Energy Efficiency (2022) 15:46
https://doi.org/10.1007/s12053-022-10055-8

ORIGINAL ARTICLE

Energy poverty assessment in the Belt and Road Initiative countries: based on entropy weight-TOPSIS approach

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Received: 27 September 2021 / Accepted: 11 August 2022 / Published online: 22 August 2022

Abstract The Belt and Road Initiative (BRI) countries are mainly developing countries with severe energy poverty. This study combines the entropy weight and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to measure energy poverty at the household, enterprise, and national levels in 82 BRI countries. This study aims to investigate and discuss how to encourage BRI countries to develop effective decision-making mechanisms for developing more targeted supply-side solutions to domestic energy poverty. A geographic information system (GIS) is also used to construct spatial distribution maps to assess energy poverty. The findings show that countries in South Asia, Southeast Asia, and North Africa have the highest levels of energy poverty, while countries in West Asia and Europe have the lowest. East Timor, Tonga, and Equatorial Guinea are of the most extremely lowest. The assessment methodology used in this paper focuses not only on the energy poverty faced by households, but also on the overall energy supply and service situation at the enterprise and national levels. These perspectives are likely to influence policy making and help the governments in addressing domestic energy poverty more effectively from the supply side.

Keywords Energy poverty · Spatial distribution · TOPSIS method · BRI countries

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Introduction

The concept of energy poverty originated in the UK's fuel use rights movement in the early 1970s. Since the 1980s, it had become a British government legislation project and had developed into a policy research topic of concern for European academia (Li et al., 2014). The European Union Energy Poverty Observatory (EU EPOV) defined energy poverty as where "individuals or households are not able to adequately heat or provide other required energy services in their homes at affordable cost" (Thomson & Bouzarovski, 2018). The United Nations Development Programme (UNDP, 2000) defined energy poverty as "the lack of sufficient option in accessing adequate, accessible, reliable, high-quality, clean, and environmentally benign energy services to sustain economic development." In early research, energy poverty usually referred to a household's inability to obtain enough energy to meet their living and heating needs. The International Energy Agency (IEA) defined energy poverty as a lack of electricity and heavy reliance on traditional biomass (IEA & OECD, 2002).

As Sovacool (2012) argued, energy poverty is a complex and multidimensional phenomenon. When a person's energy-related needs are not being met at the household level—including basic lighting, cooking, and heating needs, as well as further education, recreation, communication (Nussbaumer et al., 2012), and comfort (Castaño-Rosa et al., 2019)—the person is said to be in energy poverty (Team and Baffert, 2015). Additionally, these needs must be affordable. Some researchers defined "energy poverty" as the inability to attain socially and physically required levels of household energy services due to "deprivation" of household energy usage (Bouzarovski & Petrova, 2015; Buzar, 2007; Groh, 2014; Sovacool, 2012). This term stressed citizens' rights to obtain energy to meet their basic needs, which should not be denied due to poverty. It also emphasized the importance of satisfying demand for "energy service." Although it might seem self-evident, it is important to note that the object of energy consumption was to provide energy services from various sources of energy (González-Eguino, 2015). Some studies included community and micro enterprises because micro enterprises operate closer to consumers; therefore, some community and micro enterprises also face energy poverty (Ayodele et al., 2018; Groh, 2014).

According to a World Bank study from 2016, 980 million people lacked access to clean energy (World Bank, 2017). Even among those who had access to renewable energy, a significant number still relied on conventional energy sources including coal, charcoal, and animal dung. During use, these invariably create indoor air pollution, which harms human health (WHO, 2006). In 2016, there were approximately 114 deaths per 100,000 people as a result of such practices (Vardell, 2020). In 2018, about 790 million people, or 10.4% of the world's population, lacked access to electricity (WDI, 2020). In sub-Saharan Africa, approximately 580 million people lacked access to electricity in 2019, and this number is projected to rise by 2020 (IEA, 2020). One of the Sustainable Development Goals (SDGs) set by the United Nations is to "Ensure access to affordable, secure, sustainable, and modern energy for all" by 2030 (Sachs, 2012). However, hundreds of millions of people around the world still lacked this basic service, and development in clean cooking fuels and technology had slowed, putting billions of women's and children's health at risk (United Nations Statistics Division, 2020).

