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Research article

# Revisiting the relationships between energy consumption, economic development and urban size: A global perspective using remote sensing data

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ABSTRACT

Existing methods of measuring energy consumption require complex statistics and computing. A real-time and globally applicable approach for comparing energy consumption across different cities is still lacking. Additionally, the nonlinear relationships and varying thresholds of energy consumption in relation to economic activities and urbanization remain unconfirmed. This study aims to fill these gaps by utilizing Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (NPP-VIIRS) nighttime light data in 2015 and a top-down approach based on a multiple regression model to examine energy consumption in global cities employing a redefined urban boundary. It also explores the accurate relationship between energy consumption, population density (as a proxy of urbanization), and per capita gross domestic product (GDP) across different regions and urban sizes using generalized additive models and regression models. High-resolution gridded population and GDP datasets covering the entire planet are utilized for this purpose. The study also estimates the development potentiality. The study yields followings outcomes: Firstly, the top 30 cities with the highest per capita energy consumption account for over 0.66% of the total per capita energy consumption of all cities. Secondly, in East Asia (EA) and Southeast Asia (SEA), the per capita energy consumption decreases when per capita GDP reaches $40,000 and $75,000, respectively, while it remains stable in cities located in Western Europe (WE) and North America (NA) as per capita GDP increases. Thirdly, the per capita energy consumption declines with increasing urban population density until reaching 10,000 person/km$^2$, 22,000 person/km$^2$, and 4000 person/km$^2$ in EA, SEA, and NA, respectively. Fourthly, in Central Asia (CA), megacities can save over 100 Mbtu/population when per capita GDP increases by $1000 compared to big cities. This pioneering study provides a comparable investigation of energy consumption at the global city level, exploring its relationship with urbanization and economy by employing a unified calculation standard. It will facilitate long-term energy-saving policies and urban planning strategies.

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## 1. Introduction

The broader impacts of urban economic activities and urbanization on energy consumption are closely linked to Sustainable Development Goals 7 and 13. Currently, cities are responsible for a staggering 78 percent of global energy consumption and contribute to over 60 percent of the world's greenhouse gas emissions [1]. With the projected expansion of urban land by 50–100 percent by 2050 [2], the energy burden is set to escalate exponentially. Thus, it is imperative to effectively quantify the energy consumption of cities worldwide in order to enable targeted political interventions and formulate policies that foster urban sustainability.

While most studies have primarily focused on evaluating energy consumption at the provincial and national levels, the investigation of energy consumption at the city level remains relatively scarce. There are three main approaches to assess city-level energy consumption. The first approach involves using a single indicator with robust stability, such as total electricity consumption, land use, construction type or GDP [3–5]. For instance, Pereira and Assis [6] mapped energy consumption in the city of Belo Horizonte, Brazil, using data on residential equipment. Another approach involves disaggregating the total energy consumption at a larger scale into sub-cities based on the proportion of specific indicators. Dhakal [7] employed the percentage of GDP in cities as indicator due to its significant correlation with energy consumption, thus distributing urban energy consumption from provinces.

Moreover, the estimation of city energy consumption has also been accomplished through urban energy balance table. This method utilizes indicators to downscale energy consumption from provinces according to sectors specified in the balance table. Jing et al. [8] exemplify this top-bottom approach by recognizing cities as components of provinces and estimate city-scale energy in 41 Chinese cities, utilizing provincial energy balance tables and city-level socioeconomic indicators. Compared to employing a single indicator, the utilization of multiple indicators enables a more precise evaluation of energy consumption as it encompasses various facets of urban overall energy consumption.

However, there are still limitations to the extent that statistical data can accurately capture energy consumption for every city, and different measurement standards rely on proxy features making it challenging to compare energy consumption across cities. Additionally, energy consumption at the city scale are often inaccessible for many developing countries. Consequently, there remains a dearth of studies that objectively evaluate energy consumption using a comparable method. To fill this research gap, this study evaluate city-level energy consumption for global cities by employing a top-down approach and multiple regression model based on nighttime light data from the Suomi National Polar-orbiting Partnership satellite's Visible Infrared Imaging Radiometer Suite (NPP-VIIRS).

The NPP-VIIRS nighttime light images are transformed into a global latitude-longitude grid, enabling the proposed approach to be replicated in various geographic areas worldwide and evaluate energy consumption for different years since 2012. This grid-based approach, leveraging accurate and wide-ranging nighttime light, is particularly suitable for cities in developing countries where monitoring of energy consumption is lacking [9].

In addition, in contrast to previous studies that investigate energy consumption of cities based on administrative boundaries. This innovative approach utilizes redefined urban agglomerations as a benchmark through relying on NPP-VIIRS nighttime light data, gridded population of the world and global land use, ensuring comparability across global cities. This is crucial as city administrative boundaries may not align perfectly with built-up areas or boundaries of human activity, which is a common challenge in urban studies [10–12]. Moreover, this study also explores urban development potentialities, a factor that has been largely overlooked in existing energy consumption studies.

The energy crises of 1974 and 1981 prompted extensive scholarly investigations into the relationships among energy consumption, economic development, and urbanization, utilizing various econometric approaches for analysis [4,13,14]. The relationship between economic development and energy consumption has been the subject of both theoretical and empirical debates, yielding inconclusive findings [15,16]. The "growth hypothesis" suggests that high energy utilization plays a significant role in driving economic growth. In contrast, the "conservation hypothesis" argues that implementing conservation policies focused on improving energy efficiency, reducing energy consumption, and minimizing waste can enhance energy use efficiency and ultimately stimulate the economy [17].

In this context, valuable studies exploring the relationship among economic growth, public infrastructure, and energy consumption

**Table 1**
Data information and source.

| Reagent or resource | Source | Available at: |
|---|---|---|
| Deposited data | | |
| International energy statistics in 2015 | U.S. Energy Information Administration | https://www.eia.gov/international/data/world |
| NPP-VIIRS nighttime light data in 2015 | NOAA | https://www.ngdc.noaa.gov/eog/viirs/download_dnb_composites.html |
| Gridded population of the world in 2015 | SEDAC | https://sedac.ciesin.columbia.edu/data/sets/browse |
| Gridded global datasets for gross domestic product in 2015 | Kummu et al. (2018) | https://www.nature.com/articles/sdata20184 |
| Global land use in 2015 | ESA | http://maps.elie.ucl.ac.be/CCI/viewer/index.php |
| Global administrative areas in 2018 | GADM | http://gadm.org/country |
| International urban road network in 2015 | OpenStreetMap | https://www.openstreetmap.org |
| Software and algorithms | | |
| ArcGIS 10.5 | ESRI | https://www.arcgis.com |
| R4.2.0 | Lucent Technologies | https://cran.r-project.org |

have been conducted by Magazzino and Giolli [18] using Italy as a case study. The findings of these studies have yielded inconclusive and mixed results due to spatial heterogeneity, variations in data periods, and divergent methodologies. Recognizing this, Magazzino and Schneider [19] provided a state-of-the-art review highlighting key approaches to understanding these relationships. Moreover, previous studies have primarily focused on either emerging economies [20] or developed countries [21–23], leading to a limited understanding of the global scope of these relationships.

To understand the relationship between energy consumption and the urban economy and population across global cities. Firstly, the estimation of city-level GDP and population is unified by utilizing fine-grained spatial grid data that covers the entire planet based on a redefined city boundary, which ensures a consistent measture framework. Moreover, unlike previous studies that predominantly rely on long-term time series data from a limited set of typical cities, employing the regression model this study use nighttime light data, enabling real-time analysis of the relationship for a broader range of global cities. Lastly, this study considers the heterogeneous effects resulting from different regions and city sizes, providing a comprehensive understanding of the complexities involved.

