Global Identification of Unelectrified Built-Up Areas by Remote Sensing

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Abstract: Access to electricity (the proportion of the population with access to electricity) is a key indicator for the United Nations’ Sustainable Development Goal 7 (SDG7), which aims to provide affordable, reliable, sustainable, and modern energy services for all. Accurate and timely global data on access to electricity in all countries is important for the achievement of SDG7. Current survey-based access to electricity datasets suffer from short time spans, slow updates, high acquisition costs, and a lack of location data. Accordingly, a new method for identifying the electrification status of built-up areas based on remote sensing of nighttime light is proposed in this study. More specifically, the method overlays global built-up area data with nighttime light remote sensing data to determine whether built-up areas are electrified based on a threshold nighttime light value. By using our approach, electrified and unelectrified built-up areas were extracted at 500 m resolution on a global scale for the years 2014 and 2020. The acquired results show a significant reduction in unelectrified built-up area between 2014 and 2020, from 51,301.14 km² to 22,192.52 km², or from 3.05% to 1.32% of the total built-up area. Compared to 2014, 117 countries or territories had improved access to electricity, and 18 increased their proportion of unelectrified built-up area by >0.1%. The identification accuracy was evaluated by using a random sample of 10,106 points. The accuracies in 2014 and 2020 were 97.29% and 98.9%, respectively, with an average of 98.1%. The outcomes of this method are in high agreement with the spatial distribution of access to electricity data reported by the World Bank. This study is the first to investigate the global electrification of built-up areas by using remote sensing. It makes an important supplement to global data on access to electricity, which can aid in the achievement of SDG7.

Keywords: SDG7; access to electricity; unelectrified built-up areas; night-lights imagery

1. Introduction

On 25 September 2015 at the Sustainable Development Summit, 17 Sustainable Development Goals (SDGs) were officially adopted by the 193 member states of the United Nations [1]. The United Nations SDGs aim for sustainable development by thoroughly addressing the three dimensions of global development—social, economic, and environmental—in an integrated manner between 2015 and 2030 [2]. Ensuring access to affordable, reliable, sustainable, and modern energy services for all by 2030 is a key element of the United Nations Sustainable Development Goal 7 (SDG7) [3]. Access to electricity refers to the proportion of the population with access to electricity. It is one of six indicators used by the United Nations to measure SDG7 in each country [3]. More than 700 million people lacked access to electricity in 2019, and many developing countries have low rates of access [4,5]. Accurate and timely access to national data on access to electricity is also considered to be of great importance in guiding global efforts to achieve SDG7.
The current data on global data on access to electricity are mainly derived from surveys conducted by large institutions such as the International Energy Agency (IEA) and World Bank (WB). As far as the IEA is concerned, it focuses on global electricity access in its annual *World Energy Outlook* report. The *World Energy Outlook 2019* focuses on Africa and estimates that 600 million people in sub-Saharan Africa do not have access to electricity services [5]. On the other hand, the *World Energy Outlook 2020* focuses on changes in electricity access in the context of the COVID-19 pandemic. It estimates that about 770 million people have no access to electricity, and that the pandemic will increase this number for the first time since 2013 [6]; however, the report does not provide country-specific data on access to electricity. The report *Tracking SDG7: The Energy Progress Report 2021* was jointly produced by the WB, IEA, International Renewable Energy Agency, United Nations, and World Health Organization. It provides national-level data on access to electricity for the 2000–2019 period, and analyzes the access situation in countries around the world, noting that sub-Saharan Africa remains the region with the largest access gap in the world [3]. The data on access to electricity used in this report was obtained from the WB, which provides comprehensive and timely data on global access to electricity at the country level from 1990 to 2019 [4].

However, there are some problems with these data: most national access to electricity data are collected through surveys, which are subject to human error due to differences in survey capacity between countries. Survey methods are time-consuming and costly. Historical surveys are unavailable for some countries, many of which have been updated since 2000, with Albania being the latest country to start updating in 2012; data on access to electricity are slow to be updated and are currently only up to 2019, making it difficult to reflect the level of electrification in individual countries in a timely manner. In addition, data on access to electricity are mostly available from the governmental websites of each country. For example, data for Cambodia are published on the official website of the Electricity Authority of Cambodia, including access-rate data for 2006–2020. Such official data can be updated more quickly than World Bank data. However, not all developing countries are able to set up their own statistics departments. For example, the survey of the National Institute of Statistics was obtained with the financial assistance of the United Nations Development Programme. In addition, numerous countries do not have the capacity to obtain data on access to electricity using a statistics department, and these countries are often those with lower levels of access to electricity. The indicator of access to electricity itself has some problems, as it describes the number of the population with non-access to electricity in a country, but not their geographical distribution. On top of that, spatialized electricity data are more informative to governmental and/or corporate investment decision-making.

In recent years, the use of remote sensing to monitor the SDG process has become a focus of research. For three consecutive years, the Chinese Academy of Sciences has published the report *Big Data for Sustainable Development Goals* [7], which is an important summary of research on SDG spatial information monitoring technologies. The development and use of night-light remote sensing began in the 1970s with the Defence Meteorological Satellite Program’s (DMSP) Operational Linescan System (OLS) [8]. The system was originally designed for weather forecasting, but other research was prompted by the discovery that this system can also clearly capture the luminescence associated with human activity on the Earth’s surface [9], unlike traditional remote sensing imagery, which is commonly used for land feature classification [10–12]. Night-time light data are now widely used for the estimation of gross national product [13], population [14], electricity consumption [15], poverty [16,17], carbon emissions [18], mapping of urbanization processes [19], monitoring disasters [20], monitoring armed conflicts [21], examining ecological light pollution [22], mapping fires [23], monitoring fisheries [24], monitoring outages [25], and grid reliability [26].

Numerous studies have shown that the degree of electrification can influence the brightness of nighttime lights. By using DMSP-OLS night-lights imagery and ground
survey data on electricity usage in Malian villages, Min et al. found that electrified villages tend to be brighter than unelectrified villages, thus demonstrating the feasibility of utilizing night-lights imagery to detect global electricity penetration [27]. A subsequent study of a similar nature was conducted in Vietnam by Min and Gaba. The authors observed that electrified rural villages with no public streetlights could still be detected by DMSP-OLS night-lights imagery. They also found that monthly and annual image composites indicate a one-point increase in brightness (on the DMSP-OLS’s 63-point brightness scale) for every 240–270 electrified homes [28]. By using DMSP-OLS night-lights imagery from 2011, Dugoua et al. investigated the correlation between night-light values and the number of electrified households in villages, finding a relatively high linear correlation between the two [29]. By using DMSP-OLS night-lights imagery, Ramdani et al. manually defined electrification levels corresponding to different luminance intervals to assess the progress of electrification in Indonesia [30]. Andrade-Pacheco et al. employed DMSP-OLS night-lights imagery and land cover data with a model-based geostatistical approach to produce maps of electricity access between 2000 and 2013 at a 5 km resolution [31]. Falchetta et al. used the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) night-lights imagery, with a threshold value used, to determine lit and unlit areas in sub-Saharan Africa (SSA). The threshold was determined from the examination of by-definition zero-radiance pixels—such as within large water bodies and forests—this resulted in a 1 km-resolution electricity access dataset covering SSA [32]. The threshold was set only for the distribution of luminous values in non-electrified built-up areas, without removing areas with high luminosity (such as water bodies) and without considering the distribution of luminous values in electrified built-up areas. Principe et al. used VIIRS-DNB night-lights imagery with a threshold of 5 nW cm$^{-2}$ sr$^{-1}$, below which, pixels were considered unlit, to identify electrified areas in the Asia-Pacific region [33]. However, the threshold for this study was set too high, with numerous electrified regions having pixels with luminosity < 5 nW cm$^{-2}$ sr$^{-1}$, resulting in numerous electrified regions not being identified. The previous research proves the feasibility of using night-lights imagery to identify electrified areas. Previous studies have also demonstrated that areas with a higher number of electrified households will have higher night-light values, with a threshold being the most common way to identify electrified areas. However, there are some problems with previous research: (1) Previous studies have often selected a small number of regions for study, and there is a lack of research on the global scale. (2) Previous studies have produced electrification datasets with low resolution, being ≥1000 m. (3) Previous studies have only used night-light data, and few have combined built-up area data. Night-light imagery can only identify electrified built-up areas, and not unelectrified ones. However, to achieve SDG7, the identification of unelectrified areas is even more important. (4) Thresholds from previous studies are only set in consideration of the distribution of night-lights in non-electrified areas, and not in electrified areas.