Energy poverty is a common global problem, both in developed regions and developing regions. Aristondo and Onaindia (2018a) studied the evolution of energy poverty in Spain between 2005 and 2016, using the home comfort level as a measure. All factors were weighed, including the family's desire to remain warm, whether the electric bill was past due, and whether the windows and walls were damp or rotting. The results showed that energy poverty in Spain was increasing. Papada and Kaliampakos (2016) took a similar approach in a study on energy poverty in Greece, focusing on both the level of home comfort and the proportion of household energy expenditure. The results showed that 58% of Greek households were in energy poverty. Meyer et al. (2018) designed a set of tools from three categories—measurable energy poverty, hidden energy poverty, and perceived energy poverty—to measure local energy poverty in Belgium. The study found that approximately 21.3% of Belgians were experiencing at least one of these three types of energy poverty.

Energy poverty is more severe in developing countries' rural areas than in more developed areas. According to research based on cross-sectional data from a representative rural Bangladesh household survey conducted in 2004, 58% of rural households were in energy poverty (Barnes et al., 2011). In Ghana, the proportion of people who are energy poor has decreased from 88.4% in 2005/2006 to 82.5% in 2012/2013. Although overall energy poverty has decreased in Ghana, the incidence of energy poverty has remained high. Furthermore, the rural population suffers from almost twice the amount of energy scarcity as the urban population (Adusah-Poku & Takeuchi, 2019).

Many studies have found that energy poverty harms residents' welfare and health (Thomson et al., 2017; D. Zhang et al., 2019). In India, for example, research had linked health problems like asthma and tuberculosis to energy poverty (Sadath & Acharya, 2017). This was because energy poverty increases the use of biomass energy, which was detrimental to human health when used inefficiently. According to research, rising paraffin prices, essential fuel for the urban poor, had pushed Ethiopian households into energy poverty (Alem & Demeke, 2020). Furthermore, in response to the drastic rise in kerosene rates, households had consumed vast quantities of charcoal, which has significant environmental, climate, and health implications. Besides, energy poverty hearted socioeconomic (Scarpellini et al., 2019) and gender equality (Robinson, 2019), problems that were particularly severe in developing countries. According to Ürge-Vorsatz & Tirado Herrero (2012), ambitious climate change action would increase energy poverty levels. On the other hand, significant improvements in energy efficiency created strong synergies between addressing energy poverty and addressing climate change. As a result, policy priorities must be combined to resolve both problems at the same time. According to Chakravarty & Tavoni (2013), only a 7% rise in energy consumption would be needed to provide essential energy to the entire world's energy-poor population. This would have little effect on the environment, resulting in additional CO_2 emissions of 44–183 $GtCO_2$ over the rest of the twenty-first century and a net warming contribution of just 0.13 C. As the widespread existence of energy poverty causes serious consequences in terms of health, welfare, and social inequality, urgent policy attention is needed on this issue.

China introduced the Belt and Road Initiative (BRI) to lead globalization and regional economic cooperation with countries situated along the land-based "Silk Road Economic Belt" and the oceangoing "Maritime Silk Road" in 2013 (Zhang et al., 2017). By the end of January 2020, China had signed 200 cooperation documents on the BRI with 138 countries and 30 international organizations (Nedopil, 2021). As shown in Fig. 1, the land area of BRI countries was about 66.15 million km^2, accounting for 52% of the global landmass, and contained a population of 3.36 billion people, accounting for 43.8% of the global population. In 2019, the BRI countries' GDP totaled about US$19 trillion, accounting for 22.0% of global GDP. It is crucial to research a region with such a large area, a large population, and a high total GDP, especially because energy poverty was prevalent in BRI countries.

Globally, there was a significant body of literature related to energy poverty including countries in the Belt and Road Initiative (BRI). Nearly 600 million people in these countries did not have access to electricity, and only 56.7% of the population in the bottom 20% of GDP per capita had access to electricity (World Bank, 2020). For example, energy poverty was prevalent in Pakistan, Bangladesh, etc. Sher et al. (2014) found that 47%, 51%, 69%, and 66% of households in Punjab, Sindh, Khyber Pakhtunkhwa (KPK), and Baluchistan were in energy shortage, respectively. In Indonesia, Sambodo & Novandra (2019) found that