Utilizing a high-resolution dataset covering the entire planet, the objectives of this study are: firstly, to develop a novel top-down approach for estimating energy consumption and validate it across diverse cities; secondly, to explore the relationship between energy consumption and per capita GDP as well as population density, encompassing cities of varying sizes and regions; and thirdly, to assess the development potential for over 8000 cities. While this study acknowledges certain limitations by only using the nighttime light which can be affected by other factors, this proposed approach and its resultant findings possess the potential to significantly enhance urban sustainability, mitigate energy consumption and support effective urban management. In detail, the government can establish ambitious targets for energy efficiency interventions and identify best practices that can be replicated in other cities, based on the performance of other cities. The relationship between energy consumption, GDP, and population growth is beneficial for long-term urban planning and monitoring, as well as providing suggestions for sustainable economic growth and population movement.

## 2. Literature review

As the SDGs have become a significant discussion, numerous studies have focused on evaluating energy consumption at different scales [24]. Existing data sources like the global atmospheric research carbon emission database were widely to evaluate energy consumption globally, its low spatial resolution and non-grid features have limited applicability at small scales [25]. Moreover, the availability of energy statistics is limited to only a few cities, and there are challenges associated with the nonuniform and inaccurate data collection methods, lack of transparency in reporting methods and data sources as well as varying definitions from different statistic institutions.

Nighttime light, aided by advancements in earth observation techniques, has emerged as a valuable tool for capturing economic activity [26], population density [27,28], and electrical power consumption at various scales [29]. Due to its ability to reflect light generated from different energy sources, including fossil fuels and oil, remote sensing data of nighttime light has been effectively utilized to estimate energy consumption [30–32]. Wu et al. [33] supported the use of nighttime light for estimating energy consumption by establishing a linear relationship between nighttime light and energy statistics data spanning over a decade across 30 provinces in China.

At city level, the city-level estimation of energy consumption over long-term series was conducted by scholars such as Du et al. [34] and Wang and Li [35]. In US cities, Fragkias et al. [36] demonstrated the assessment of distinct urban energy features, such as energy use, using nighttime light. However, the application of nighttime light has been predominantly limited to national or provincial scales, or small-scale analyses, with no existing studies evaluating city-level energy consumption on a global level.

The nexus between population, economy and energy consumption has been extensively debated in the current literature. Economic growth resulting from industrial and manufacturing development leads to increased in the energy consumption enhance [37–39]. Previously studies have examined the energy-intensive utilization and its long-term effects on the economy in different countries and regions, including Turkey [37], Pakistan [40] and Europe [41].

Magazzino et al. [23] revealed the causal relationship between energy consumption and economic growth at various time scales using Italy as case scenario. Wang et al. [42] suggested that the associations between economic growth and ecological footprint varied across different development stages, using the urbanization as threshold variables. Wang and Zhang [43] decoupling economic growth from energy consumption in top five energy consumers (China, the United States, India, Japan and Russia), he impact of technological factors and urbanization factor on energy consumption.

Although economic growth is expected to increase the population density, only a few studies have incorporated population density in energy consumption analysis [16,44]. The compact city theory has suggested that a denser and more compact urban forms can contribute to sustainable urban development, including reduced energy consumption [45]. According to this view, encourage larger cities with higher population density can lead to reduce infrastructure requirement, minimize land consumption and thus promote energy-efficient use. Empirical studies have revealed conflicting findings regarding the impact of population density on energy consumption.

Sarkodie and Adom [46] found that while population density reduces fossil fuel energy consumption, it has a limited impact on electricity consumption. In contrast, Muzayanah et al. [47], who examined data from 33 provinces in Indonesia between 2010 and 2018, observed a positive relationship between population density and energy consumption, including total, electricity, and fuel consumption. Khan et al. [48], in their analysis of the United States, discovered a unidirectional causality from population growth to energy consumption when evaluating the impact of natural resources, energy consumption, and population growth on the ecological footprint. However, another study by Yongling [49] found that population density did not significantly affect energy reduction. These inconclusive results highlight the need for further research in this area.

Moreover, while previous studies have investigated the relationship between economic growth, population density, and energy consumption at a global scale, there is a dearth of research specifically focusing on global cities. Therefore, this study aims to provide valuable insights into city-level energy consumption worldwide, while also addressing the challenges associated with capturing the relationship between population density, economic growth, and energy consumption. By utilizing a comprehensive dataset covering the planetary scale, this study seeks to support the formulation of appropriate policies for urbanization and the achievement of SDGs.

## 3. Results

### 3.1. Spatial distribution characteristics of cities' energy consumption: city level

A redefined set of cities is used as a benchmark for computing energy consumption. The cities are categorized into nine regions: North America (NA); Western Europe (WE); Eastern Europe (EE); Africa (AF); East Asia (EA); Southeast Asia (SEA); Central Asia (CA); South Asia (SA); and Oceania (OC) (Fig. S1).

The average per capita energy consumption of cities in each region is depicted using a color scale ranging from dark gray to light gray, representing high to low values (Fig. 1). Notably, NA, EE, and EA have relatively high per capita EC levels. In contrast, SEA has the lowest average per capita energy consumption among the nine regions, with all cities averaging 330 Mbtu, which is 10.25% of the value in NA, the region with the highest per capita energy consumption.

Fig. 1 also displays the per capita energy consumption of the 8425 redefined cities. Cities with high per capita energy consumption are concentrated in NA, WE, and EA, while they are sparsely distributed in SA, AF, and OC. Among all cities, Szczecin in Poland has the highest per capita energy consumption, with 38,761 Mbtu. AI Wakrah in Qatar (35,083 Mbtu) and Trondheim in Norway (30,771 Mbtu) rank second and third, respectively.

The column show the identified top 30 cities with the highest per capita energy consumption, which collectively account for more than 0.66% of the total per capita energy consumption across all cities examined. Out of these 30 cities, 21 cities have per capita energy consumption exceeding 10,000 Mbtu. Five of these cities are located in Qatar (Al Wakrah, Umm Salal Muhammad, Ar Rayyan, Al Wukayr, and Umm Salal Muhammad), while three are in South Korea (Pusan, Gwangju, and Moppo). The remaining cities are concentrated in the United Arab Emirates, the United States of America, Germany, Slovenia, the Russian Federation, Poland, Norway, the Netherlands, and Canada.

Regarding total EC (Fig. S3), CA exhibits the highest overall energy consumption, followed by OC and EA. Interestingly, high rates of energy consumption are no longer limited to developed countries. Cities such as Dongguan ($37.14 \times 10^{10}$Mbtu), Shanghai ($24.22 \times 10^{10}$Mbtu), Abudhabi ($24.00 \times 10^{10}$Mbtu), Beijing ($20.80 \times 10^{10}$Mbtu), and Moron ($10.10 \times 10^{10}$Mbtu) showcase the greatest total energy consumption.

These findings provide valuable insights into the spatial distribution of energy consumption in cities, highlighting regional disparities and identifying cities with the highest per capita energy consumption and total energy consumption. Such comparable knowledge can serve as a valuable tool for policymakers, urban planners, and researchers in formulating effective energy strategies, such as learning the experiences from cities with lower per capita energy consumption and identifying cities with higher energy demands to allocate resources accordingly.

### 3.2. Overall energy efficiency in cities: regional level

The hypothesis that larger cities are more energy efficient than smaller cities and suburban areas has been a subject of discussion. For example, previous research has suggested that apartment buildings in larger cities have higher energy efficiency for heating and cooling compared to detached houses [50]. To investigate this idea further, we conducted a comparative analysis of the average per capita energy consumption of global cities across adjacent city sizes[1] in the nine regions.

The analysis focused on the difference in energy consumption between two adjacent city sizes, such as small city and medium city, medium city and big city, and so on. A positive difference would indicate that an increase in urban size yields significant energy-saving advantages (color in green).

