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Exploring spatiotemporal patterns of electric power consumption in countries along the Belt and Road

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ABSTRACT

Fully understanding spatiotemporal patterns of electric power consumption (EPC) is one of the key questions related to sustainable socioeconomic and environmental development in countries along the Silk Road Economic Belt and the 21st-Century Maritime Silk Road (hereinafter referred to as the Belt and Road countries). However, studies about spatiotemporal patterns of EPC in the Belt and Road countries are still scarce due to the lack of reliable data. This study attempted to investigate spatiotemporal patterns of EPC in the Belt and Road countries from multiple perspectives. Firstly, the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) nighttime stable light data were used to estimate EPC from 1992 to 2013. Subsequently, the mathematical statistic method, standard deviational ellipse, rank size rule, and correlation analysis were employed to evaluate the EPC change in detail. The results reveal that the EPC growth mainly occurs in the developing countries, especially in China. The geographical distribution of EPC in the Belt and Road countries is oriented in the Northwest-Southeast direction between 1992 and 2013. Based on the rank size rule analysis, the slope values of q are −2.392 and −2.175 between 1992 and 2013, with an average R^2 value of 0.664, indicating a clear clustering pattern of EPC. It is also proved that GDP is a more important impact factor to EPC than the population. Our findings can offer an effective way to understand spatiotemporal evolution characteristics of EPC in the Belt and Road countries, and provide references for regional socioeconomic development and cooperation.

1. Introduction

In the face of the fragile recovery of the global economy in the 21st century, it is critical for us to carry on the spirit of cooperation, development, peace, and mutual benefit. In this context, the Chinese government proposed the initiative of jointly building the Silk Road Economic Belt and the 21st-Century Maritime Silk Road (hereinafter referred to as the Belt and Road) in September and October 2013 [1,2]. The aim of the Belt and Road initiative is to promote orderly and free flow of economic factors, highly efficient allocation of resources, and deep integration of markets between different countries, which have attracted global attention [3,4]. Hence, a better understanding of the socioeconomic dynamics is a critical prerequisite for encouraging the Belt and Road countries to achieve economic policy coordination and carry out broader and more in-depth regional cooperation in the future.

As an important component of the socioeconomic indicators, electric power consumption (EPC) is related to every aspect of modern society, such as industrial productions, commercial activities, and daily activities of residents [5–8]. As such, the EPC is usually one of the main sources of CO_2 emissions, playing an important role in driving and accelerating climate warming [9,10]. The Belt and Road, which goes across Asia, Africa, and Europe, covers more than 60 countries and holds about 4 billion population [3]. The EPC in the Belt and Road countries showed a massive increase of about four-fold from 2534 billion kWh in 1992 to 9792

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billion kWh in 2013 [11]. The rapid growth of EPC in the Belt and Road countries is not only closely related to the world energy market but also affects the global sustainable development. Therefore, a better understanding of spatiotemporal patterns of EPC in the Belt and Road countries is of critical importance for strengthening international cooperation with respect to energy-saving and emission reduction.

Previous studies have explored EPC changes in several ways in the Belt and Road countries. For example, Prakasvudhisarn [12] forecasted long-term EPC in Thailand, and indicated that the EPC of the country would reach 160,136 million kWh in 2010 and 216,986 million kWh in 2020. Lean et al. [13] examined the causal relationship between EPC and economic growth in the Association of Southeast Asian Nations, and found that there was unidirectional Granger causality running from EPC to economic growth. Taking China as an example, Wang et al. [14] evaluated the changes in industrial EPC, and proved that EPC in the industrial sector experienced a dramatic increase from 1998 to 2007, accounting for approximately 75% of China's total EPC. In addition, Huang et al. [15] developed a Grey–Markov forecasting model to analyze the electric-power supply and demand in China. Ranjan et al. [16] presented linear multiple regression models to model EPC for different seasons in Delhi. While the existing literature has enriched our understanding of EPC changes in the Belt and Road countries, it has predominantly focused on the individual countries (or cities). Studies that considered spatiotemporal patterns of EPC in the Belt and Road countries are still scarce. This is partly due to the fact that the statistical data of EPC are not available in some underdeveloped countries. In addition, there are incomparability issues for the statistical data between different administrative units because the local calculation may be compromised by data availability [17,18]. Despite their authoritativeness, the statistical data only provide digital records of EPC for an entire administrative unit without showing spatial distributions [19]. Owing to the absence of spatial details, spatiotemporal patterns of EPC within an administrative unit have not been identified [11]. Consequently, it is urgent for us to provide an efficient and economical way to map spatiotemporal patterns of EPC in the Belt and Road countries.