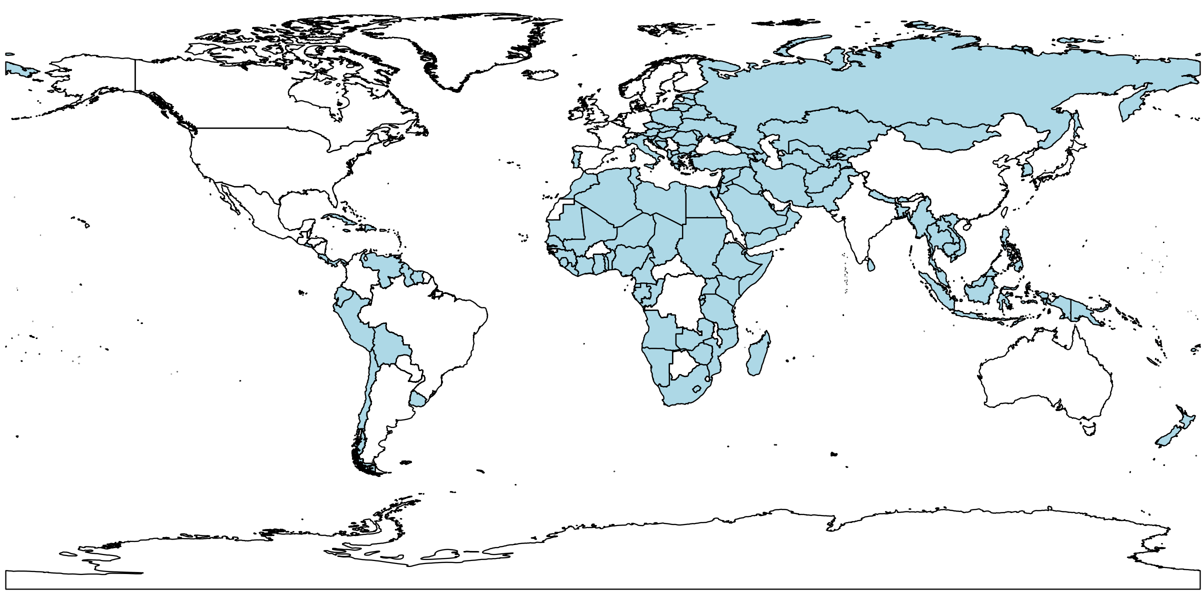


Fig. 1 Distribution of Belt and Road Initiative countries

the proportion of household energy poverty based on expenditure criteria was 53%. Many countries had high mortality rates attributed to household and ambient air pollution due to the lack of access to clean energy. For example, 211 out of every 100,000 people in Afghanistan died because of household and ambient air pollution. In countries with the lowest 20% of GDP per capita in the BRI, for every 100,000 people, about 166 died because of household and ambient air pollution (WDI, 2020).

Energy poverty is a complex and multidimensional phenomenon. And when considering the situation of a country, the issue becomes even more complex. One solution is to count the number of households in energy poverty, but it will be very difficult. Moreover, we are trying to measure energy poverty in several countries with significant variations of economic, cultural, geographical, and climatic at the same time, so it is difficult to give a direct and accurate measure of energy poverty. A more feasible alternative is to measure energy poverty in a multi-dimensional way through a series of macroeconomic indicators. We therefore construct a multidimensional energy poverty indicator system. As in the current study, we first consider household energy poverty (Nussbaumer et al., 2012). In addition to households, communities and micro enterprises face the same problems in this regard (Ayodele et al., 2018; Groh, 2014), while enterprises play an active role in energy poverty. We therefore also created enterprise-level indicators. At the same time, national policies, infrastructure, etc. have an important role in energy poverty reduction (Teschner, Sinea, Vornicu, Abu-Hamed, & Negev, 2020), so country-level indicators are also used in order to provide a clearer and more comprehensive picture of a country's energy poverty level.

This paper has developed a composite approach to promote the alleviation of energy poverty in BRI countries, allowing cross-country comparisons. The methodology allowed policy makers to assess each country's unique weaknesses and strengths at various levels, as well as the country's overall situation, providing an objective reference for policy formulation. First, based on a review of previous studies, a specific system of assessment indicators was established at three levels: household, enterprise, and national. Second, the energy poverty status of 82 BRI countries was measured and ranked by the entropy weight and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. Third, based on the ranking results, three countries were selected in each of the best, medium, and worst energy poverty intervals for further analysis. Finally, corresponding policy recommendations were made in response to the study findings.

