. Therefore, a larger sample, which includes balanced shares of buildings from different countries, can provide more robust findings in the future.

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Data Availability

Data supporting this study are openly available and the data source is specified in the paper.

Author Contributions

Conceptualization: Y.X.; Data curation: D.D.; Formal analysis: D.D., & Y.X.; Methodology: Y.X.; Software: D.D., & Y.X.; Writing – original draft: D.D., & Y.X.; Writing – review & editing: D.D., & Y.X.

Conflicts of Interest

The authors have no conflict of interest to declare.

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Appendix A. Correlation Matrix

Model 1

```
. correlate city regulation lngni lnppp lnpop
(obs=56,199)

             |   cityor regula~n    lngni    lnppp    lnpop
-------------+---------------------------------------------
      cityor |   1.0000
  regulation |  -0.0575   1.0000
       lngni |  -0.1142   0.4433   1.0000
       lnppp |  -0.0625   0.6193   0.5070   1.0000
       lnpop |   0.1781  -0.3978  -0.7681  -0.5831   1.0000
```

Figure A1. Correlation matrix for Model 1.

Table A1. Correlation matrix for Model 1.

	Whether the building is located in the urban centre	Use of building energy codes	Ln(PGNI)	Ln(PPP)	Ln(Population density)
Whether the building is located in the urban centre	1.00				
Use of building energy codes	−0.06	1.00			
Ln(PGNI)	−0.11	0.44	1.00		
Ln(PPP)	−0.06	0.62	0.50	1.00	
Ln(Population density)	0.18	−0.40	−0.77	−0.58	1.00

Model 2 (Four different climate zones)

Climate Zone A

```
. correlate city regulation lngni lnppp lnpop
(obs=2,610)

             |   cityor regula~n    lngni    lnppp    lnpop
-------------+---------------------------------------------
      cityor |   1.0000
  regulation |   0.0401   1.0000
       lngni |   0.1415   0.3440   1.0000
       lnppp |   0.0422   0.8405   0.4912   1.0000
       lnpop |  -0.0699  -0.3261  -0.8642  -0.4316   1.0000
```

Figure A2. Correlation matrix for Model 2 (Climate Zone A).

Table A2. Correlation matrix for Model 2 (Climate Zone A).

	Whether the building is located in the urban centre	Use of building energy codes	Ln(PGNI)	Ln(PPP)	Ln(Population density)
Whether the building is located in the urban centre	1.00				
Use of building energy codes	0.04	1.00			
Ln(PGNI)	0.14	0.34	1.00		
Ln(PPP)	0.04	0.84	0.49	1.00	
Ln(Population density)	−0.07	−0.33	−0.86	−0.43	1.00

Climate Zone B

```
. correlate city regulation lngni lnppp lnpop
(obs=6,898)

             |   cityor regula~n    lngni    lnppp    lnpop
-------------+---------------------------------------------
      cityor |   1.0000
  regulation |  -0.0325   1.0000
       lngni |   0.0566   0.2444   1.0000
       lnppp |   0.2445   0.7084   0.5731   1.0000
       lnpop |  -0.1878  -0.4191  -0.8313  -0.7928   1.0000
```

Figure A3. Correlation matrix for Model 2 (Climate Zone B).

Table A3. Correlation matrix for Model 2 (Climate Zone B).

	Whether the building is located in the urban centre	Use of building energy codes	Ln(PGNI)	Ln(PPP)	Ln(Population density)
Whether the building is located in the urban centre	1.00				
Use of building energy codes	−0.03	1.00			
Ln(PGNI)	0.06	0.24	1.00		
Ln(PPP)	0.24	0.71	0.57	1.00	
Ln(Population density)	−0.19	−0.42	−0.83	−0.79	1.00

Climate Zone C

```
. correlate city regulation lngni lnppp lnpop
(obs=32,852)

             |   cityor regula~n    lngni    lnppp    lnpop
-------------+---------------------------------------------
      cityor |   1.0000
  regulation |  -0.0764   1.0000
       lngni |  -0.1895   0.4618   1.0000
       lnppp |  -0.1425   0.5741   0.4959   1.0000
       lnpop |   0.2681  -0.3947  -0.7509  -0.6164   1.0000
```

Figure A4. Correlation matrix for Model 2 (Climate Zone C).