In response to the above problems, this work proposes a new method for remote sensing identification of unelectrified built-up areas. The method extracts electrified and unelectrified areas by overlaying night-light image data and global built-up land data using a threshold method. The method was used to produce global maps of unelectrified built-up areas at 500 m resolution for 2014 and 2020. The method provides accurate, timely, and cost-effective data on global electrified and unelectrified built-up areas, thus providing an important complement to traditional data on access to electricity. At the same time, the electrification process can be visualized in geospatial terms, helping local, national, and international institutions to identify priority areas of concern, and contribute to the global achievement of SDG7.
2. Materials and Methods

2.1. Materials

2.1.1. European Commission’s Built-Up Area Data

The Global Human Settlement Layer (GHSL) is a large-scale habitat mapping project undertaken by the European Commission’s (EC) Joint Research Centre (JRC). The project uses Landsat remote sensing imagery to derive global built-up area mapping products with detailed data on global building and population growth over the last 40 years (1975–2015). The GHSL is an open, free, and downloadable dataset that contains multiple products, and features open inputs, open methods, and open outputs. The present study used the second version of the Global Human Settlement (GHS) built-up area grid (GHS-BUILT) dataset [34], which improved the dataset generation method, reduced omission and commission errors, and improved spatial coverage [34]. The dataset describes human settlements over 40 years (1975, 1990, 2000, and 2014), with each year including products at 30 m, 250 m, and 1000 m resolutions. The concept of built-up area is defined in GHS-BUILT as: buildings are enclosed constructions above ground, which are intended or used for the shelter of humans, animals, things, or for the production of economic goods, and refer to any structure constructed or erected on a site [35]. The GHS-BUILT dataset utilizes the core methodology of Symbolic Machine Learning (SML) for data extraction [36], capturing detailed information not only on large cities, but also on smaller settlements (e.g., towns and villages). This study uses version 2 of the 250 m-resolution built-up area remote sensing mapping product from 2014 from the GHS-BUILT dataset. The 250 m GHS-BUILT data are aggregated from 30 m GHS-BUILT data, and each raster value (0–100) of the data product at this resolution represents the percentage of the built-up area within that 250 m raster.

2.1.2. NPP/VIIRS Night-Light Image Data

The current mainstream night-light images are provided by NPP/VIIRS and DMSP/OLS, with the DMSP/OLS data having a spatial resolution of 1000 m, and the images covering the period 1992–2013. The digital number (DN) range of the night-light images acquired by its OLS sensor is only 0–63, which leads to problems with oversaturation in areas of high light intensity. In addition, DMSP data are taken by satellites of different ages, and there are some differences that require continuity correction. NPP/VIIRS, the second generation of night-light imagery, offers significant improvements in data quality while inheriting the characteristics of DMSP data. The NPP/VIIRS data do not suffer from oversaturation, have a spatial resolution of 500 m, and imagery covers the period from 2012 to the present. There have been many studies on how to handle these two types of night-light images to make them more suitable for use [37–39]. Compared to DMSP/OLS data, NPP/VIIRS data are better in all aspects of application [40].

There are two versions of NPP/VIIRS annual night-light imagery data, both of which have been radiometrically corrected. Version 1 (V1) of the annual night-light imagery data only contains the years 2015 and 2016 [41]. This study uses version 2 (V2) of the annual night-light imagery data, which contains the 2012–2020 time series, and was obtained by improving the synthesis method of version 1 [42]. Version 2 of the annual night-light imagery data uses filtering to remove extraneous features such as biomass burning, auroras, and backgrounds. The V2 product can detect more areas of dim lighting. The key advantages of the V2 time series include consistent processing and threshold levels across all years, thus optimizing the set for change detection analyses [42]. The release of this version of annual night-light images makes it easier for researchers to use the images without extensive data pre-processing. The V2 night-light images from 2014 and 2020 were used in the present study. Although the brightness of the lights in an area will change at different times of the night, the satellite only takes one night-light image per night. The V2 version of the annual light image is combined with the daily night-light images of the year, with each raster value in the image representing the annual average.
2.2. Methods

To identify electrified and unelectrified areas, a new method of remote sensing identifying unelectrified built-up areas is proposed in this work. The input data for this method are the v2 global NPP/VIIRS annual night-light images for 2014 and 2020, the EC’s global built-up area data, and the World Bank’s access to electricity data. By using the annual night-light images and the global built-up area data, the night-light values for the global built-up area in 2014 and 2020 can be obtained, and the night-light values can then be used to determine whether or not the electricity is on. Firstly, a sample database was constructed by randomly selecting the night-light values of non-built-up areas as samples of unelectrified areas using the European Commission’s built-up area data. We randomly selected the night-light values of built-up areas from countries with 100% access to electricity as samples of electrified areas, and all samples were visually verified by high-resolution remote sensing images. Two-thirds of the samples were selected from the sample pool, and the accuracy of distinguishing between electrified and unelectrified area samples under different thresholds was calculated. The threshold with the highest average accuracy was taken as the identification threshold. This threshold was then used to identify the 2014 and 2020 unelectrified built-up areas and calculate the percentage of unelectrified built-up areas in each country globally. The accuracy of the identification results was verified by using the remaining one-third of the sample pool, and the spatial coupling of the percentage of unelectrified built-up area with IEA’s non-access to electricity (the proportion of the population with non-access to electricity) was examined using Geographical Detector (i.e., Geodetector [http://www.geodetector.cn/, 201 Spatial Analysis Group, IGSNRR, CAS, Beijing, China], is a statistical tool to measure Spatial Stratified Heterogeneity). Figure 1 provides a detailed technical flowchart of the process.

2.2.1. Data Preprocessing

We downloaded V2 of the EU 250 m built-up area dataset, and reprojected it to the GCS_WGS_1984 coordinate system, thus aligning it with the geographic coordinate system of the NPP/VIIRS night-light images. We converted the EC’s built-up area data from 250 m to 500 m resolution by using an aggregate algorithm to match the resolution of the NPP/VIIRS night-light images. Finally, based on the aggregated image raster values, areas with built-up areas ≥ 25% of each raster were extracted. Areas ≥ 25% were chosen because the larger the electrified built-up area in each night-light image raster, the brighter that area will be, and the greater the difference in brightness between it and non-electrified built-up areas will be. When areas ≥ 25% are selected for identification, the identification accuracy can be significantly improved. Therefore, areas, where the built-up area accounted for ≥25% of the 500 m night-light raster were selected for study. The 2014 and 2020 night-light images were downloaded, and the EC’s built-up areas were used to mask the NPP/VIIRS annual night-light data to obtain night-light images of built-up and non-built-up areas. Transient lights, such as lights on fishing boats and headlights on cars in motion, were present in the non-built-up areas of night-light images; these were considered noise, and had been mostly removed by the Earth Observation Group (EOG) [41,42]. The masking operation determined the spatial distribution of the built-up area, thus excluding residual noise in the subsequent determination of whether the built-up area was electrified or not, and making the identification results more accurate.
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Figure 1. Technical flowchart of the method of non-electrified area identification.

### 2.2.2. Sample Pool Construction

A raster overlay of the EC built-up area data and NPP/VIIRS data was used to obtain night-light values for built-up and non-built-up areas. As non-built-up areas do not have lights, their night-light values should be the same as those of unelectrified built-up areas. Selecting samples from unelectrified areas in non-built-up areas can greatly reduce the difficulty of selecting samples from unelectrified areas, so the night-light values of non-built-up areas were randomly selected as samples from unelectrified areas. Based on the WB's global access to electricity data, the night-light values of built-up areas were randomly selected from countries with 100% electricity access to form a sample of electrified areas. To more accurately select a threshold to distinguish electrified and unelectrified areas, the sample points for built-up areas were selected mainly from rural areas in these countries. Due to the dispersive nature of light, the light emitted from built-up areas brightens not only built-up areas, but also nearby non-built-up areas. To avoid this, we used EC built-up-area data to create 500 m buffer zones around built-up areas that were excluded from unelectrified areas.