Literature review

The assessment of energy poverty has been approached from a variety of perspectives by researchers. Early researchers used the proportion of energy expenditure, that a household is in "fuel poverty" if more than 10% of its total expenditure is spent on fuel (Boardman, 1991); degree of energy use (Barnes et al., 2011); electricity consumption (Pereira et al., 2010); and other factors to decide if a household was in energy poverty. Energy poverty has been identified as a vulnerability by some researchers (Chester & Morris, 2011; Gouveia et al., 2019; Okushima, 2016), indicating that poor households will be more affected by energy price fluctuations. Moreover, in recent years, a growing number of scholars moved away from using a single indicator to measure energy poverty. For example, Nussbaumer et al. (2012) introduced the Multidimensional Energy Poverty Index (MEPI), a new composite index for measuring energy poverty that focuses on the lack of access to modern energy. It covers the prevalence and severity of energy poverty and offers innovative resources to improve decision-making. The MEPI comprised six indicators in five dimensions (cooking, lighting, services offered by household appliances, entertainment/education, and communication), with this study being a benchmark for the MEPI. Many researchers have subsequently conducted studies based on this approach. For example, Acharya & Sadath (2019) estimated the MEPI to investigate energy poverty in India, finding that energy poverty and low socioeconomic status in India were highly correlated. Crentsil et al. (2019) added an indicator based on MEPI services provided by a household appliance—to evaluate energy poverty in Ghana, finding that although the level of multidimensional energy poverty decreased between 2008 and 2014, the incidence and intensity of multidimensional energy poverty have remained high. Okushima (2017) measured the energy poverty of Japanese households in terms of three dimensions:

energy costs, income, and the energy efficiency of the house.

Previous research on energy poverty at the household level has focused on two areas: access to clean fuel and housing comfort. Andadari et al. (2014) focused on Indonesian residents' access to clean fuel. Results showed that traditional biomass energy consumption accounted for about one-third of the total household energy consumption on average; in contrast, LPG consumption remained very limited at less than 3% of total household energy consumption. Mirza & Szirmai (2010) constructed a composite indicator to measure regional energy poverty in Pakistan by considering the energy type, energy shortage, and household size. The results showed that 23.1% of rural households in Pakistan had significant energy inconvenience and spent a lot of time and energy collecting or purchasing different energy sources and that 96.6% of rural households had severe energy shortages.

The first concern regarding housing comfort is house heating. Aristondo & Onaindia (2018b) conducted a micro-level residential survey to measure energy poverty in Spain through indicators such as housing warmth and whether utility bills were in arrears, and found that the population's energy poverty was progressively worsening. In addition to house heating, some researchers have also observed high-temperature discomfort for people in low latitudes in recent years. Considering a combination of climate, housing type, electricity supply, and air conditioning equipment, Mastrucci et al. (2019) found that about 1.8 to 4.1 billion people in the world may need air conditioning to avoid heat-related stress, mainly in India, Southeast Asia, and sub-Saharan Africa. Thomson et al.(2019) argued that some families in Europe could not ensure adequate cooling conditions, which negatively impacted their health, well-being, and productivity. The data they collected in Gdansk (Poland), Prague (Czech Republic), Budapest (Hungary), and Skopje (North Macedonia) verified this conclusion.

Some previous studies have been concerned with further demand for energy in society. In addition to the basic lighting and heating needs of rural households, Kaygusuz (2011) focused on energy demand for production and social services, such as agricultural production and services in communication, commerce, and health. Sovacool et al. (2012) also argued that in addition to general energy services, attention should be paid to mobility and mechanical power as essential energy services used for transportation and industrial production. Furthermore, some studies have been conducted at the enterprise level. Ayodele et al. (2018) constructed a set of indicators to measure electricity energy poverty in micro and small businesses and found that insufficient electricity supply to businesses in Ibadan, Nigeria, severely affected business productivity.

In addition to the above studies on energy poverty in households and enterprises, several international institutions have explored energy poverty across countries. The Energy Development Index (EDI), introduced by the International Energy Agency (IEA), was used to measure the degree of energy modernization in 75 countries (IEA, 2004). The EDI consists of three indicators: per capita commercial energy consumption, the proportion of commercial energy consumption in terminal energy consumption, and the number of people with access to electricity. The United Nations officially adopted sustainable development indicators in 2015; the seventh goal (SDG7) is to ensure that everyone has access to affordable, reliable, and sustainable modern energy by 2030. SDG7 includes five components: affordable modern energy, renewable energy, energy efficiency, clean energy technologies, and energy technologies for developing countries, and this indicator system is used to evaluate the energy poverty of countries (United Nations Statistics Division, 2020). Papada and Kaliampakos (2018) constructed a Stochastic Model of Energy Poverty (SMEP) at the national level based on Monte Carlo simulation. The SMEP was applied to the case of Greece, revealing an energy poverty level of 70.4%. The authors believe that this method can also evaluate energy poverty in other countries and regions.