Table A4. Correlation matrix for Model 2 (Climate Zone C).

	Whether the building is located in the urban centre	Use of building energy codes	Ln(PGNI)	Ln(PPP)	Ln(Population density)
Whether the building is located in the urban centre	1.00				
Use of building energy codes	−0.08	1.00			
Ln(PGNI)	−0.19	0.46	1.00		
Ln(PPP)	−0.14	0.57	0.50	1.00	
Ln(Population density)	0.27	−0.39	−0.75	−0.62	1.00

Climate Zone D

```
. correlate city regulation lngni lnppp lnpop
(obs=13,839)

             |   cityor regula~n    lngni    lnppp    lnpop
-------------+---------------------------------------------
      cityor |   1.0000
  regulation |  -0.0387   1.0000
       lngni |  -0.1261   0.2611   1.0000
       lnppp |  -0.1154   0.3293   0.2898   1.0000
       lnpop |   0.2213  -0.1451  -0.6660  -0.3623   1.0000
```

Figure A5. Correlation matrix for Model 2 (Climate Zone D).

Table A5. Correlation matrix for Model 2 (Climate Zone D).

	Whether the building is located in the urban centre	Use of building energy codes	Ln(PGNI)	Ln(PPP)	Ln(Population density)
Whether the building is located in the urban centre	1.00				
Use of building energy codes	−0.04	1.00			
Ln(PGNI)	−0.13	0.26	1.00		
Ln(PPP)	−0.12	0.33	0.29	1.00	
Ln(Population density)	0.22	−0.15	−0.67	−0.36	1.00

Model 3 (Four different building types)

Civil Industrial Buildings

```
. correlate city regulation lngni  lnppp lnpop
(obs=1,926)

             |   cityor regula~n    lngni    lnppp    lnpop
-------------+---------------------------------------------
      cityor |   1.0000
  regulation |   0.0385   1.0000
       lngni |  -0.0455   0.6121   1.0000
       lnppp |   0.0320   0.7243   0.6109   1.0000
       lnpop |   0.1365  -0.4760  -0.7491  -0.5965   1.0000
```

Figure A6. Correlation matrix for Model 3 (Civil Industrial Buildings).

Table A6. Correlation matrix for Model 3 (Civil Industrial Buildings).

	Whether the building is located in the urban centre	Use of building energy codes	Ln(PGNI)	Ln(PPP)	Ln(Population density)
Whether the building is located in the urban centre	1.00				
Use of building energy codes	0.04	1.00			
Ln(PGNI)	−0.05	0.61	1.00		
Ln(PPP)	0.03	0.72	0.61	1.00	
Ln(Population density)	0.14	−0.48	−0.75	−0.60	1.00

Civil Public Buildings

```
. correlate city regulation lngni lnppp lnpop
(obs=21,324)

             |   cityor regula~n    lngni    lnppp    lnpop
-------------+---------------------------------------------
      cityor |   1.0000
  regulation |  -0.0606   1.0000
       lngni |  -0.1163   0.3722   1.0000
       lnppp |  -0.0956   0.5943   0.3833   1.0000
       lnpop |   0.2197  -0.3750  -0.7937  -0.5012   1.0000
```

Figure A7. Correlation matrix for Model 3 (Civic Public Buildings).

Table A7. Correlation matrix for Model 3 (Civic Public Buildings).