To avoid sample selection errors caused by errors in EC built-up-area data, the correctness of the selection of all sample points was manually compared by using high-resolution imagery. From this, 3789 points with errors were removed, resulting in a total of 30,317 sample points. These points of error fell into three main categories: (a) night-light points...
located within electrified built-up areas that had no surrounding built-up area according to comparison with high-resolution remote sensing imagery; (b) night-light points located in non-electrified areas that had a built-up area around the point according to comparison with high-resolution remote sensing imagery; and (c) night-light spots located in non-electrified areas located in water bodies and perennial snow areas by comparison with high-resolution remote sensing imagery. The high reflectance of visible light from water bodies and snow can result in high night-light values in these areas, making it difficult to distinguish them from electrified built-up areas. So, night-light spots in these areas were excluded.

2.2.3. Threshold Selection and Identification of Electrified and Unelectrified Built-Up Areas

Two-thirds of the points in the sample pool were randomly selected, and the histograms of the electrified and non-electrified samples were analyzed. Consequently, the night-light values that distinguished between electrified and non-electrified samples with the highest average accuracy were selected as the thresholds for both 2014 and 2020. The thresholds for each year were used to classify whether the global built-up area was electrified in 2014 and 2020. Greater than or equal to this threshold is considered an electrified built-up area, and less than this threshold is considered an unelectrified built-up area. It is interesting to notice that a relatively big built-up area of a country could lead to misjudgments in terms of being electrified or not. This effect could make the judgement of the country’s electrification status based on unelectrified built-up areas more one-sided. To address this situation, the concept of access to electricity was followed, and the proportion of unelectrified built-up area for each country was calculated as an indicator of its overall access to electricity:

\[ R_{NB} = \frac{A_{NB}}{A_B} \]  

where \( R_{NB} \) indicates the unelectrified-to-electrified built-up area ratio in the country, \( A_{NB} \) indicates the unelectrified built-up area, and \( A_B \) indicates the total built-up area in the country.

2.2.4. Accuracy Verification

The accuracy of the results was calculated in two ways. The first was to evaluate the accuracy of the identification results for known electrified built-up areas using one-third of the random sample points in the sample pool. As there was no known spatial distribution of unelectrified building stock, the first evaluation method was only used for known electrified built-up areas, and was calculated as follows:

\[ A = \frac{P_F}{10106} \times 100\% \]  

where \( A \) denotes identification accuracy, and \( P_F \) denotes the points in the sample pool that were misidentified.

The concept of non-access to electricity focuses on the number of people without access to electricity, whereas the percentage of unelectrified built-up area focuses on the area of unelectrified buildings. Although the two concepts are expressed differently, they are related. Data on the percentage of unelectrified built-up area in each country should be spatially coupled with WB data on non-access to electricity, i.e., a relatively bigger rate of non-access to electricity in a country leads to a higher percentage of unelectrified built-up area. When access to electricity is 0, the percentage of the electrified built-up area should also be 0.

In this work, Geodetector (a statistical model for spatial analysis) was used to investigate whether the percentage of unelectrified built-up areas was coupled with the non-access to electricity dataset, to further evaluate the accuracy of the extraction results. Geodetector is a set of statistical methods that detect spatially stratified heterogeneity, and reveal its drivers [43]. Geodetector can indicate whether the spatial distribution of two variables is coupled by measuring the extent to which the independent variable explains the dependent variable. Its main areas of application include land use [44], meteorology [45], ecology [46],
environmental science [47], and many other fields. The core idea is based on an assumption that if an independent variable has a significant impact on a dependent variable, then the spatial distribution of the independent and dependent variables should be similar [48,49]. In this work, the data on non-access to electricity was considered the independent variable, and unelectrified built-up area percentage was the dependent variable. The degree of coupling between the two was judged by using Geodetector to obtain the explanatory power $q$ of the independent variable on the dependent variable. A big degree of coupling in the spatial distribution of the two variables increases the value of $q$, which ranges between 0 and 1. The $q$-values, thus, indicate whether the results of this study are reasonable.

3. Results

3.1. Threshold of Determination of whether Built-Up Areas Are Electrified

A total of 20,211 night-light points were randomly selected from known electrified built-up and unelectrified areas around the world to obtain a threshold of determination, of which, 1369 were from built-up areas, and 18,842 were from unelectrified areas. These points were manually confirmed by high-resolution remote sensing imagery to ensure that all points met the needs of this work. A statistical analysis of the night-light values at these points revealed significant differences between electrified built-up areas and unelectrified areas. Table 1 shows the identification accuracy by using different thresholds. Table 1 shows that for the years 2014 and 2020, the average identification accuracy was highest using light thresholds $\geq 0.35 \text{nW/cm}^2/\text{sr}$ and $0.48 \text{nW/cm}^2/\text{sr}$, respectively. Moreover, the accuracy with which 20,211 points could be classified using different thresholds is also shown in Table 1. It was reasonable that the 2020 threshold would be higher than the 2014 one owing to calibration adjustments in lunar correction, and the launch of a new VIIRS-equipped satellite (JPSS J1) in 2017.

Table 1. Identification accuracy of 20,211 night-light points using different identification thresholds.

| Year | Identification Threshold (nW/cm$^2$/sr) | Number of Identification Errors in Built-Up Areas | Number of Identification Errors in Unelectrified Areas | Built-Up Area Identification Accuracy | Unelectrified Area Identification Accuracy |
|------|----------------------------------------|-----------------------------------------------|-------------------------------------------------|-------------------------------------|---------------------------------------------|
| 2014 | 0.30                                   | 46                                            | 1672                                            | 96.64%                             | 91.13%                                      |
|      | 0.35                                   | 68                                            | 939                                             | 95.03%                             | 95.02%                                      |
|      | 0.40                                   | 93                                            | 724                                             | 93.21%                             | 96.16%                                      |
|      | 0.43                                   | 38                                            | 1024                                            | 97.22%                             | 94.57%                                      |
| 2020 | 0.48                                   | 50                                            | 685                                             | 96.35%                             | 96.36%                                      |
|      | 0.52                                   | 65                                            | 525                                             | 95.25%                             | 97.21%                                      |

Figure 2 shows a histogram of night-light values in 2014 for electrified built-up areas and unelectrified areas. As can be seen from both Table 1 and Figure 2, a proportion of the sample could not be accurately classified using the thresholds. There were two main types of misidentification errors: (A) where night-light values in electrified built-up areas were less than the threshold, and (B) where night-light values in unelectrified areas were greater than the identification threshold. The analysis reveals that the night-light points that produced category A errors were mainly located in rural areas. These areas have small built-up areas, often without street lighting, and where residents may turn off their home lights at night, making their night-light values difficult to distinguish from those in unelectrified areas. Most of the night-light points that produced category B errors were located close to built-up areas, and were susceptible to transient light from travel, resulting in high night-light values that were difficult to distinguish from those of built-up areas.
These results were disaggregated by using country boundary data to obtain the unelectrified years of war. The city does not have a municipal grid to supply electricity to the population, that produced category A errors were mainly located in rural areas. These areas have greater than the identification threshold. The analysis reveals that the night-light points of misidentification errors: (A) where night-light values in electrified built-up areas were small built-up areas, often without street lighting, and where residents may turn off their sample could not be accurately classified using the thresholds. There were two main types areas.

3.2. Global Identification of Unelectrified Built-Up Areas

Built-up areas at the global scale were judged as electrified or not in 2014 and 2020 based on lighting thresholds of 0.35 nW/cm²/sr and 0.48 nW/cm²/sr, respectively. The results show that in 2014, there was 1,680,268.85 km² of built-up area globally, of which, 51,301.14 km² was unelectrified (3.05% of the global built-up area). There was 22,192.52 km² of built-up area without access to electricity in 2020 (1.32% of the global built-up area). These results were disaggregated by using country boundary data to obtain the unelectrified built-up areas of each country (Appendix A, Table A1).