The results reveal that megalopolises consume less energy per capita compared to megacities in six regions (NA, EA, SA, EE, WE, and CA), with an average reduction of 29.88%. The observed reductions in per capita energy consumption are 70.17% in CA, 48.40% in EE, and 47.71% in WE, compared to adjacent city sizes. Notably, megacities account for 18.55%, 13.22%, and 23.44% of the total cities in CA, EE, and WE, respectively. This suggests that developing these megacities into larger urban areas could be beneficial from the perspective of energy efficiency.

On average, medium-sized cities demonstrate higher energy efficiency than small cities in six regions (NA, EA, AF, SEA, EE, and CA), albeit with a modest energy-saving percentage of 18.35%. Big cities are more energy efficient than medium-sized cities in four regions, with per capita energy consumption decreasing by 6.23%, 27.83%, 16.8%, and 20.25% in NA, AF, SEA, and WE, respectively. However, the transition from big city to megacity does not result in a significant decline in energy consumption (Fig. 2).

These findings shed light on the relationship between city size and energy consumption. Understanding these patterns can inform urban planning strategies, emphasizing the importance of compact and sustainable urban development to optimize energy usage and

[1] We defined urban scales into five categories based on the urban population: small city (population $<$ 10,000); medium city (10,000 $\leq$ population $<$ 50,000); big city (50,000 $\leq$ population $<$ 100,000); megacity (100,000) $\leq$ population $<$ 500,000) and megalopolis (population $\geq$500,000).

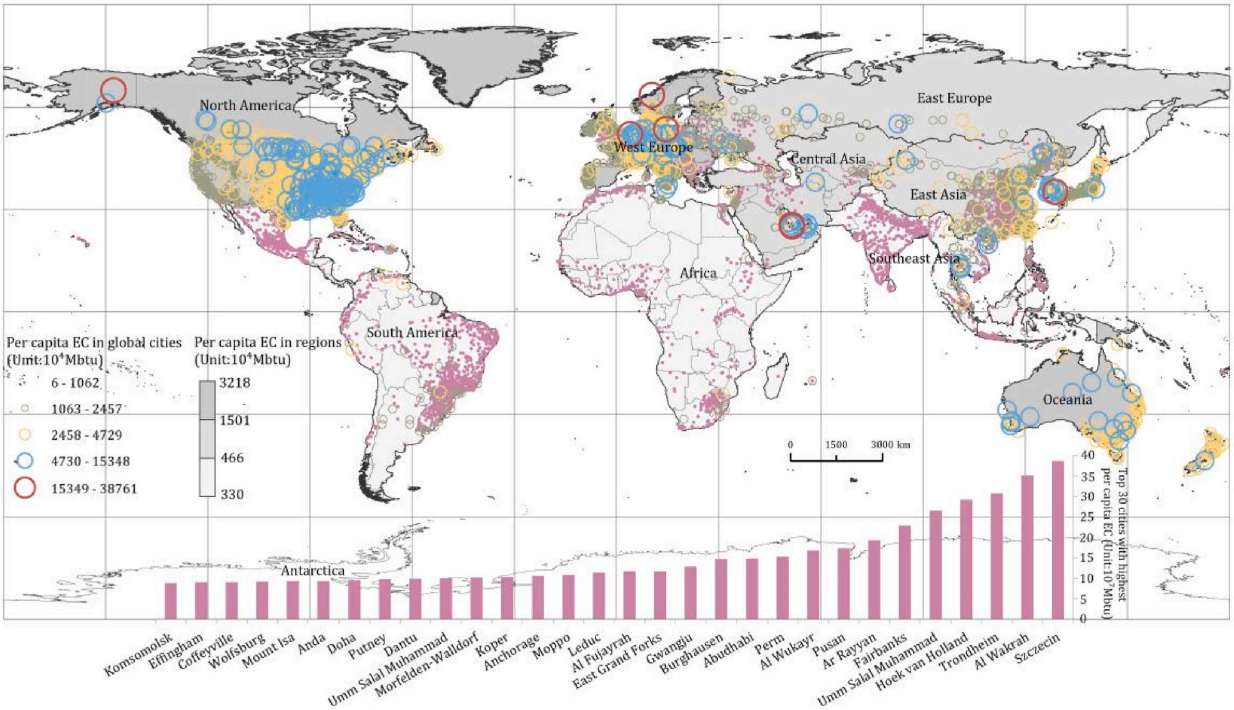


**Fig. 1.** The per capita energy consumption in global cities
Note: In this study, a redefined city boundary was applied, which means that the city boundary used does not align with the administrative boundary of the original cities. The city names assigned to the redefined urban areas correspond to the cities that exhibit the highest spatial consistency with the original cities; the image was drawn by ArcGIS 10.5.

reduce environmental impacts for special regions and urban sizes.

### *3.3. Disparities in the relationships between economic development and energy consumption across various urban sizes: regional level*

This study has revealed significant disparities in the relationship between economic development and energy consumption across cities of various sizes in different regions. Fig. 3 provides an overview of the per capita energy consumption relative to per capita GDP in the nine regions.

In general, as per capita GDP increases, per capita energy consumption also tends to rise. However, in EA and SEA, an interesting inverted U-shaped curve relationship is observed, with the peaks of energy consumption appearing at approximately $35,000 and $55,000 per capita GDP, respectively. This suggests that beyond these thresholds, further economic growth may not lead to a proportional increase in energy consumption. On the contrary, most other cities lie on the left side of the turning point, indicating that as economic trends continue to rise, per capita energy consumption is likely to keep growing.

In AF and SA, per capita energy consumption experiences a rapid increase with the rise in per capita GDP, although cities in these regions generally have lower per capita energy consumption levels. In fact, in 95.45% of cities in AF and 96.40% of cities in SA, per capita energy consumption remains below 1000 Mbtu (the corresponding percentages are less than 10% in NA and OC). For cities in EE, the impact of per capita GDP on per capita energy consumption remains relatively stable within the economic range of $5000 to $50,000. However, beyond this threshold, continued economic development leads to a significant rise in energy consumption.

In CA, per capita energy consumption gradually increases with the growth of per capita GDP, indicating a relatively slower pace of energy consumption increase. Meanwhile, cities in WE and NA exhibit stable per capita energy consumption levels as per capita GDP increases, although energy consumption remains low in WE compared to NA. The figure also reveals fluctuating growth patterns of per capita energy consumption with increasing per capita GDP in cities located in OC. Notably, the lowest per capita energy consumption is observed when per capita GDP ranges between $8000 and $10,000, while the worst effect on energy savings occurs at a per capita GDP of $4000.

The relationship between economic development and energy consumption is complex and varies across regions. The inverted U-shaped curve observed in EA and SA indicates the existence of optimal points where further economic growth may not translate into proportionate increases in energy consumption. The regions with faster urbanization rates, such as AF and Asia, are likely to experience accelerated energy consumption in the coming decades. Policymakers can use the identified trends and relationships between energy consumption and economic development to develop tailored strategies that promote sustainable energy practices.