	Whether the building is located in the urban centre	Use of building energy codes	Ln(PGNI)	Ln(PPP)	Ln(Population density)
Whether the building is located in the urban centre	1.00				
Use of building energy codes	−0.06	1.00			
Ln(PGNI)	−0.12	0.37	1.00		
Ln(PPP)	−0.10	0.59	0.38	1.00	
Ln(Population density)	0.22	−0.38	−0.79	−0.50	1.00

Civil Residence

```
. correlate city regulation lngni lnppp lnpop
(obs=25,961)

             |   cityor regula~n    lngni    lnppp    lnpop
-------------+---------------------------------------------
      cityor |   1.0000
  regulation |   0.0321   1.0000
       lngni |   0.0863   0.1684   1.0000
       lnppp |   0.1237   0.5094   0.7316   1.0000
       lnpop |  -0.0139  -0.1798  -0.6045  -0.6113   1.0000
```

Figure A8. Correlation matrix for Model 3 (Civic Residence).

Table A8. Correlation matrix for Model 3 (Civic Residence).

	Whether the building is located in the urban centre	Use of building energy codes	Ln(PGNI)	Ln(PPP)	Ln(Population density)
Whether the building is located in the urban centre	1.00				
Use of building energy codes	0.03	1.00			
Ln(PGNI)	0.09	0.17	1.00		
Ln(PPP)	0.12	0.51	0.73	1.00	
Ln(Population density)	−0.01	−0.18	−0.60	−0.61	1.00

Non-civil Building

```
. correlate city regulation lngni lnppp lnpop
(obs=6,988)

             |   cityor regula~n    lngni    lnppp    lnpop
-------------+---------------------------------------------
      cityor |   1.0000
  regulation |  -0.0705   1.0000
       lngni |  -0.1058   0.4727   1.0000
       lnppp |  -0.1068   0.6448   0.5234   1.0000
       lnpop |   0.2035  -0.4523  -0.7882  -0.6130   1.0000
```

Figure A9. Correlation matrix for Model 3 (Non-civic Building).

Table A9. Correlation matrix for Model 3 (Non-civic Building).

	Whether the building is located in the urban centre	Use of building energy codes	Ln(PGNI)	Ln(PPP)	Ln(Population density)
Whether the building is located in the urban centre	1.00				
Use of building energy codes	−0.07	1.00			
Ln(PGNI)	−0.11	0.47	1.00		
Ln(PPP)	−0.11	0.64	0.52	1.00	
Ln(Population density)	0.20	−0.45	−0.79	−0.61	1.00