Figure 3 shows the electricity access in Wau, the third-largest city in South Sudan. Wau has a population of approximately 140,000 and is relatively underdeveloped as a result of years of war. The city does not have a municipal grid to supply electricity to the population, and its sources of electricity are mainly diesel generators, with most households having no electricity supply. This study successfully identified numerous built-up areas in Wau that were not electrified, and mapped out their specific locations. Figure 3 depicts the electrification of the built-up area in the Wau region, with its unelectrified built-up area reducing from 12.70 km² in 2014 to 10.80 km² in 2020. The successful identification of small cities, such as Wau, for electricity access demonstrates the effectiveness of this method at the city level. Due to the lack of rural-specific surveys on access to electricity, this study uses World Bank data on access to electricity for each country to provide a brief analysis of identification at the national level. This analysis is based on the assumption that: if a country’s access to electricity data is 100%, and the proportion of unelectrified built-up areas is also close to 0, then the method is accurate for that country, i.e., the method is accurate for both the urban and rural levels of the country. The results show that a total of 82 countries had 100% access to electricity in 2014, with 30 countries also having a value of 0 for the percentage of unelectrified built-up areas, and 41 countries having a value of less than 1% for the percentage of unelectrified built-up areas. This effect indicates that the method has high identification accuracy in both rural and urban areas in 71 countries around the world, which leads us to believe that the method can also be applied effectively on a global scale.

![Figure 2. Histogram of night-light values in non-electrified areas (a) and electrified built-up areas (b) in 2014.](image_url)
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Figure 3 shows the electricity access in Wau, the third-largest city in South Sudan. Wau has a population of approximately 140,000 and is relatively underdeveloped as a result of years of war. The city does not have a municipal grid to supply electricity to the population, and its sources of electricity are mainly diesel generators, with most households having no electricity supply. This study successfully identified numerous built-up areas in Wau that were not electrified, and mapped out their specific locations. Figure 3 depicts the electrification of the built-up area in the Wau region, with its unelectrified built-up area reducing from 12.70 km² in 2014 to 10.80 km² in 2020. The successful identification of small cities, such as Wau, for electricity access demonstrates the effectiveness of this method at the city level. Due to the lack of rural-specific surveys on access to electricity, this study uses World Bank data on access to electricity for each country to provide a brief analysis of identification at the national level. This analysis is based on the assumption that: if a country’s access to electricity data is 100%, and the proportion of unelectrified built-up areas is also close to 0, then the method is accurate for that country, i.e., the method is accurate for both the urban and rural levels of the country. The results show that a total of 82 countries had 100% access to electricity in 2014, with 30 countries also having a value of 0 for the percentage of unelectrified built-up areas, and 41 countries having a value of less than 1% for the percentage of unelectrified built-up areas. This effect indicates that the method has high identification accuracy in both rural and urban areas in 71 countries around the world, which leads us to believe that the method can also be applied effectively on a global scale.

3.3. Percentage of Unelectrified Built-Up Areas

To understand each country’s overall access to electricity, the percentage of unelectrified built-up area in each country was calculated based on the concept of access to electricity. Detailed global data for 2014 and 2020 are shown in Table A1. Figure 4 displays the percentage of the unelectrified built-up area by country in 2014. Figure 4 and Table A1 show that the countries with the largest percentages of the unelectrified built-up area were mainly in sub-Saharan Africa, Central Asia, and South East Asia, which happen to be the three regions with the lowest access to electricity according to the World Bank.

Figure 4. Distribution of the percentage of unelectrified built-up areas by country, 2014.
3.4. Accuracy Verification

3.4.1. Random Sample Accuracy Validation

A total of 10,106 sample points from one-third of the sample pool were used to test the accuracy of classifying known electrified built-up areas. In 2014, 274 sample points out of 10,106 were incorrectly classified as unelectrified areas, with a final identification accuracy of 97.29%. In 2020, 111 out of 10,106 sample points were incorrectly classified, with a final identification accuracy of 98.9%. Furthermore, a total of 385 sample points were misclassified in 2014 and 2020, yielding an overall identification accuracy of 98.1%. These results indicate a high identification accuracy by using the threshold method. The spatial distribution of the validation sample points is also shown in Figure 5.

![Figure 5. Distribution of validation sample points.](image)

3.4.2. Spatial Coupling between the Percentage of Unelectrified Built-Up Area and Non-Access to Electricity Data

Figure 6 represents the non-access to electricity data for 2014. Non-access to electricity data was considered the independent variable, and the percentage of unelectrified built-up area was the dependent variable. The degree of coupling was judged using a Geodetector probe. The acquired results reveal that non-access to electricity data explained 55.2% of the spatial distribution of unelectrified built-up areas, which indicates that their spatial distributions are related. This effect also indicates that the results of this work are reasonable for determining unelectrified built-up areas, and can describe the electrification of these countries.
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4. Discussion

4.1. Comparative Analysis of Results in Two Years

Global electrification rates improved between 2014 and 2020. The global unelectrified built-up area decreased from 51,301.14 km$^2$ to 22,192.52 km$^2$ (from 3.05% to 1.32% of the total built-up area). At the national level, 117 countries or territories exhibited decreases in the share of the unelectrified areas between 2014 and 2020, 67 had no change (these are areas with no unelectrified built-up area), and 32 had increases in an unelectrified built-up area, although only 18 of these had increases >0.1%. The detailed data are shown in Table A1, whereas the changes in unelectrified built-up area percentages in each country between 2014 and 2020 are shown in Figure 7. The countries that were improved, in terms of electrification in 2020, were mainly in sub-Saharan Africa, Central Asia, and South East Asia—the three regions with the worst access to electricity. Electrification in the sub-Saharan Africa region increased overall, but there was a decrease in Ethiopia, and slight decreases in Namibia, the Democratic Republic of the Congo, Cameroon, and Libya. In addition to Ethiopia, there were decreases in electrification in Haiti, Yemen, Belarus, Ukraine, and Moldova, with an increase of >1% in unelectrified built-up areas.

An analysis of six countries with decreasing electrification revealed that they were facing volatile situations, such as political instability, armed conflict, and economic regression. On the one hand, volatile situations caused people to turn off their lights at night, which may increase the built-up area classified as unelectrified; on the other hand, they may cause regional power cuts that reduce night-light values.

4.2. Error Analysis

This section compares the percentage of unelectrified built-up areas and non-access to electricity data in each country. Countries with a non-access to electricity = 0 should have an unelectrified built-up area = 0. If not, errors may exist, and countries with significantly larger errors in the results have been analyzed accordingly. The World Bank’s data on access to electricity are only updated to 2019, so this section provides error analysis for these countries for 2014. In 2014, 82 countries had a non-access to electricity = 0, of which, 30 countries also had 0% built-up areas that were not electrified. A further 41 countries had <1% built-up areas that were not electrified. Only four countries had unelectrified built-up areas > 2.71% (theoretical error, 100%-identification accuracy): China (10.54%), Moldova (7.28%), the Maldives (6.17%), and Belarus (2.80%).

Figure 6. Spatial distribution of non-access to electricity data by country, 2014.
Analysis of the unelectrified built-up areas of France reveals that they are mainly small.

The population outflow from Henan, Anhui, and Shandong Provinces is the serious rural

volatility that causes people to turn off their lights at night, which may increase

situations, such as political instability, armed conflict, and economic regression. On the one

of six countries with decreasing electrification revealed that they were facing volatile sit-

Ukraine, and Moldova, with an increase of >1% in unelectrified built-up areas. An analysis

addition to Ethiopia, there were decreases in electrification in Haiti, Yemen, Belarus,

Namibia, the Democratic Republic of the Congo, Cameroon, and Libya. In

haran Africa region increased overall, but there was a decrea-

Asia—the three regions with the worst access to  electricity. Electrification in the sub-Sa-

of electrification in 2020, were mainly in sub-Saharan Africa, Central Asia, and South East

4.2. Error Analysis

Figure 7. Changes in the percentage of the unelectrified built-up area between 2014 and 2020.

We found that the misclassified unelectrified built-up areas in Moldova, the Maldives,

and Belarus were mainly located in rural areas where the lower building density makes

identification error-prone [28]. The incorrectly classified sub-regions in China were mainly

located in small built-up areas in the rural areas of Henan, Anhui, and Shandong Provinces. Misidentification means that the night-light values in these areas were extremely low. The causes of misidentification in the context of China’s population movements were analyzed. China has a large number of rural people who work in urban areas year-round. As a result of this outflow from rural areas, the vacancy rate of houses in many villages is extremely high, and the phenomenon of numerous “hollow villages” has emerged [50]. The population outflow from Henan, Anhui, and Shandong Provinces is the serious rural outflow in China, and has resulted in many built-up areas being practically uninhabited and unlit, resulting in these areas being misclassified as unelectrified built-up areas [51].