To investigate the influence of urban size on the relationship between economic development and energy consumption, we conduct

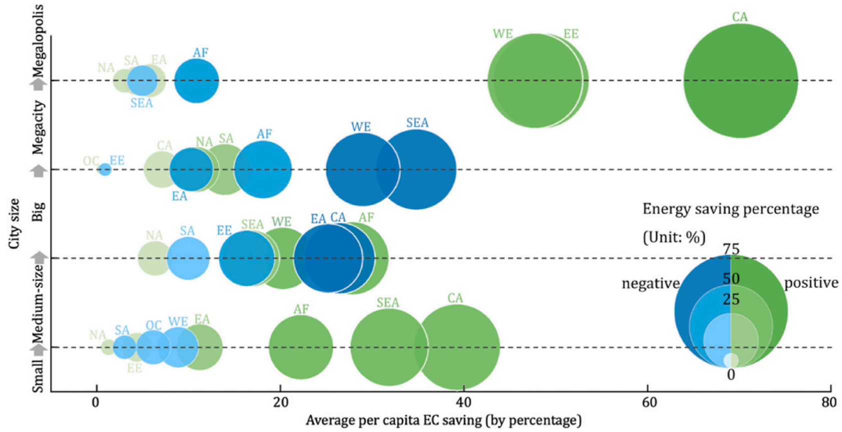


**Fig. 2.** Comparison of average per capita energy consumption across various city sizes in the nine regions.

separate tests for five urban sizes (Fig. 4). The results reveal that in SEA, megalopolises and megacities demonstrate better energy-saving effects, while for other city sizes in the region, economic development is related to the high energy consumption. Notably, the higher slope in CA exhibits the worst rate of energy efficiency ($k = 0.163$), requiring over 100 Mbtu of energy per $1000 GDP per capita compared to the big city ($k = 0.061$).

In EA, the megacity exhibits the highest energy efficiency among all city types, while medium-sized cities show significantly lower energy consumption than small cities for the same level of per capita GDP. In SA, there are minor differences in per capita energy consumption among big cities, medium-sized cities, and small cities. On the other hand, in AF, clear disparities in energy savings are observed across different city sizes, with the megacity exhibiting the highest energy efficiency ($k = 0.036$), saving approximately 50% of the energy consumed by big cities ($k = 0.071$) at the same level of per capita GDP.

In EE and WE, rising trend of per capita energy consumption becomes less steep as city size increases. In CA, the megacity, big city, and medium-sized city show relatively high slopes, indicating low energy efficiency as economic production grows. Megalopolises (only in SEA) and megacities in EA, AF, and SEA exhibit energy-saving benefits during economic production. Promoting the development of small- and medium-sized cities into big cities in WE and CA can lead to more efficient energy utilization.

To ensure the regression accuracy, we only consider the city size when the total number exceed 18. The regression results were kept when $P < 0.1$. The slopes in CA are relatively high in the megacity, big city, and the medium-sized city, which reflect the low energy efficiency as economic production grows. The megalopolis (only in SEA) and megacity in EA, AF and SEA are conducive to energy savings during the economic production process. Developing small- and medium-sized cities into big cities in WE and CA can lead to more efficient energy use.

In summary, cities in regions other than WE should learn from its strategies. OC exhibits fluctuating trends, and cities with per capita GDP between $4000 and $8000 require further study to closely examine the effectiveness of energy-saving policies in each city. Cities located on the right side of the turning points in EA and SEA should be studied further to provide practical suggestions for energy strategies in these large economies, considering the increasing energy efficiency along with GDP growth. Currently, megalopolises and megacities hold promise in some regions like EA, AF, and SEA. Energy use efficiency should be prioritized in CA and WE, where the construction of big cities instead of small- and medium-sized cities could yield significant benefits. In addition, other factors including regional context and economic dynamics, should also be considered.

### *3.4. Disparities in the relationship between population density and energy consumption across various urban scales: regional level*

Looking at the relationship between population density and energy consumption (Fig. 5), it becomes evident that population density exerts a regionally varying negative influence on energy consumption. In EA, SEA, and NA, the maximum impact of population density on energy consumption occurs at 10,000, 22,000, and 4000 person/$km^2$, respectively, and this influence remains consistent as population density increases. However, in CA, population density exhibits a cliff-like effect on energy savings until it reaches 2500 persons/$km^2$.

This suggests that in CA, dense cities can effectively control energy consumption during the early stages of urban development, even with lower population density. Notably, population density negatively impacts energy consumption, resulting in small, fluctuating increases when it ranges from 2000–2,500, 1500–2,000, and 6000–8000 persons/$km^2$ in EE, WE and AF, respectively. and then as the value became larger, the per capita continued to slowly decline.

In NA, per capita energy consumption shows a relatively slow descent that is amplified by population density, rather than a steep decline. In SA and OC, per capita energy consumption experiences a significant drop as population density increases until it reaches 2000 and 800 persons/km2, respectively, after which the rate of decline slows down.

The analysis of the relationship between per capita energy consumption and population density across different urban sizes (Fig. 6) reveals that higher population density is associated with better energy efficiency in megacities ($k = -0.259$) and big cities in CA ($k =$

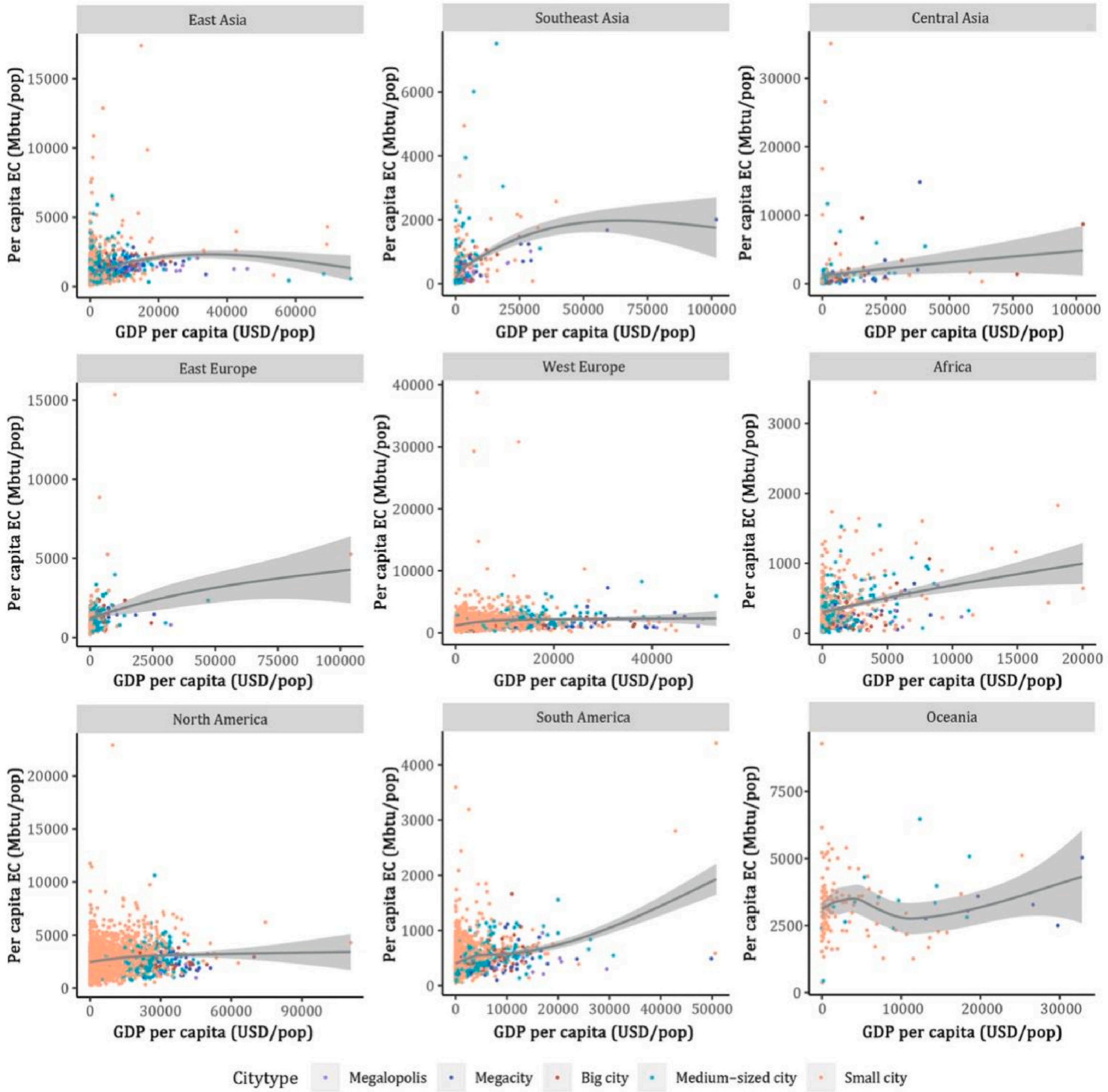


**Fig. 3.** Relationship between per capita energy consumption and per capita GDP in the nine regions. Panel 1: East Asia, Panel 2: Southeast Asia, Panel 3: Central Asia, Panel 4: East Europe, Panel 5: West Europe, Panel 6: Africa, Panel 7: North America, Panel 8: South America, Panel 9: Oceania. Note: The fit line and error bands reflect the best fitting model. The error bands are 95% prediction intervals fitted using R4.2.0.