Appendix B. Interaction among Variables

Original

```
. asdoc reg pa city regulation i.Climate i.TYPE lnpop city##regulation##i.Climate##i.TYPE
(File Myfile.doc already exists, option append was assumed)
note: 2.cityor omitted because of collinearity
note: 1.regulation omitted because of collinearity
note: 2.cityor#0b.regulation identifies no observations in the sample
note: 2.cityor#1.regulation omitted because of collinearity
note: 2.cityor#1b.Climate identifies no observations in the sample
note: 2.cityor#2.Climate identifies no observations in the sample
note: 2.cityor#3.Climate identifies no observations in the sample
note: 2.cityor#4.Climate omitted because of collinearity
note: 2.cityor#0b.regulation#1b.Climate identifies no observations in the sample
note: 2.cityor#0b.regulation#2.Climate identifies no observations in the sample
note: 2.cityor#0b.regulation#3.Climate identifies no observations in the sample
note: 2.cityor#0b.regulation#4.Climate identifies no observations in the sample
note: 2.cityor#1.regulation#1b.Climate identifies no observations in the sample
note: 2.cityor#1.regulation#2.Climate identifies no observations in the sample
note: 2.cityor#1.regulation#3.Climate identifies no observations in the sample
note: 2.cityor#1.regulation#4.Climate omitted because of collinearity
note: 2.cityor#1b.TYPE identifies no observations in the sample
note: 2.cityor#2.TYPE identifies no observations in the sample
note: 2.cityor#3.TYPE identifies no observations in the sample
note: 2.cityor#4.TYPE omitted because of collinearity
note: 2.cityor#0b.regulation#1b.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#2.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#3.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#4.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#1b.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#2.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#3.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#4.TYPE omitted because of collinearity
note: 2.cityor#1b.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#1b.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#1b.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#1b.Climate#4.TYPE identifies no observations in the sample
note: 2.cityor#2.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#2.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#2.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#2.Climate#4.TYPE identifies no observations in the sample
note: 2.cityor#3.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#3.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#3.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#3.Climate#4.TYPE identifies no observations in the sample
note: 2.cityor#4.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#4.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#4.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#4.Climate#4.TYPE omitted because of collinearity
note: 0b.regulation#4.Climate#1b.TYPE identifies no observations in the sample
note: 1.regulation#4.Climate#4.TYPE omitted because of collinearity
note: 0b.cityor#0b.regulation#1b.Climate#1b.TYPE identifies no observations in the sample
note: 0b.cityor#0b.regulation#4.Climate#1b.TYPE identifies no observations in the sample
note: 0b.cityor#0b.regulation#4.Climate#4.TYPE identifies no observations in the sample
note: 1.cityor#0b.regulation#4.Climate#1b.TYPE identifies no observations in the sample
note: 1.cityor#1.regulation#3.Climate#4.TYPE omitted because of collinearity
note: 1.cityor#1.regulation#4.Climate#3.TYPE omitted because of collinearity
note: 1.cityor#1.regulation#4.Climate#4.TYPE omitted because of collinearity
note: 2.cityor#0b.regulation#1b.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#1b.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#1b.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#1b.Climate#4.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#2.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#2.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#2.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#2.Climate#4.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#3.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#3.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#3.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#3.Climate#4.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#4.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#4.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#4.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#0b.regulation#4.Climate#4.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#1b.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#1b.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#1b.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#1b.Climate#4.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#2.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#2.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#2.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#2.Climate#4.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#3.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#3.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#3.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#3.Climate#4.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#4.Climate#1b.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#4.Climate#2.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#4.Climate#3.TYPE identifies no observations in the sample
note: 2.cityor#1.regulation#4.Climate#4.TYPE omitted because of collinearity
```

Figure B1. Correlation coefficient among the independent variables in the regression model.

Source	SS	df	MS			
				Number of obs	=	56,200
				F(61, 56138)	=	282.15
Model	3390144.9	61	55576.1459	Prob > F	=	0.0000
Residual	11057631.1	56,138	196.972302	R-squared	=	0.2346
				Adj R-squared	=	0.2338
Total	14447776	56,199	257.082439	Root MSE	=	14.035