Compared to the traditional statistical data, satellite remote sensing imageries, such as the nighttime stable light data obtained by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS), have enormous potential for estimating socioeconomic indicators [11,20–25]. The DMSP-OLS data reflect lights mainly from cities and rural settlements generated by human activities [26,27], which have a significant correlation with EPC [28,29]. Thus, the data provide an effective way to quantify spatiotemporal dynamics of EPC in detail over large geographic areas [30–33]. Elvidge et al. [30] firstly demonstrated that there was a positive correlation between nighttime lights and EPC at the national scale. He et al. [43] proposed a saturation-corrected method to model the spatiotemporal EPC at a 1-km resolution in China by integrating the DMSP-OLS data with the Normalized Difference Vegetation Index (NDVI) data. Townsend et al. [34] also estimated the spatial distribution of EPC throughout Australia from the DMSP-OLS data using an Overglow Removal Model. Although a large number of studies have documented the success of the DMSP-OLS data for modeling EPC at different scales, most of the studies aimed at improving the accuracy of EPC estimation. What is missing in the literature is the analysis of the DMSP-OLS data for quantifying spatiotemporal patterns of EPC in the Belt and Road countries, resulting in bias in the evaluation of EPC changes in these areas.

This study, therefore, aims to comprehensively evaluate spatiotemporal patterns of EPC in the Belt and Road countries. To achieve this goal, the study first estimated EPC using the DMSP-OLS data. Then, spatiotemporal patterns of EPC were explored and compared from multiple perspectives. Moreover, this study also tested the correlation between EPC and Gross Domestic Product (GDP), as well as the correlation between EPC and population.

The remainder of the study is organized as follows. Section 2 describes study areas and data sources. Section 3 presents the methodology for estimating EPC and evaluating spatiotemporal patterns of EPC. The results and discussion are given in Section 4. Finally, the conclusions are summarized in Section 5.

2. Study areas and data sources

The Belt and Road covers the continents of Asia, Europe, and Africa, connecting the East Asia economic circle and the European economic circle, which encompass countries with huge potential for economic development. The Silk Road Economic Belt links China with Central Asia, West Asia, Southeast Asia, South Asia, Russia, and Europe. The 21st-Century Maritime Silk Road spans from China's coast to Europe through the South China Sea, the Indian Ocean, and the South Pacific (http://www.xinhuanet.com/silkroad/english/index.htm). Currently, there is no explicit spatial scope for the Belt and Road countries. With the development of economic exchanges and cooperation in different countries, more and more countries are likely to join the Belt and Road countries. Therefore, referencing the definition of Li et al. [35], we selected more than 60 countries as our study areas, including China, Russia, India, Thailand, etc. (Table 1). The spatial map of the Belt and Road countries is shown in Fig. 1 (http://tagd.org.cn/Item/2197.aspx).

Four types of data were utilized in this study: the DMSP-OLS data, the radiance calibrated nighttime light (RCNL) data, statistical data, and administrative boundaries. The DMSP-OLS data from 1992 to 2013 were downloaded from the National Oceanic and Atmospheric Administration's National Geophysical Data Center (NOAA/NGDC) website (https://ngdc.noaa.gov/eog/index.html). These data were acquired by different satellites, and annual composites were collected from each satellite [36,37], which resulted in the lack of continuity and comparability of the data [38,39]. The DMSP-OLS data were recorded as 6-bit digital numbers (DN) ranging from 0 to 63, which led to the problem of pixel saturation in the urban centers of large cities. Compared with the DMSP-OLS data, the RCNL data did not have saturated pixels. Hence, the 2006 RCNL data collected from NOAA/NGDC website were used to correct the discontinuity and pixel saturation of the DMSP-OLS data [40]. All the nighttime light data were given a spatial resolution of 30-arc-second (about 1 km), covering an area of -180 to $180°$ in longitude and -65 to $75°$ in latitude. The statistical data, including country-level EPC, GDP, and population, were applied to model spatiotemporal patterns of EPC and evaluate the impact factors of EPC in the Belt and Road countries. These data were obtained from the World Bank Open Database (http://www.worldbank.org/). In addition, the global boundary data for countries were extracted from the Global Administrative Areas (http://gadm.org/).

3. Methodology

The methodology consists of five analytical procedures: 1) estimating EPC using the DMSP-OLS data; 2) describing spatiotemporal variations of EPC at different scales; 3) evaluating the overall evolution direction of EPC using the standard deviational ellipse (SDE); 4) analyzing spatiotemporal scales of EPC using the rank size rule; and 5) exploring the correlation between EPC and GDP, as well as the correlation between EPC and population.