−0.130). In WE, high population density benefits energy savings for big cities (k = −0.211) and medium-sized cities (k = −0.391). In NA, apart from megalopolises and big cities, energy consumption shows a significant correlation with population density across all city types. Generally, per capita energy consumption significantly declines with increasing population density.

The energy efficiency trends in SEA and SA are similar, with population density improvements observed across different sizes, and the absolute value of k (k = −0.033 and k = −0.079, respectively) is highest in small cities. In AF and EE, population density is significantly associated with per capita energy consumption only in medium-sized and small cities. Comparing the slopes in these two types suggests that small cities are more effective in energy saving.

These findings emphasize the crucial role of population density in shaping energy consumption patterns and highlight the potential for energy efficiency improvements through urban planning and development strategies. For example, strategies that promote higher population density, particularly in megacities and big cities, can contribute to enhanced energy efficiency. Furthermore, the findings underscore the importance of tailoring energy-saving measures to specific urban sizes and regional contexts to achieve sustainable and

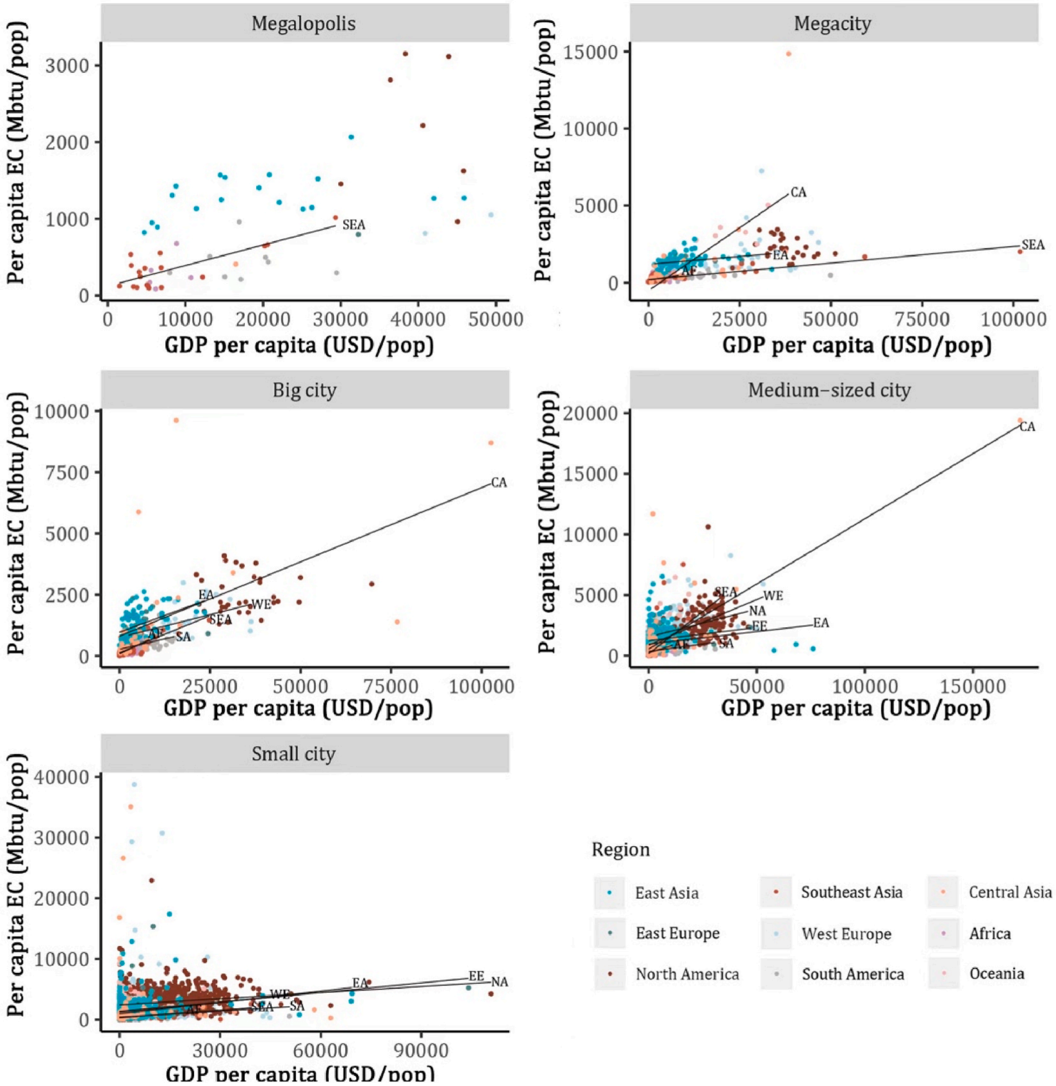


**Fig. 4.** Relationship between per capita energy consumption and per capita GDP across urban sizes. Panel 1: Megalopolis, Panel 2: Megacity, Panel 3: Big city, Panel 4: Medium-sized city, Panel 5: Small city.
Note: To ensure the regression accuracy, we only consider the city size when the total number exceed 18. The regression results were kept when $P < 0.1$.

resilient urbanization.

### 3.5. Global city development potential: city level

To evaluate urban development potential, we utilize a quantile approach in ArcGIS 10.5 to classify the per capita GDP, population density and per capita energy consumption values of cities into three categories: high (H), middle (M) and low (L). This allows us to create a comprehensive three-dimensional judgment matrix (Fig. S4), resulting in the identification of 889 cities with the highest development potential, 2588 cities with relatively high potential, 2405 cities with medium potential, 1718 cities with relatively low potential, and 825 cities with the lowest potential (Fig. 7).

Our findings indicate that approximately 41.27% of the analyzed cities, totaling 3,477, possess high or relatively high development potential. These cities are predominantly located in southern NA, SA, AF and SEA. Interestingly, although higher development potential tends to be observed in less developed regions, some cities in these areas still face challenges in achieving significant development potential. Examples include Trujillo Alto, Maracay, and Huacho in SA, Phalaborwa, Awsim, and Quwaysina in AF, and Bang Lamung, Putrajaya, and Singapore in SEA.