pa	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
cityor	2.856833	7.032205	0.41	0.685	-10.92633	16.64
regulation	-3.190512	11.42709	-0.28	0.780	-25.58768	19.20666
Climate						
B	-20.68689	11.7027	-1.77	0.077	-43.62426	2.250474
C	-5.128189	9.281093	-0.55	0.581	-23.31919	13.06281
D	41.36587	14.95669	2.77	0.006	12.05067	70.68106
TYPE						
2 Civil industrial buildings	-9.718751	11.7495	-0.83	0.408	-32.74784	13.31034
3 Civil public buildings	-17.48082	11.84519	-1.48	0.140	-40.69747	5.73582
4 Non-civil building	-9.796205	10.52447	-0.93	0.352	-30.42424	10.83183
lnpop	4.560179	.1169538	38.99	0.000	4.330949	4.789409
cityor						
1	-18.49313	13.10372	-1.41	0.158	-44.17651	7.190244
2	0	(omitted)				
1.regulation	0	(omitted)				
cityor#regulation						
1 1	17.40303	10.81642	1.61	0.108	-3.797221	38.60328
2 0	0	(empty)				
2 1	0	(omitted)				
cityor#Climate						
1#B	53.35578	11.27438	4.73	0.000	31.25793	75.45363
1#C	-.8126604	7.976771	-0.10	0.919	-16.44718	14.82186
1#D	-35.57147	14.57241	-2.44	0.015	-64.13349	-7.009459
2#A	0	(empty)				
2#B	0	(empty)				
2#C	0	(empty)				
2#D	0	(omitted)				
regulation#Climate						
1#B	32.85482	11.50027	2.86	0.004	10.31421	55.39543
1#C	-4.88528	9.016845	-0.54	0.588	-22.55835	12.78779
1#D	-35.54511	14.79075	-2.40	0.016	-64.53507	-6.555141
cityor#regulation#Climate						
1#1#B	-66.65082	11.04664	-6.03	0.000	-88.30232	-44.99933
1#1#C	6.655281	7.636447	0.87	0.383	-8.312202	21.62276
1#1#D	28.3274	14.38394	1.97	0.049	.1347975	56.52001
2#0#A	0	(empty)				
2#0#B	0	(empty)				
2#0#C	0	(empty)				
2#0#D	0	(empty)				
2#1#A	0	(empty)				
2#1#B	0	(empty)				
2#1#C	0	(empty)				
2#1#D	0	(omitted)				
cityor#TYPE						
1#2 Civil industrial buildings	14.41326	11.22639	1.28	0.199	-7.590529	36.41706
1#3 Civil public buildings	16.94713	11.3025	1.50	0.134	-5.205836	39.10011
1#4 Non-civil building	11.26176	9.826942	1.15	0.252	-7.999109	30.52263
2#1 Civil residential buildings	0	(empty)				
2#2 Civil industrial buildings	0	(empty)				
2#3 Civil public buildings	0	(empty)				
2#4 Non-civil building	0	(omitted)				
regulation#TYPE						
1#2 Civil industrial buildings	-4.503368	12.09821	-0.37	0.710	-28.21594	19.2092
1#3 Civil public buildings	12.71996	11.70575	1.09	0.277	-10.22338	35.66329
1#4 Non-civil building	1.857402	9.747817	0.19	0.849	-17.24838	20.96318
cityor#regulation#TYPE						
1#1#2 Civil industrial buildings	-15.70935	11.78222	-1.33	0.182	-38.80256	7.383869
1#1#3 Civil public buildings	-27.36102	11.14557	-2.45	0.014	-49.20641	-5.515624
1#1#4 Non-civil building	-13.36174	8.918919	-1.50	0.134	-30.84288	4.119394
2#0#1 Civil residential buildings	0	(empty)				
2#0#2 Civil industrial buildings	0	(empty)				
2#0#3 Civil public buildings	0	(empty)				
2#0#4 Non-civil building	0	(empty)				
2#1#1 Civil residential buildings	0	(empty)				
2#1#2 Civil industrial buildings	0	(empty)				
2#1#3 Civil public buildings	0	(empty)				
2#1#4 Non-civil building	0	(omitted)				