In addition to the four countries mentioned above, there is a large error in the per-

centage of unelectrified built-up areas in France. France, as a first-world country, is fully
electrified according to the IEA. However, the identification results show the proportion

of unelectrified built-up areas to be 2.37% in 2014 and 1.73% in 2020, a reduction of 0.64%

compared to 2014. Anomalies in the French data can also be found in Figures 4 and 7. Analysis of the unelectrified built-up areas of France reveals that they are mainly small

built-up areas, far from large built-up areas, and often located in rural areas. The errors in

identification in France are similar to those in Moldova, the Maldives, and Belarus, and are

mainly due to the low resolution of the NPP/VIIRS night-light imagery (500 m), making it
difficult to distinguish the night-lights of these small built-up areas from unelectrified areas.

4.3. Application Scenarios

The available data on access to electricity only give a general picture of each country,

and it is impossible to know whether specific locations are electrified. This method produces
data on electrified and unelectrified built-up areas as spatialized metadata, allowing precise
knowledge of whether a specific location is electrified or not, which is vital for governmental

and business investment decisions. In the context of electricity infrastructure development,
this dataset maps the global spatial distribution of unelectrified built-up areas, allowing
governments, businesses, and the international community to identify under-electrified

areas, and, thus, plan more precisely for the development of electricity infrastructure. These
data can be combined with gridded data on the spatial population distribution to provide
a detailed spatial distribution of the global unelectrified population. This approach can help in the construction of electricity infrastructures, such as the siting of energy plants, or the building of power grids. Combined with gridded population data, it can also be used to estimate the effort required to achieve global electrification, such as the number of new energy plants that need to be installed, and the number of new transmission networks. In fully electrified countries, this dataset has the ability to detect temporarily unoccupied buildings, thus reflecting the global phenomenon of “hollow villages” or ghost towns, thereby helping governments in their urban and rural construction planning, and avoiding unnecessary waste of construction resources.

4.4. Limitations of This Study

Global unelectrified built-up areas were determined with high accuracy in this work; however, it does have the following limitations.

(1) The available night-light data have a resolution of 500 m. To ensure accuracy, only areas with built-up areas accounting for ≥25% of the 500 m night-light raster were selected. This neglects smaller built-up areas, which may bias the results.

(2) The balanced accuracy of the EC’s built-up area data is 83%. Errors in the portrayal of built-up areas will directly affect the identification of electrification, and some built-up areas may not contain any human structures. These data are available for 2014, and the present study continued to monitor electrification in 2020 relative to 2014 built-up area data, thus ignoring the impact of new construction. Built-up area data matching the year of analysis will be used in subsequent studies.

(3) Human occupancy within built-up areas is variable. If a building is electrified but unoccupied, the area may be misclassified as unelectrified. The phenomenon of “hollow villages”, such as those in China, can also cause misidentification. Also, the annual night-light images were synthesized using annual averages, which do not capture short-term human occupancy. Subsequent studies could use the 90th-percentile night-light value of the year as an annual image to capture changes in night-light due to short-term occupancy.

(4) In this work, a single threshold was adopted to distinguish between electrified and unelectrified areas; however, there may be spatial heterogeneity between different regions, and identification may be more accurate by using multiple thresholds following partitioning of different areas.

5. Conclusions

This study proposes a new method for extracting global unelectrified built-up areas using the EC’s built-up area remote sensing data, NPP/VIIRS night-light imagery, and high-resolution remote sensing imagery, which overcomes many of the shortcomings of previous studies. This method was used to extract global electrified and unelectrified built-up areas for 2014 and 2020 for the first time. The conclusions are as follows.

(1) Using night-light imagery and built-up area data makes it possible to identify globally electrified and unelectrified areas with high accuracy. The accuracy of determining whether or not a built-up area is electrified was 98.1%. The relationship between data on non-access to electricity and the percentage of unelectrified built-up area in each country was probed using Geodetector. The results show that the two sets of data tend to be related spatially. The data on non-access to electricity explained 55.2% of the spatial distribution of unelectrified built-up areas, indicating that the unelectrified built-up area data obtained by this method have a high degree of confidence.

(2) The global electrification situation in 2020 has improved significantly compared to that in 2014. The unelectrified built-up area decreased from 51,301.14 km² in 2014 to 22,192.52 km² in 2020, whereas the percentage of the unelectrified built-up areas decreased from 3.05% to 1.32%. In this period, electrification improved in 117 countries or territories, remained unchanged in 67, and increased by >0.1% in 18, in terms of the percentage of unelectrified built-up area.
(3) Volatile situations are one of the main factors affecting global electrification, with countries such as Ukraine experiencing an increase in unelectrified built-up area due to political instability, armed conflict, economic regression, and other factors.

(4) The dataset demonstrates the ability to monitor temporarily uninhabited built-up areas, and can depict the global phenomenon of “hollow villages” or ghost towns.

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Appendix A

Table A1. Identification of built-up area electrification in each country.