Cities with the highest development potential are primarily concentrated in India, the Gulf of Mexico, Southwest Brazil, South Africa, and Nigeria. These cities exhibit relatively low levels of economic development, population density, and per capita energy

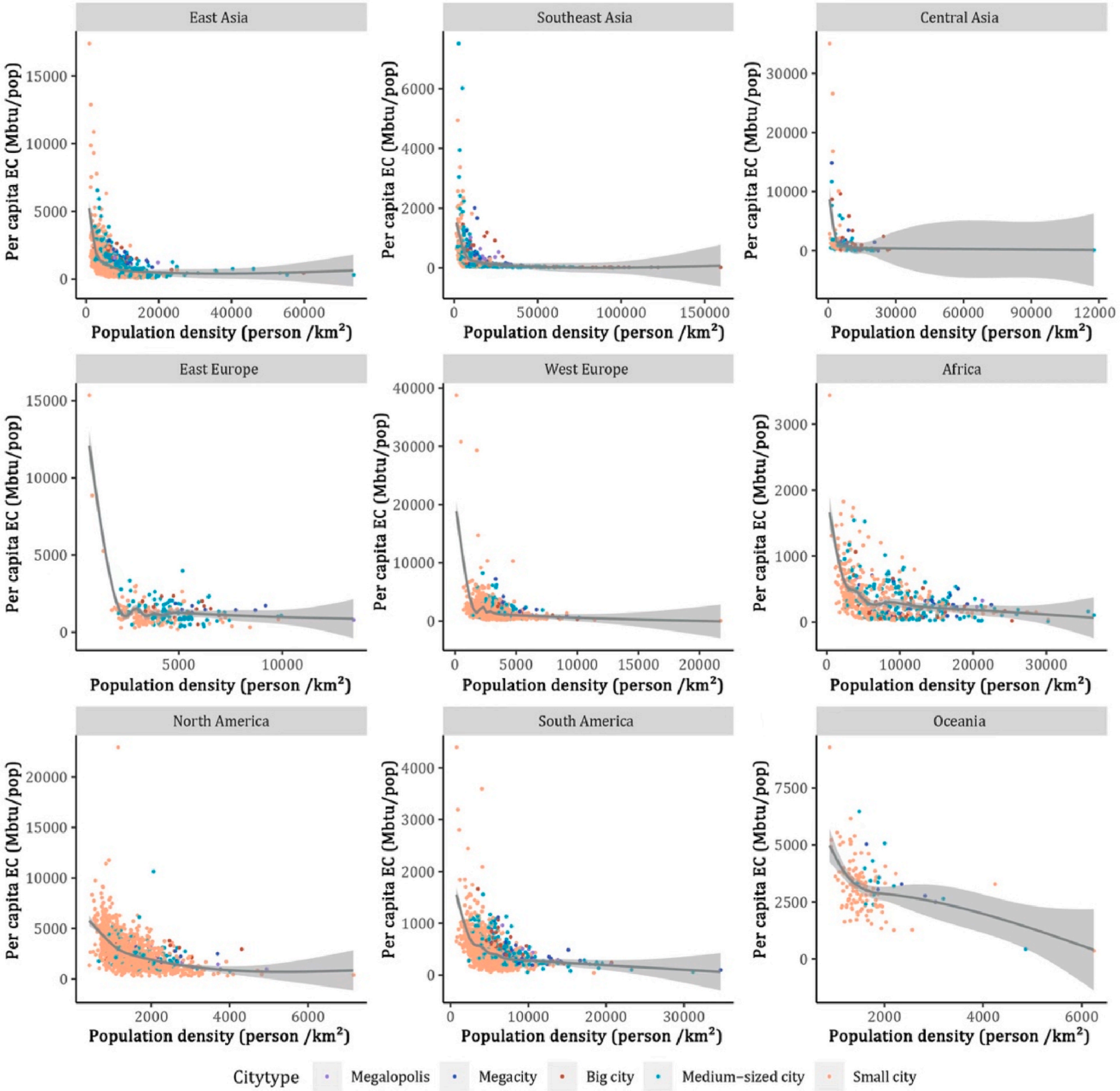


**Fig. 5.** Relationship between per capita energy consumption and population density in the nine regions. Panel 1: East Asia, Panel 2: Southeast Asia, Panel 3: Central Asia, Panel 4: East Europe, Panel 5: West Europe, Panel 6: Africa, Panel 7: North America, Panel 8: South America, Panel 9: Oceania. Note: The fit line and error bands reflect the best fitting model. The error bands are 95% prediction intervals fitted using R4.2.0.

consumption, indicating opportunities for sustainable energy use, the development of cleaner industries, and improvements in urban planning. Relatively high development potential cities are mainly distributed across India, Bangladesh, Vietnam, as well as various cities in SEA, central Africa, and western EE. Cities with medium development potential represent 28.55% of the total cities and have a widespread global distribution, including regions such as Australia, eastern China, and WE.

Cities with relatively low development potential are predominantly found in highly urbanized countries and regions, including WE, NA, Japan, and countries rich in oil and gas resources such as Qatar and Saudi Arabia. For these cities, strategies should focus on transforming energy consumption habits and promoting clean energy sources, especially considering their significant oil and gas reserves. Cities with the lowest development potential are concentrated in NA, WE, and urban agglomerations in China (such as Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta), as well as South Korea. These cities face significant energy burdens due to their large populations and high per capita energy consumption. However, since they are already developed areas, implementing new technologies to improve energy efficiency and explore alternative energy sources can be effective in enhancing their development potential.

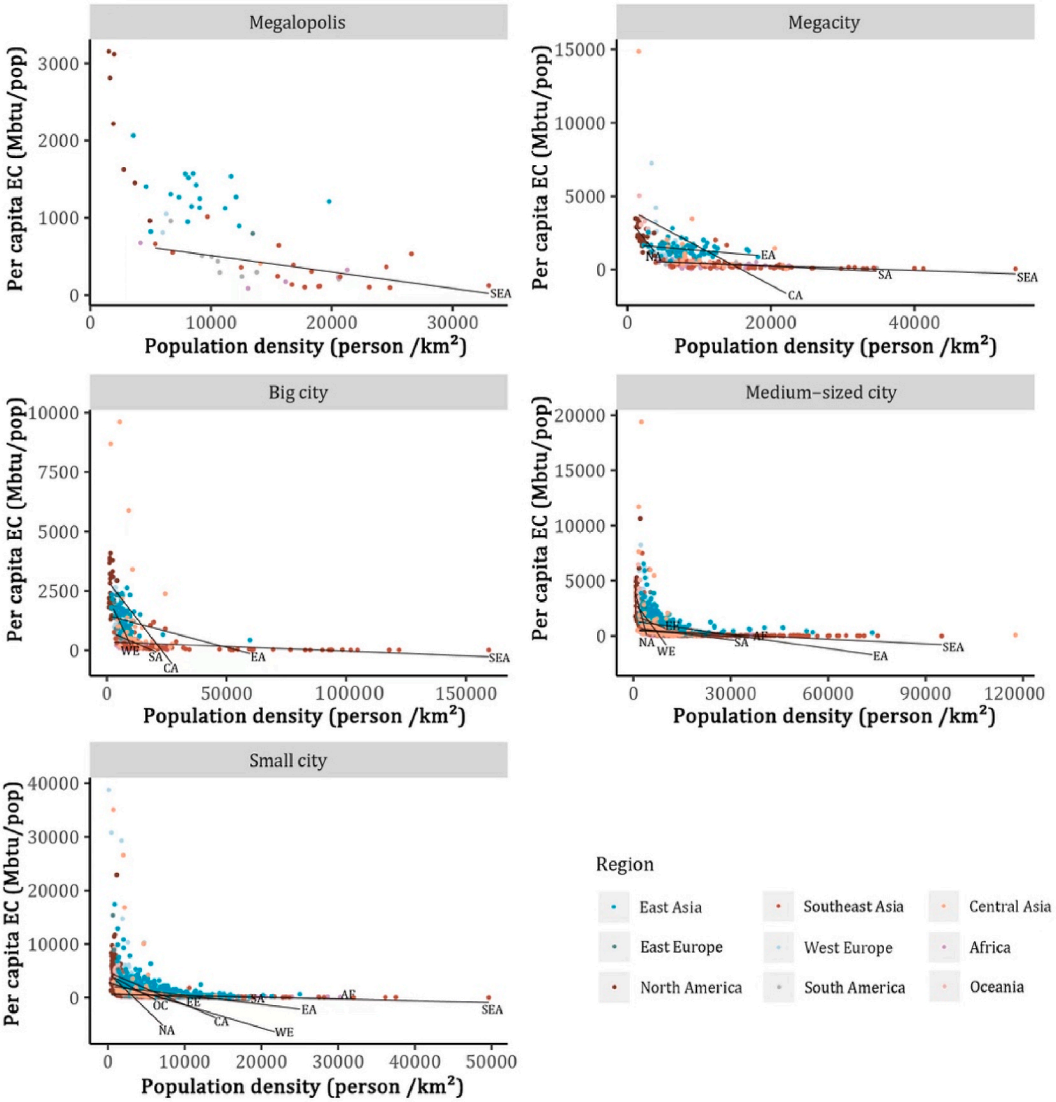


**Fig. 6.** Relationship between per capita energy consumption and population density across urban sizes. Panel 1: Megalopolis, Panel 2: Megacity, Panel 3: Big city, Panel 4: Medium-sized city, Panel 5: Small city.
Note: To ensure the regression accuracy, we only consider the city size when the total number exceed 18. The regression results were kept when P < 0.1.