Figure B1. *(Continued)*

Climate#TYPE						
B#2 Civil industrial buildings	1.627042	12.22553	0.13	0.894	-22.33507	25.58915
B#3 Civil public buildings	21.73184	12.31771	1.76	0.078	-2.410945	45.87462
B#4 Non-civil building	25.75109	11.49037	2.24	0.025	3.229884	48.27229
C#2 Civil industrial buildings	-3.985593	9.622545	-0.41	0.679	-22.84584	14.87466
C#3 Civil public buildings	2.75272	9.917699	0.28	0.781	-16.68603	22.19147
C#4 Non-civil building	4.844641	6.467185	0.75	0.454	-7.831082	17.52036
D#2 Civil industrial buildings	-39.16623	16.60216	-2.36	0.018	-71.70657	-6.625898
D#3 Civil public buildings	-15.60029	4.671784	-3.34	0.001	-24.75702	-6.443568
D#4 Non-civil building	-11.52063	4.091808	-2.82	0.005	-19.5406	-3.500662
cityor#Climate#TYPE						
1#B#2 Civil industrial buildings	-43.3882	12.05031	-3.60	0.000	-67.00687	-19.76952
1#B#3 Civil public buildings	-57.02824	11.98096	-4.76	0.000	-80.511	-33.54548
1#B#4 Non-civil building	-59.27858	11.08647	-5.35	0.000	-81.00812	-37.54904
1#C#2 Civil industrial buildings	2.708681	8.593654	0.32	0.753	-14.13493	19.5523
1#C#3 Civil public buildings	-1.853535	8.76295	-0.21	0.832	-19.02897	15.3219
1#C#4 Non-civil building	.678174	4.194223	0.16	0.872	-7.542529	8.898877
1#D#2 Civil industrial buildings	29.00302	19.07484	1.52	0.128	-8.383792	66.38982
1#D#3 Civil public buildings	18.74621	2.720652	6.89	0.000	13.41371	24.0787
1#D#4 Non-civil building	14.02312	4.263348	3.29	0.001	5.666929	22.37931
2#A#1 Civil residential buildings	0	(empty)				
2#A#2 Civil industrial buildings	0	(empty)				
2#A#3 Civil public buildings	0	(empty)				
2#A#4 Non-civil building	0	(empty)				
2#B#1 Civil residential buildings	0	(empty)				
2#B#2 Civil industrial buildings	0	(empty)				
2#B#3 Civil public buildings	0	(empty)				
2#B#4 Non-civil building	0	(empty)				
2#C#1 Civil residential buildings	0	(empty)				
2#C#2 Civil industrial buildings	0	(empty)				
2#C#3 Civil public buildings	0	(empty)				
2#C#4 Non-civil building	0	(empty)				
2#D#1 Civil residential buildings	0	(empty)				
2#D#2 Civil industrial buildings	0	(empty)				
2#D#3 Civil public buildings	0	(empty)				
2#D#4 Non-civil building	0	(omitted)				
2#1#A#4 Non-civil building	0	(empty)				
2#1#B#1 Civil residential buildings	0	(empty)				
2#1#B#2 Civil industrial buildings	0	(empty)				
2#1#B#3 Civil public buildings	0	(empty)				
2#1#B#4 Non-civil building	0	(empty)				
2#1#C#1 Civil residential buildings	0	(empty)				
2#1#C#2 Civil industrial buildings	0	(empty)				
2#1#C#3 Civil public buildings	0	(empty)				
2#1#C#4 Non-civil building	0	(empty)				
2#1#D#1 Civil residential buildings	0	(empty)				
2#1#D#2 Civil industrial buildings	0	(empty)				
2#1#D#3 Civil public buildings	0	(empty)				
2#1#D#4 Non-civil building	0	(omitted)				
_cons	35.83416	11.67106	3.07	0.002	12.9588	58.70952

Figure B1. (*Continued*)

Improved Version 1

Table B1. Correlation coefficient among the independent variables in regression model.

Dep. var. = PA	Coef.	St. Err.	t-value	p-value	[95% Conf	Interval]	Sig
Constant	35.83	11.67	3.07	0.00	12.96	58.71	***
Whether the building is located in the urban centre	2.86	7.03	0.41	0.69	−10.93	16.64	
Use of building energy codes	−3.19	11.43	−0.28	0.78	−25.59	19.21	
Climate Zone A (base A)	0.00						
Climate Zone B	−20.69	11.70	−1.77	0.08	−43.62	2.25	*
Climate Zone C	−5.13	9.28	−0.55	0.58	−23.32	13.06	
Climate Zone D	41.37	14.96	2.77	0.01	12.05	70.68	***
Residential buildings (base 1Res~l)	0.00						
Civilian industrial buildings	−9.72	11.75	−0.83	0.41	−32.75	13.31	
Civilian public buildings	−17.48	11.85	−1.48	0.14	−40.70	5.74	
Non-civilian buildings	−9.80	10.52	−0.93	0.35	−30.42	10.83	
Ln(Population density)	4.56	0.12	38.99	0.00	4.33	4.79	***
Whether the building is located in the urban centre (base no)	0.00						
1	−18.49	13.10	−1.41	0.16	−44.18	7.19	
Use of building energy codes (base no)	0.00						
1	0.00						