| Country or Territory                  | Unelectrified Built-Up Area, 2014 (km²) | Proportion of Built-Up Area Not Electrified, 2014 (%) | Unelectrified Built-Up Area, 2020 (km²) | Proportion of Built-Up Area Not Electrified, 2020 (%) | Change in Proportion of Unelectrified Built-Up Area (%) |
|---------------------------------------|----------------------------------------|-----------------------------------------------------|----------------------------------------|-----------------------------------------------------|-----------------------------------------------------|
| Afghanistan                           | 111.8342                               | 14.5603                                             | 87.4974                                | 11.3917                                             | 3.16853                                             |
| Albania                               | 14.6296                                | 2.1460                                              | 14.4622                                | 2.1214                                              | 0.02455                                             |
| Algeria                               | 6.1967                                 | 0.1169                                              | 5.6085                                 | 0.1058                                              | 0.01110                                             |
| Andorra                               | 0.0000                                 | 0.0000                                              | 0.0000                                 | 0.0000                                              | 0.0000                                              |
| Angola                                | 104.4335                               | 7.5607                                              | 93.1601                                | 6.7445                                              | 0.81617                                             |
| Anguilla                              | 0.0000                                 | 0.0000                                              | 0.0000                                 | 0.0000                                              | 0.0000                                              |
| Antigua and Barbuda                   | 0.0000                                 | 0.0000                                              | 0.0000                                 | 0.0000                                              | 0.0000                                              |
| Argentina                             | 6.9920                                 | 0.0758                                              | 5.3780                                 | 0.0583                                              | 0.01751                                             |
| Armenia                               | 45.0957                                | 4.6220                                              | 27.7899                                | 2.8483                                              | 1.77372                                             |
| Aruba                                 | 0.2544                                 | 0.3015                                              | 0.0000                                 | 0.0000                                              | 0.30146                                             |
| Australia                             | 170.7810                               | 1.0717                                              | 133.5447                               | 0.8380                                              | 0.23367                                             |
| Austria                               | 29.6767                                | 0.4790                                              | 17.4595                                | 0.2818                                              | 0.19720                                             |
| Azerbaijan                            | 4.6436                                 | 0.2019                                              | 7.9572                                 | 0.3459                                              | −0.14404                                            |
| Bahamas                               | 0.9338                                 | 0.4430                                              | 1.7395                                 | 0.8252                                              | −0.38221                                            |
| Bahrain                               | 0.0000                                 | 0.0000                                              | 0.0000                                 | 0.0000                                              | 0.0000                                              |
| Bangladesh                            | 4137.9592                              | 35.5531                                             | 2893.5518                              | 24.8612                                             | 10.69187                                            |
| Barbados                              | 0.0000                                 | 0.0000                                              | 0.0000                                 | 0.0000                                              | 0.0000                                              |
| Belarus                               | 255.0775                               | 2.7966                                              | 541.2175                               | 5.9337                                              | −3.13712                                            |
| Belgium                               | 0.0000                                 | 0.0000                                              | 0.0000                                 | 0.0000                                              | 0.0000                                              |
| Belize                                | 0.2604                                 | 0.4506                                              | 0.0000                                 | 0.0000                                              | 0.45062                                             |
| Benin                                 | 93.1004                                | 13.4938                                             | 42.7384                                | 6.1697                                              | 7.27017                                             |
| Bermuda                               | 0.0000                                 | 0.0000                                              | 0.0000                                 | 0.0000                                              | 0.0000                                              |
| Bhutan                                | 0.2799                                 | 4.8913                                              | 0.2799                                 | 4.8913                                              | 0.0000                                              |
| Bolivia                               | 4.9033                                 | 0.5947                                              | 3.6276                                 | 0.4400                                              | 0.15472                                             |
| Bosnia and Herzegovina                | 2.0774                                 | 0.2000                                              | 1.7247                                 | 0.1660                                              | 0.03395                                             |
| Botswana                              | 3.7657                                 | 1.0054                                              | 2.6912                                 | 0.7185                                              | 0.28687                                             |
| Brazil                                | 23.3945                                | 0.0804                                              | 26.5648                                | 0.0913                                              | −0.01090                                            |
| British Indian Ocean Territory        | 0.0000                                 | 0.0000                                              | 0.0000                                 | 0.0000                                              | 0.0000                                              |
| British Virgin Islands                | 0.1889                                 | 3.1480                                              | 0.1889                                 | 3.1480                                              | 0.0000                                              |
| Brunei                                | 0.0000                                 | 0.0000                                              | 0.0000                                 | 0.0000                                              | 0.0000                                              |
| Country or Territory               | Unelectrified Built-Up Area, 2014 (km$^2$) | Proportion of Built-Up Area Not Electrified, 2014 (%) | Unelectrified Built-Up Area, 2020 (km$^2$) | Proportion of Built-Up Area Not Electrified, 2020 (%) | Change in Proportion of Unelectrified Built-Up Area (%) |
|-----------------------------------|---------------------------------------------|------------------------------------------------------|---------------------------------------------|------------------------------------------------------|------------------------------------------------------|
| Bulgaria                          | 25.3332                                     | 0.5599                                               | 23.7142                                     | 0.5242                                               | 0.03578                                              |
| Burkina Faso                      | 16.4915                                     | 3.7346                                               | 8.1188                                      | 1.8386                                               | 1.89608                                              |
| Burundi                           | 8.2126                                      | 9.0198                                               | 4.9762                                      | 5.4653                                               | 5.55449                                              |
| Cambodia                          | 46.1479                                     | 15.7150                                              | 19.1609                                     | 6.5249                                               | 9.19002                                              |
| Cameroon                          | 109.5802                                    | 13.3651                                              | 112.8128                                    | 13.7594                                              | −0.39427                                             |
| Canada                            | 48.7055                                     | 0.1393                                               | 68.4845                                     | 0.1958                                               | −0.05655                                             |
| Canary Islands                    | 0.0000                                      | 0.0000                                               | 0.2842                                      | 0.1213                                               | −0.12134                                             |
| Cape Verde                        | 0.0000                                      | 0.0000                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| Cayman Islands                    | 0.0000                                      | 0.0000                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| Central African Republic          | 82.4083                                     | 51.0310                                              | 62.6977                                     | 38.8253                                              | 12.20570                                             |
| Chad                              | 60.9334                                     | 27.9816                                              | 51.2279                                     | 23.5247                                              | 4.46592                                              |
| Chile                             | 9.7061                                      | 0.4153                                               | 9.3934                                      | 0.4019                                               | 0.01338                                              |
| China                             | 30972.6748                                  | 10.5381                                              | 6201.8089                                   | 2.1101                                               | 8.42798                                              |
| Colombia                          | 2.2409                                      | 0.1114                                               | 0.4972                                      | 0.0247                                               | 0.08667                                              |
| Commonwealth of Dominica          | 0.0000                                      | 0.0000                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| Commonwealth of the Northern Mariana Islands | 0.0000                                      | 0.0000                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| Comoros                           | 20.3706                                     | 59.7781                                              | 13.3745                                     | 39.2478                                              | 20.53033                                              |
| Cook Islands                      | 0.2666                                      | 7.6271                                               | 0.0000                                      | 0.0000                                               | 7.62712                                              |
| Costa Rica                        | 0.2526                                      | 0.4369                                               | 0.0000                                      | 0.0000                                               | 0.04358                                              |
| Cote d'Ivoire                     | 158.8210                                    | 11.4453                                              | 90.2525                                     | 6.5040                                               | 4.94134                                              |
| Croatia                           | 4.1983                                      | 0.1546                                               | 5.3086                                      | 0.1955                                               | −0.04088                                             |
| Cuba                              | 4.8220                                      | 0.3307                                               | 2.1396                                      | 0.1467                                               | 0.18397                                              |
| Cyprus                            | 0.0000                                      | 0.0000                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| Czech                             | 6.9295                                      | 0.0769                                               | 2.3052                                      | 0.0256                                               | 0.05135                                              |
| Democratic Republic of the Congo  | 1205.6779                                   | 55.9208                                              | 1135.9253                                   | 52.6856                                              | 3.23521                                              |
| Denmark                           | 77.2307                                     | 0.9287                                               | 19.0495                                     | 0.2291                                               | 0.69960                                              |
| Djibouti                          | 0.0000                                      | 0.0000                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| Dominica                          | 5.6264                                      | 0.5117                                               | 1.0469                                      | 0.0952                                               | 0.41646                                              |
| Ecuador                           | 0.2484                                      | 0.0308                                               | 0.4967                                      | 0.0617                                               | −0.03083                                             |
| Egypt                             | 0.5644                                      | 0.0884                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| El Salvador                       | 2.3006                                      | 0.4581                                               | 0.5107                                      | 0.1017                                               | 0.35641                                              |
| Equatorial Guinea                 | 0.2484                                      | 0.5914                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| Eritrea                           | 0.2575                                      | 5.4876                                               | 0.0000                                      | 0.0000                                               | 5.48759                                              |
| Estonia                           | 9.6082                                      | 0.8278                                               | 20.9352                                     | 1.8037                                               | −0.97587                                             |
| Ethiopia                          | 37.1955                                     | 5.2713                                               | 57.5592                                     | 8.8536                                               | −3.13227                                             |
| Federated States of Micrones      | 0.0792                                      | 4.1178                                               | 0.0792                                      | 4.1178                                               | 0.0000                                               |
| Fiji                              | 0.2536                                      | 0.7185                                               | 0.0000                                      | 0.0000                                               | 0.71853                                              |
| Finland                           | 39.5123                                     | 0.7520                                               | 89.8960                                     | 1.7109                                               | −0.95889                                             |
| France                            | 1394.8523                                   | 2.3745                                               | 1018.7433                                   | 1.7343                                               | 0.64027                                              |
| French Guiana                     | 0.0000                                      | 0.0000                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| French Polynesia                  | 0.5312                                      | 1.3741                                               | 0.0000                                      | 0.0000                                               | 1.37405                                              |
| Gabon                             | 0.4970                                      | 0.4783                                               | 0.2438                                      | 0.2390                                               | 0.23929                                              |
| Gambia                            | 33.9575                                     | 21.9800                                              | 8.1701                                      | 5.2883                                               | 16.69164                                             |
| Georgia                           | 27.6368                                     | 2.2566                                               | 4.6726                                      | 0.3815                                               | 1.87507                                              |
| Germany                           | 409.7373                                    | 0.5233                                               | 114.1249                                    | 0.1458                                               | 0.37754                                              |
| Ghana                             | 95.2585                                     | 3.5951                                               | 5.0014                                      | 0.1888                                               | 3.40633                                              |
| Gibraltar                         | 0.0000                                      | 0.0000                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| Greece                            | 16.7507                                     | 0.3619                                               | 12.7043                                     | 0.2745                                               | 0.08743                                              |
| Grenada                           | 0.0000                                      | 0.0000                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| Guadeloupe                        | 0.0000                                      | 0.0000                                               | 0.0000                                      | 0.0000                                               | 0.0000                                               |
| Guatemala                         | 2.8212                                      | 0.3267                                               | 2.8206                                      | 0.3266                                               | 0.0000                                               |
| Guinea                            | 205.0289                                    | 35.3655                                              | 172.7847                                    | 29.8037                                              | 5.56183                                              |
| Guinea-Bissau                     | 26.0958                                     | 37.5126                                              | 19.4987                                     | 28.0293                                              | 9.48328                                              |
### Table A1. Cont.