## 4. Conclusion

As rural populations are still rapidly moving to urban areas, especially in China, India, Viet Nam, the delay of publishing energy statistics prevents the timely assessment of energy consumption. Such an assessment is crucial for investigating urban energy consumption and its association to attain Sustainable Development Goal 11 related to sustainable cities.

This study apply the NPP-VIIRS nighttime light to calculate the real-time energy consumption across global cities based the redefined urban agglomerations for comparability, which also allow replication across diverse geographic areas and evaluating energy consumption for different years. Using fine-grained spatial grid data, the approach unifies the estimation of city-level GDP and population, providing a consistent measurement framework to analyze the impacts of GDP and population on urban energy consumption through regression models and the heterogeneous impact from different regions and city sizes are considered. Additionally, it explores urban development potentialities often overlooked in existing studies.

short-term strategies including increasing public transport, recycling waste, and reducing building electricity usage have been proposed. However, it is likely that these short-term strategies will be overwhelmed by rapid urbanization, especially in cities in Asia and Africa. The findings in this study will support long-term urban construction and development. In terms of identifying efficiency levels: by comparing per capita energy consumption, it becomes possible to identify cities that are less/more energy-efficient than

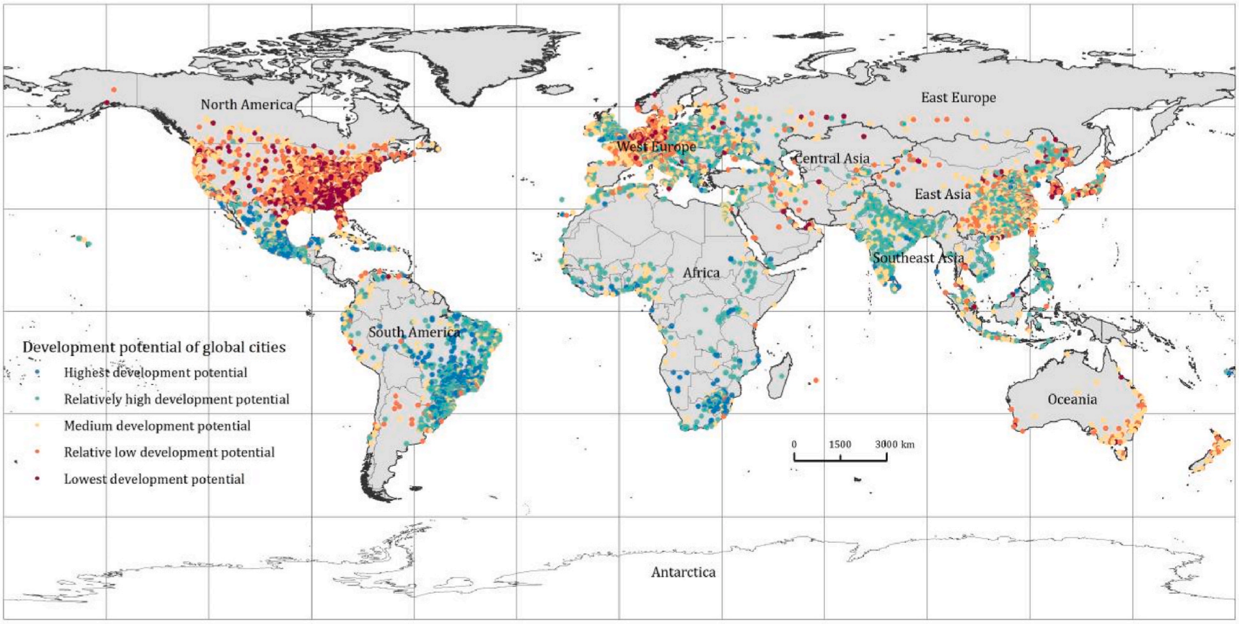


**Fig. 7.** Spatial distribution of the cities with different development potentiality across the world
Note: the image was drawn by ArcGIS 10.5.

others. Cities with worst energy efficiency, such as Szczecin in Poland, Al Wakrah in Qatar, Pusan in South Korea can learn practices and strategies that can be replicated in other cities to promote energy conservation.

In terms of fostering international cooperation: the global level study can set benchmarks and targets for energy efficiency and encourage collaboration and knowledge sharing globally especially across same regions. For instance, the economic growth of cities in the SA is driving rapid energy consumption, therefore there is a need to enhance collaboration among cities within the region to collectively reduce energy consumption. Certain economically prosperous cities in EA have already started to decrease their energy consumption and thus, the energy consumption practices of these successful cities can serve as valuable lessons for other cities in the region to learn from.

In terms of planning and development of larger cities: the study underscores the potential benefits of developing cities into larger sizes in terms of energy efficiency, especially in regions where they have shown significant reductions in per capita energy consumption. For example, megalopolises consumed less energy than megacities in six regions, showing an average decrease of 29.88% (particularly megalopolises in CA demonstrated a significant reduction of 70.17% per capita energy consumption). Additionally, medium-sized cities were generally more energy efficient than small cities in six regions.

In terms of population movement: the study highlights the importance of considering population density and different city sizes in urban planning and policy formulation. For example, In SA and OC, the per capita energy consumption drops significantly as population density rises until reaching 2000 and 800 person/km$^2$, respectively, after which the decline slows down. It will be valuable for designing energy-efficient cities.

In term of regional disparities and contextual factors: The study identifies regional disparities in the relationship between energy consumption, population density and economic development, thus during the political implements more. The reproducibility of this paper is evident through the utilization of open-source data, accompanied by provided links to each dataset. The data is accessible at a grid scale, facilitating research not only on a global scale but also enabling investigations in diverse geographic regions, including countries and regions.

Urbanization contributes to increased energy consumption through factors such as industrialization, electricity usage, and urban transportation construction [4,51]. However, alternative findings suggest that higher population density and urban size can potentially lead to energy savings, as indicated by studies conducted by scholars like Muzayanah et al. [47].

The Environmental Kuznets Curve (EKC) theory proposes an inverted U-shaped relationship between economic growth and environmental degradation, including energy consumption. Initially, as economies develop, energy consumption tends to rise. However, beyond a certain level of economic development, countries may adopt cleaner technologies and transition toward more sustainable paths, resulting in a decline in environmental degradation [52]. This theory implies that focusing on economic growth may indirectly address environmental problems. However, this study suggests that the inverted U-shaped relationship is observed primarily in EA and SA, indicating that other factors such as technological advancements and structural changes may also influence the EKC pattern [53].