Table B1. (*Continued*)

Whether the building is located in the urban centre (base no) # Use of building energy codes (base no)	0.00						
Yes_Yes	17.40	10.82	1.61	0.11	-3.80	38.60	
Whether the building is located in the urban centre (base no) # Climate Zone (base Climate Zone A)	0.00						
Yes_Climate Zone B	53.36	11.27	4.73	0.00	31.26	75.45	***
Yes_Climate Zone C	−0.81	7.98	−0.10	0.92	−16.45	14.82	
Yes_Climate Zone D	−35.57	14.57	−2.44	0.02	−64.13	−7.01	**
Use of building energy codes (base no) # Climate Zone (base Climate Zone A)	0.00						
Yes_Climate Zone B	32.86	11.50	2.86	0.00	10.31	55.40	***
Yes_Climate Zone C	−4.89	9.02	−0.54	0.59	−22.56	12.79	
Yes_Climate Zone D	−35.55	14.79	−2.40	0.02	−64.54	−6.56	**
Whether the building is located in the urban centre (base no) # Use of building energy codes (base no) # Climate Zone (base Climate A)	0.00						
Yes_Yes_Climate Zone B	−66.65	11.05	−6.03	0.00	−88.30	−45.00	***
Yes_Yes_Climate Zone C	6.66	7.64	0.87	0.38	−8.31	21.62	
Yes_Yes_Climate Zone C	28.33	14.38	1.97	0.05	0.14	56.52	**
Whether the building is located in the urban centre (base no) # Building types (base Residential buildings)	0.00						
Yes_Civil industrial buildings	14.41	11.23	1.28	0.20	−7.59	36.42	
Yes_Civil public buildings	16.95	11.30	1.50	0.13	−5.21	39.10	
Yes_Non-civil building	11.26	9.83	1.15	0.25	−8.00	30.52	
Use of building energy codes (base no) # Building types (base Residential buildings)	0.00						
Yes_Civil industrial buildings	−4.50	12.10	−0.37	0.71	−28.22	19.21	
Yes_Civil public buildings	12.72	11.71	1.09	0.28	−10.22	35.66	
Yes_Non-civil building	1.86	9.75	0.19	0.85	−17.25	20.96	
Whether the building is located in the urban centre (base no) # Use of building energy codes (base no) # Building types (base Residential buildings)	0.00						
Yes_Yes_Civil industrial buildings	−15.71	11.78	−1.33	0.18	−38.80	7.38	
Yes_Yes_Civil public buildings	−27.36	11.15	−2.45	0.01	−49.21	−5.52	**
Yes_Yes_Non-civil building	−13.36	8.92	−1.50	0.13	−30.84	4.12	
Climate Zone (base Climate Zone A) # Building types (base Residential buildings)	0.00						
Climate Zone B_Civil industrial buildings	1.63	12.23	0.13	0.89	−22.34	25.59	
Climate Zone B_Civil public buildings	21.73	12.32	1.76	0.08	−2.41	45.88	*
Climate Zone B_Non-civil building	25.75	11.49	2.24	0.03	3.23	48.27	**
Climate Zone C_Civil industrial buildings	−3.99	9.62	−0.41	0.68	−22.85	14.88	
Climate Zone C_Civil public buildings	2.75	9.92	0.28	0.78	−16.69	22.19	
Climate Zone C_Non-civil building	4.85	6.47	0.75	0.45	−7.83	17.52	
Climate Zone D_Civil industrial buildings	−39.17	16.60	−2.36	0.02	−71.71	−6.63	**
Climate Zone D_Civil public buildings	−15.60	4.67	−3.34	0.00	−24.76	−6.44	***
Climate Zone D_Non-civil building	−11.52	4.09	−2.82	0.01	−19.54	−3.50	***