| Country or Territory         | Unelectrified Built-Up Area, 2014 (km²) | Proportion of Built-Up Area Not Electrified, 2014 (%) | Unelectrified Built-Up Area, 2020 (km²) | Proportion of Built-Up Area Not Electrified, 2020 (%) | Change in Proportion of Unelectrified Built-Up Area (%) |
|-----------------------------|----------------------------------------|-----------------------------------------------------|----------------------------------------|-----------------------------------------------------|--------------------------------------------------|
| Guyana                      | 3.7354                                 | 6.3486                                              | 3.4910                                  | 5.9332                                              | 0.41541                                          |
| Haiti                       | 47.9069                                | 11.2086                                             | 57.9351                                 | 13.5455                                             | −2.3463                                          |
| Honduras                    | 1.0233                                 | 0.1481                                              | 0.7709                                  | 0.1116                                              | 0.03654                                          |
| Hungary                     | 12.4644                                | 0.1372                                              | 3.2951                                  | 0.0363                                              | 0.1090                                          |
| Iceland                     | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| India                       | 988.7891                               | 2.4650                                              | 452.5820                                | 1.1283                                              | 3.3672                                          |
| Indonesia                   | 416.2179                               | 2.5624                                              | 84.1484                                 | 0.5181                                              | 2.0438                                          |
| Iran                        | 1.2433                                 | 0.0123                                              | 0.2966                                  | 0.0030                                              | 0.0931                                          |
| Iraq                        | 0.2975                                 | 0.0078                                              | 3.3296                                  | 0.0876                                              | −0.07981                                        |
| Ireland                     | 9.5884                                 | 0.3937                                              | 7.5292                                  | 0.3092                                              | 0.08455                                         |
| Israel                      | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Italy                       | 40.1984                                | 0.1179                                              | 38.1973                                 | 0.1120                                              | 0.00587                                         |
| Jamaica                     | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Japan                       | 140.3028                               | 0.2534                                              | 135.6812                                | 0.2451                                              | 0.00835                                         |
| Jordan                      | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Kazakhstan                  | 15.8222                                | 0.1661                                              | 15.5984                                 | 0.1637                                              | 0.00235                                         |
| Kenya                       | 6.9580                                 | 2.1331                                              | 2.9816                                  | 0.9141                                              | 1.21908                                         |
| Kiribati                    | 0.2398                                 | 39.4158                                             | 0.0000                                  | 0.0000                                              | 39.41579                                        |
| Democratic People’s Republic of Korea | 380.3245                           | 37.1298                                             | 204.3360                                | 19.9486                                              | 17.18114                                        |
| Korea                       | 0.9233                                 | 0.0115                                              | 0.3158                                  | 0.0039                                              | 0.00758                                         |
| Kuwait                      | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Kyrgyzstan                  | 1.1261                                 | 0.0527                                              | 0.0000                                  | 0.0000                                              | 0.05270                                         |
| Laos                        | 3.7437                                 | 2.4275                                              | 2.6055                                  | 1.6894                                              | 0.73802                                         |
| Latvia                      | 4.1133                                 | 0.3504                                              | 3.1859                                  | 0.2714                                              | 0.07900                                         |
| Lebanon                     | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Lesotho                     | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Liberia                     | 77.8050                                | 30.3199                                             | 56.0539                                 | 21.8437                                             | 8.47620                                         |
| Libya                       | 4.3342                                 | 0.1748                                              | 9.0320                                  | 0.3643                                              | −0.18948                                        |
| Liechtenstein               | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Lithuuania                  | 14.5081                                | 0.6837                                              | 8.3566                                  | 0.3938                                              | 0.28990                                         |
| Luxembourg                  | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Madagascar                  | 3.3832                                 | 1.5656                                              | 2.6089                                  | 1.2073                                              | 0.35831                                         |
| Madeira                     | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Malawi                      | 0.5138                                 | 0.2629                                              | 0.5138                                  | 0.2629                                              | 0.0000                                          |
| Malaysia                    | 8.9171                                 | 0.1805                                              | 4.9626                                  | 0.1005                                              | 0.08006                                         |
| Maldives                    | 0.2199                                 | 6.1713                                              | 0.0000                                  | 0.0000                                              | 6.17125                                         |
| Mali                        | 52.4993                                | 11.0030                                             | 23.1947                                 | 4.8613                                              | 6.14178                                         |
| Malta                       | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Marshall Islands            | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Martinique                  | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Mauritania                  | 7.2445                                 | 4.8262                                              | 5.1962                                  | 3.4617                                              | 1.36452                                         |
| Mauritius                   | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Mayotte                     | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Mexico                      | 44.0788                                | 0.2057                                              | 30.2135                                 | 0.1410                                              | 0.06471                                         |
| Moldova                     | 240.1905                               | 7.2783                                              | 289.4682                                | 8.7715                                              | −1.49322                                        |
| Monaco                      | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Mongolia                    | 1.4806                                 | 0.5961                                              | 1.4806                                  | 0.5961                                              | 0.0000                                          |
| Montenegro                  | 4.0925                                 | 1.6345                                              | 5.4943                                  | 2.1763                                              | −0.54187                                        |
| Morocco                     | 1.7822                                 | 0.0851                                              | 1.3077                                  | 0.0144                                              | 0.07078                                         |
| Mozambique                  | 129.8779                               | 11.4506                                             | 122.1234                                | 10.7669                                             | 0.68366                                         |
| Myanmar                     | 190.5299                               | 12.7198                                             | 70.9998                                 | 4.7399                                              | 7.97981                                         |
| Namibia                     | 4.9320                                 | 3.7227                                              | 5.4649                                  | 4.1249                                              | −0.40222                                        |
| Nauru                       | 0.0000                                 | 0.0000                                              | 0.0000                                  | 0.0000                                              | 0.0000                                          |
| Nepal                       | 9.4892                                 | 2.9450                                              | 0.0000                                  | 0.0000                                              | 2.94504                                         |
Table A1. Cont.