Additionally, it suggests that economic growth may not necessarily reduce energy consumption in most parts of the world. Developed cities often exhibit higher levels of consumption and a greater reliance on energy-intensive services and products. However, this study reveals that developing countries also have cities with significant energy consumption, such as Shanghai, Beijing, and Guangzhou. This finding is consistent with previous studies conducted by Yue et al. [31], who assessed energy consumption in regions like the Yangtze River Delta, the Pearl River Delta, and the Beijing-Tianjin-Hebei region.

This study has several limitations. Firstly, as could be seen in the methodology, we inferred the energy consumption for cities based on the nighttime light and regression model/dynamic multiple regression model, but nighttime light can be affected by a variety of policies in cities. Secondly, apart from population and economic development, the driving factors contributing to energy consumption should be further investigated through a more detailed study of cities in the same regions. Thirdly, more comprehensive political suggestions should be considered through a more thorough examination of the relationship between urban size, population density and economic development. Causal effects should be examined in future studies to provide more practical suggestions on improving energy efficiency though urban construction. Finally, the remoting images which were used to delineate the boundaries of urban agglomerations led to the creation of multiple areas within the same city (for example, two sides of a river were sometimes treated as two urban areas). As this study was an exploratory study looking at the use of this approach, this issue was not considered to be a major limitation. However, the findings need to be treated with caution when trying to apply them to the policies of actual municipalities.

We also take into consideration the future prospects for further studies. Firstly, regarding the NPP-VIIRS nighttime light data from 2012 onwards, we will monitor real-time energy consumption in different years so that to track changes in energy usage over time. Secondly, by incorporating the most recent GDP and population density data, in the future, researchers can compare and re-validate the relationship between real-time energy consumption, GDP, and population across different years. Thirdly, our current study examines the relationship between per captia GDP and energy consumption across different regions, in the future, it could categorize cities into various development stages and economic structure to provide a more comprehensive understanding of the relationship between economy and energy consumption. Additionally, it is essential to conduct smaller-scale validations, examining the correlation between city-level energy consumption identified solely through nighttime light data and energy consumption estimated using a range of indicators, including nighttime light.

## 5. Methods

### *5.1. Urban boundary extraction*

This study proposes an top-down approach to estimate city-level energy consumption using remote sensing images and spatial gridded data covering the entire planet. Firstly, we extracted global urban boundaries by overlaying nighttime light with a 500 × 500 $m^2$ spatial resolution from NPP-VIIRS nighttime light data in 2015 and land use with 300 × 300 $m^2$ remote sensing images from Global land use in 2015 at the global level in ArcGIS 10.5.

We defined the urban area as an area with night-time light value over 0 every month in 2015, and geographically continuous urban built-up areas as having at least 5000 population, which was calculated relying on 1 × 1 $km^2$ gridded population from Gridded population of the world in 2015. To remove temporary lights and background noise, we used the eight connected component labeling method to avoid the spillover effects of nighttime light, in particular at water areas and vegetation areas through Python [54] and filtered out pixels with a negative light radiance.

Finally, we redefined a total of 8425 cities and calculated the annual total nighttime light value for each city. As mentioned before, the urban administrative are hard to update or adjust to reflect the human activity boundary or urban physical boundary which change during urban growth, land use change, amalgamation of smaller towns and population movement. This redefined urban boundary was used as a benchmark to make energy consumption comparable. The data involved in study are list in Table 1.

### *5.2. Extract total urban energy consumption in countries*

Then we extracted the national urban energy consumption in each country from International energy statistics in 2015 collected by U.S. Energy Information Administration according to the proportion of urban annual nighttime light (calculated based on the defined urban boundary) out of the total annual nighttime light (calculated based on the country boundary from Global administrative areas in 2018).

### *5.3. Multiple regression model*

We applied a multiple regression model which can improve the accurate of simple linear regression, quadratic regression or power regression for exploring the association between urban energy consumption and nighttime light, especially for countries lying at two polarities of energy consumption (countries characterized by either extreme high or extreme low energy consumption) in R4.2.0. Initailly, we conducted a linear regression using equation (1):

$$EC_i = a \times \sum_{j=1}^{n} NTL_{ij} + b \tag{1}$$

where $EC_i$ is the urban energy consumption of country $i$; $a$ is the regression coefficient; and $NTL_{ij}$ represents the light radiance value of city $j$ in country $i$. The parameter $a$ is a non-negative value, and b is a constant. Considering radiance values of the nighttime light is less than 10 nW/cm2/sr in several less developed cities, the b was set as 0. Then, we applied equation (2):

$$\delta = \frac{EC_m - EC_s}{EC_s} \times 100\% \tag{2}$$

where $EC_m$ represents the estimated urban energy consumption of country $m$; and $EC_s$ is the urban energy consumption of country $s$ from the international energy statistics. We identified countries with a relatively low regression error, specifically defined as $|\delta|<20\%$. For these countries, we retained their regression coefficients. Next, we proceeded to construct a new sample for regression analysis using the remaining countries that did not meet the low regression error criterion. This new sample was generated based on equation (1). We iterated through these first two steps until more than 90% of the countries (207 countries in total) fulfilled the minimum error requirement ($|\delta|<20\%$). For the remaining 10% of countries that did not meet the minimum error criterion, we employed the regression coefficient obtained from the last regression iteration.

### 5.4. City-level energy consumption identification

Based on the derived regression coefficients for various countries, we utilized equation (3) to estimate the energy consumption of cities within each country:

$$EC_j = a \times NTL_j \tag{3}$$

where $EC_j$ is the estimated energy consumption of city $j$; and $NTL_j$ represents the light radiance value of city $j$.

### 5.5. Relationship between energy consumption and GDP and population

We investigate the relationship between per capita energy consumption, per capita GDP (collected from Gridded global datasets for gross domestic product in 2015), and population density (obtained from Gridded population of the world in 2015) in 8425 cities across nine regions in R4.2.0. This exploration is carried out using generalized additive models, a flexible statistical modeling technique capable of capturing nonlinear relationships. Additionally, we analyze the relationship across different city sizes using regression models. Supplementary information provides detailed descriptive statistics.

In term of the robustness test, this study performs a robustness test by substituting the explanatory variables. In the initial regression, per capita GDP serves as a proxy for economic development, while population density acts as a proxy for urbanization. In the robustness test, per capita nighttime light is employed as a proxy for economic development, and road network density (we calcuated the density in ArcGIS 10.5 according to the data of International urban road network in 2015) serves as a proxy for urbanization level. After changing the explanatory variables, most of the regression results maintain the same trends and retain statistical significance at the 1% level. The outcomes fulfill the criteria for passing the robustness test, affirming the validity of the study's conclusions.

## Data availability statement

Global national energy data were derived from International Energy Statistics 2015 published by the U.S. Energy Information Administration (https://www.eia.gov/index.php). Urban road network data were obtained from Openstreetmap (https://download.geofabrik.de/). NPP-VIIRS nighttime lighting data in 2015 were obtained from Earth Obsercation Group (https://eogdata.mines.edu/products/vnl/). Global land use data in 2015 were derived from European Space Agency (ESA) Climate Change Initiative (CCI) project outcomes (http://maps.elie.ucl.ac.be/CCI/viewer/index.php). Population of the world data in 2015 were derived from the Socio-economic Data and Applications Center (SEADAC) (http://sedac.ciesin.columbia.edu/data/collection/gpw-v4/sets/browse). Grided global datasets for gross domestic product in 2015 come from the research results of Kummu et al. (https://www.nature.com/articles/sdata20184) [55].

## CRediT authorship contribution statement

**Shuang Ma:** Writing – review & editing, Writing – original draft, Data curation. **Shuangjin Li:** Software, Methodology, Investigation. **Qing Luo:** Resources, Formal analysis. **Zhao Yu:** Validation, Software. **Yifei Wang:** Visualization, Software, Data curation.

## Declaration of competing interest

We stated that there are no conflicts to declare.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e27318.

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