Table B1. (*Continued*)

Whether the building is located in the urban centre (base no) # Climate Zone (base Climate Zone A) # Building types (base Residential buildings)	0.00						
Yes_Climate Zone B_Civil industrial buildings	−43.39	12.05	−3.60	0.00	−67.01	−19.77	***
Yes_Climate Zone B_Civil public buildings	−57.03	11.98	−4.76	0.00	−80.51	−33.55	***
Yes_Climate Zone B_Non-civil building	−59.28	11.09	−5.35	0.00	−81.01	−37.55	***
Yes_Climate Zone C_Civil industrial buildings	2.71	8.59	0.32	0.75	−14.14	19.55	
Yes_Climate Zone C_Civil public buildings	−1.85	8.76	−0.21	0.83	−19.03	15.32	
Yes_Climate Zone C_Non-civil building	0.68	4.19	0.16	0.87	−7.54	8.90	
Yes_Climate Zone D_Civil industrial buildings	29.00	19.08	1.52	0.13	−8.38	66.39	
Yes_Climate Zone D_Civil public buildings	18.75	2.72	6.89	0.00	13.41	24.08	***
Yes_Climate Zone D_Non-civil building	14.02	4.26	3.29	0.00	5.67	22.38	***
Use of building energy codes (base no) # Climate Zone (base Climate Zone A) # Building types (base Residential buildings)	0.00						
Yes_Climate Zone B_Civil industrial buildings	−15.34	12.71	−1.21	0.23	−40.25	9.58	
Yes_Climate Zone B_Civil public buildings	−47.56	12.23	−3.89	0.00	−71.52	−23.60	***
Yes_Climate Zone B_Non-civil building	−44.36	10.89	−4.07	0.00	−65.71	−23.02	***
Yes_Climate Zone C_Civil industrial buildings	13.73	10.08	1.36	0.17	−6.03	33.50	
Yes_Climate Zone C_Civil public buildings	−6.03	9.76	−0.62	0.54	−25.15	13.09	
Yes_Climate Zone C_Non-civil building	−0.94	5.06	−0.19	0.85	−10.86	8.97	
Yes_Climate Zone D_Civil industrial buildings	34.32	16.90	2.03	0.04	1.20	67.43	**
Yes_Climate Zone D_Civil public buildings	−3.41	3.90	−0.87	0.38	−11.05	4.23	
Yes_Climate Zone D_Non-civil building	0.00						
Whether the building is located in the urban centre (base no) # Use of building energy codes (base no) # Climate Zone (base Climate Zone A) # Building types (base Residential buildings)	0.00						
Yes_Yes_Climate Zone B_Civil industrial buildings	56.66	12.78	4.43	0.00	31.60	81.71	***
Yes_Yes_Climate Zone B_Civil public buildings	82.83	11.89	6.97	0.00	59.53	106.12	***
Yes_Yes_Climate Zone B_Non-civil building	77.63	10.43	7.44	0.00	57.18	98.08	***
Yes_Yes_Climate Zone C_Civil industrial buildings	−10.35	9.36	−1.10	0.27	−28.70	8.01	
Yes_Yes_Climate Zone C_Civil public buildings	7.55	8.57	0.88	0.38	−9.23	24.34	
Yes_Yes_Climate Zone C_Non-civil building	0.00						
Yes_Yes_Climate Zone D_Civil industrial buildings	−23.75	19.47	−1.22	0.22	−61.91	14.40	
Yes_Yes_Climate Zone D_Civil public buildings	0.00						
Yes_Yes_Climate Zone D_Non-civil building	0.00						
Number of obs	56,200.00						
R-squared	0.24						
F-test	282.15						
Prob > F				0.00			

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Note: *** indicates significance at the 1% level; ** indicates significance at the 5% level; * indicates significance at the 10% level.