| Country or Territory | Unelectrified Built-Up Area, 2014 (km²) | Proportion of Built-Up Area Not Electrified, 2014 (%) | Unelectrified Built-Up Area, 2020 (km²) | Proportion of Built-Up Area Not Electrified, 2020 (%) | Change in Proportion of Unelectrified Built-Up Area (%) |
|----------------------|----------------------------------------|------------------------------------------------------|----------------------------------------|------------------------------------------------------|----------------------------------------------------|
| Netherlands          | 1.9578                                 | 0.0123                                               | 0.0000                                 | 0.0000                                               | 0.0123                                             |
| Netherlands Antilles | 0.0000                                 | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| New Caledonia        | 0.0000                                 | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| New Zealand          | 15.7617                                | 0.6322                                               | 15.0821                                | 0.6049                                               | 0.0726                                             |
| Nicaragua            | 0.5105                                 | 0.1482                                               | 0.2548                                 | 0.0740                                               | 0.0742                                             |
| Niger                | 83.6143                                | 26.6773                                              | 72.3850                                | 23.0946                                              | 3.5827                                             |
| Nigeria              | 1247.6289                              | 13.7390                                              | 956.8827                               | 10.5372                                              | 3.2017                                             |
| Norfolk Island       | 0.2845                                 | 100.0000                                             | 0.0000                                 | 100.0000                                             | 100.0000                                           |
| North Macedonia      | 0.3308                                 | 0.0563                                               | 0.9964                                 | 0.1694                                               | -0.11317                                           |
| Norway               | 12.0534                                | 0.2056                                               | 14.0764                                | 0.2401                                               | -0.03450                                           |
| Oman                 | 0.0000                                 | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| Pakistan             | 1086.5527                              | 12.8175                                              | 869.6158                               | 10.2584                                              | 2.5591                                             |
| Palau                | 0.0000                                 | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| Panama               | 0.2516                                 | 0.0454                                               | 0.2516                                 | 0.0454                                               | 0.0000                                             |
| Papua New Guinea     | 2.0528                                 | 6.2187                                               | 0.8073                                 | 2.4455                                               | 3.7732                                             |
| Paraguay             | 0.5287                                 | 0.0850                                               | 0.5287                                 | 0.0850                                               | 0.0000                                             |
| Peru                 | 19.5824                                | 1.4003                                               | 18.3128                                | 1.3095                                               | 0.0907                                             |
| Philippines          | 79.9002                                | 3.0324                                               | 35.7553                                | 1.3570                                               | 1.6754                                             |
| Poland               | 42.3286                                | 0.1713                                               | 61.3299                                | 0.2483                                               | -0.0769                                            |
| Portugal             | 15.9723                                | 0.2196                                               | 12.7830                                | 0.1758                                               | 0.0438                                             |
| Puerto Rico          | 0.2612                                 | 0.0150                                               | 0.3260                                 | 0.0188                                               | -0.0037                                            |
| Qatar                | 0.0000                                 | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| Republic of the Congo| 12.6762                                | 5.3491                                               | 14.9115                                | 6.2924                                               | -0.9432                                             |
| Reunion              | 0.7998                                 | 0.3617                                               | 0.7999                                 | 0.3618                                               | -0.0001                                            |
| Romania              | 36.6328                                | 0.3710                                               | 28.7944                                | 0.2917                                               | 0.0793                                             |
| Russian Federation   | 703.8669                               | 0.5320                                               | 947.9048                               | 0.7165                                               | -0.1844                                             |
| Rwanda               | 10.9320                                | 6.6333                                               | 5.4659                                 | 3.3166                                               | 3.3167                                             |
| Saint Kitts-Nevis    | 0.0000                                 | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| Saint Lucia          | 0.0000                                 | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| Saint Pierre and Miquelon | 0.0000                       | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| Saint Vincent and the Grenadines | 0.0000                        | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| Sao Tome and Principe | 0.0000                                | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| Saudi Arabia         | 7.7043                                 | 0.1762                                               | 7.7043                                 | 0.1762                                               | 0.0000                                             |
| Senegal              | 49.1270                                | 6.7833                                               | 18.3221                                | 2.5299                                               | 4.2534                                             |
| Serbia               | 2.0448                                 | 0.0481                                               | 1.3699                                 | 0.0322                                               | 0.0158                                             |
| Seychelles           | 0.0000                                 | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| Sierra Leone         | 79.7038                                | 32.6631                                              | 59.9947                                | 24.5862                                              | 8.0769                                             |
| Singapore            | 0.0000                                 | 0.0000                                               | 0.0000                                 | 0.0000                                               | 0.0000                                             |
| Slovakia             | 67.0682                                | 1.4226                                               | 48.2477                                | 1.0234                                               | 0.3992                                             |
| Slovenia             | 1.8425                                 | 0.1573                                               | 2.5365                                 | 0.2165                                               | -0.0592                                            |
| Solomon Islands      | 0.5023                                 | 4.0246                                               | 0.0000                                 | 0.0000                                               | 4.0246                                             |
| Somalia              | 586.4573                               | 79.3364                                              | 561.5776                               | 75.9707                                              | 3.6574                                             |
| South Africa         | 217.9137                               | 1.9619                                               | 161.5485                               | 1.4544                                               | 0.5076                                             |
| South Sudan          | 63.4611                                | 50.1188                                              | 47.7250                                | 37.6911                                              | 12.4276                                             |
| Spain                | 160.2261                               | 0.9509                                               | 146.4375                               | 0.8691                                               | 0.0818                                             |
| Sri Lanka            | 10.5747                                | 1.0892                                               | 2.0600                                 | 0.2066                                               | 0.8825                                             |
| Sudan                | 113.6692                               | 10.1769                                              | 59.4366                                | 5.3214                                               | 4.8550                                             |
| Suriname             | 0.5007                                 | 0.3982                                               | 0.2517                                 | 0.2001                                               | 0.1980                                             |
| Swaziland            | 0.8312                                 | 1.9800                                               | 0.5547                                 | 1.3215                                               | 0.6585                                             |
| Sweden               | 35.0522                                | 0.2821                                               | 45.4066                                | 0.3654                                               | -0.0833                                            |
| Switzerland          | 5.3970                                 | 0.0928                                               | 2.1875                                 | 0.0376                                               | 0.0519                                             |
| Syria                | 251.4053                               | 8.7313                                               | 198.5683                               | 6.8963                                               | 1.8350                                             |
| Tajikistan           | 23.0878                                | 0.9432                                               | 6.7623                                 | 0.2763                                               | 0.6696                                             |
### Table A1. Cont.

| Country or Territory | Unelectrified Built-Up Area, 2014 (km²) | Unelectrified Built-Up Area Not Electrified, 2014 (%) | Unelectrified Built-Up Area, 2020 (km²) | Unelectrified Built-Up Area Not Electrified, 2020 (%) | Change in Proportion of Unelectrified Built-Up Area (%) |
|----------------------|--------------------------------------|---------------------------------------------|--------------------------------------|---------------------------------------------|--------------------------------------------------|
| Tanzania             | 79.4132                              | 7.4632                                      | 42.6739                              | 4.0105                                      | 3.45275                                          |
| Thailand             | 311.1349                             | 4.2063                                      | 67.9229                              | 0.9183                                      | 3.28806                                          |
| Timor-Leste          | 0.2939                               | 2.2661                                      | 0.2297                               | 0.1901                                      | 0.49534                                          |
| Togo                 | 12.2694                              | 4.1098                                      | 5.2572                               | 0.5760                                      | 2.34885                                          |
| Trinidad and Tobago  | 0.0000                               | 0.0000                                      | 0.0000                               | 0.0000                                      | 0.0000                                           |
| Tunisia              | 311.1349                             | 4.2063                                      | 67.9229                              | 0.9183                                      | 3.28806                                          |
| Turkey               | 17.3954                              | 0.1496                                      | 6.2782                               | 0.0540                                      | 0.09558                                          |
| Turkmenistan         | 0.0000                               | 0.0000                                      | 0.0000                               | 0.0000                                      | 0.0000                                           |
| Turks and Caicos Islands | 0.2384                           | 1.0852                                      | 0.2384                               | 1.0852                                      | 0.0000                                           |
| Ukraine              | 24.7265                              | 4.9257                                      | 9.8171                               | 1.9556                                      | 2.97004                                          |
| United Arab Emirates | 0.0000                               | 0.0000                                      | 0.0000                               | 0.0000                                      | 0.0000                                           |
| United Kingdom       | 55.9738                              | 0.1175                                      | 69.1107                              | 0.1450                                      | −0.02757                                         |
| United States        | 537.9265                             | 0.1564                                      | 585.7227                             | 0.1703                                      | −0.01390                                         |
| Uruguay              | 0.5874                               | 0.0645                                      | 0.5874                               | 0.0645                                      | 0.0000                                           |
| Uzbekistan           | 136.3654                             | 1.1354                                      | 26.0565                              | 0.2165                                      | 0.91890                                          |
| Vanuatu              | 0.0000                               | 0.0000                                      | 0.0000                               | 0.0000                                      | 0.0000                                           |
| Vatican City         | 0.0000                               | 0.0000                                      | 0.0000                               | 0.0000                                      | 0.0000                                           |
| Venezuela            | 0.0000                               | 0.0000                                      | 0.9943                               | 0.0353                                      | −0.03529                                         |
| Vietnam              | 597.7392                             | 7.5150                                      | 58.0599                              | 0.7299                                      | 6.78502                                          |
| Virgin Islands of the United States | 0.0000            | 0.0000                                      | 0.0000                               | 0.0000                                      | 0.0000                                           |
| Wake Island          | 0.0000                               | 0.0000                                      | 0.0000                               | 0.0000                                      | 0.0000                                           |
| Western Sahara       | 0.0000                               | 0.0000                                      | 0.0000                               | 0.0000                                      | 0.0000                                           |
| Yemen                | 22.4824                              | 9.6580                                      | 30.6630                              | 13.1722                                     | −3.51420                                         |
| Zambia               | 24.1539                              | 3.2525                                      | 9.3942                               | 1.2650                                      | 1.98750                                          |
| Zimbabwe             | 26.8092                              | 4.3962                                      | 15.5474                              | 2.5495                                      | 1.84672                                          |
| Other regions *      | 377.1833                             | 2.0432                                      | 272.0290                             | 1.4736                                      | 0.56962                                          |

* Other regions include all remaining regions or countries not mentioned.

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