In summary, previous studies had measured energy poverty in a variety of perspectives: household (Nussbaumer et al., 2012; Papada & Kaliampakos, 2016, 2018), company (Ayodele et al., 2018), and national (Thomson & Bouzarovski, 2018). In contrast, the economic, cultural, and climatic geographies of the BRI country houses vary considerably, from developed to developing countries, and from countries in high- to low-latitude regions. Therefore, we argue that it is necessary to combine national-, enterprise-, and household-level indicators to provide a more comprehensive and in-depth analysis of energy poverty. Therefore, based on indicators used in previous research (Aristondo & Onaindia, 2018b; Ayodele et al., 2018; Nussbaumer et al., 2012), a composite approach is developed to evaluate energy poverty based on an evaluation index which covers eight categories and eighteen indicators. The flowchart of the research methodology is shown in Fig. 2.

Evaluation of energy poverty in BRI countries

In this section, we construct a comprehensive energy poverty assessment framework which includes three parts: the construction of an energy poverty indicator system, the determination of the weights for each indicator, and the application of the TOPSIS methodology for energy poverty assessment.

Construction of energy poverty evaluation

Currently, many studies observed energy poverty from various perspectives, such as household, company, and national. However, to give a more in-depth analysis of energy poverty, it is required to combine national-, enterprise-, and household-level data into a single assessment index system. As a result, a complete evaluation index system spanning eight categories and eighteen indicators was constructed to evaluate energy poverty based on indicators used in earlier research (Aristondo & Onaindia, 2018a; Ayodele et al., 2018; Nussbaumer et al., 2012) (for details, please see Table 1).

At the household level, concerning energy poverty in BRI countries was evaluated using three categories: electricity use, cooking and heating, and modern energy needs (Nussbaumer et al., 2012). Of these, electricity use comprised two indicators: the proportion of the population with access to electricity and electricity consumption per capita. The indicator *access to electricity* was chosen because the lack of access to clean energy is a widespread energy problem in countries along the BRI. The indicator *access to electricity* reflects the difficulties of access to modern energy for the inhabitants of these regions. At the same time, per capita electricity

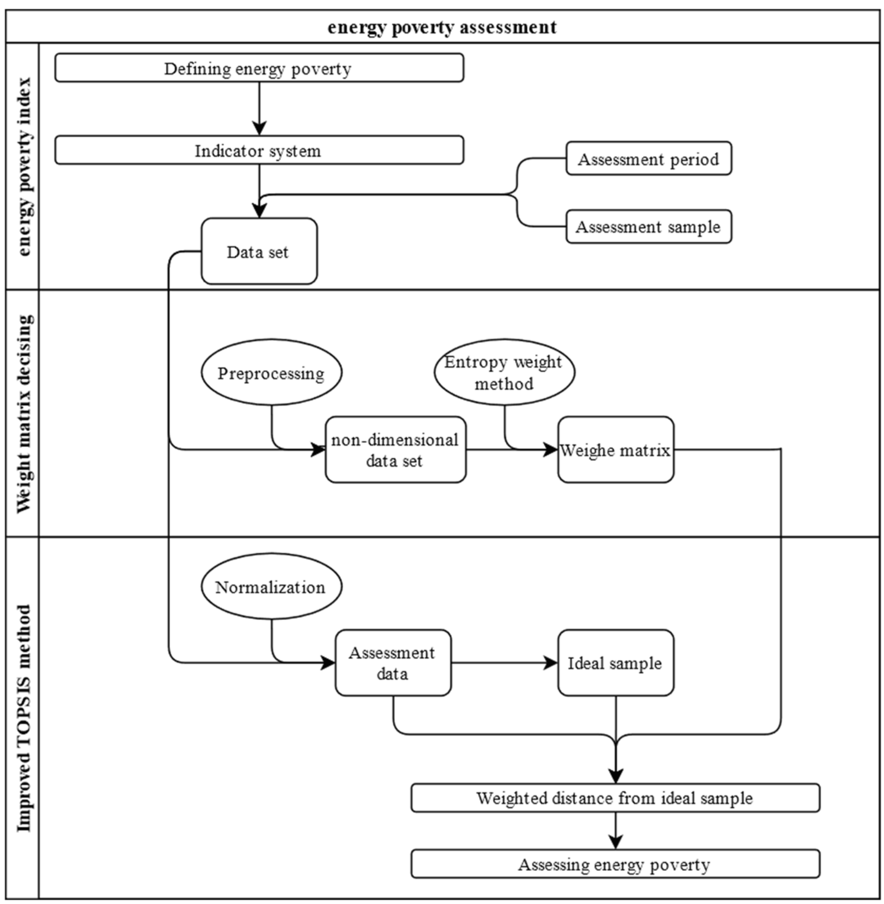


Fig. 2 Flow chart of the research methodology

Table 1 Indicators measurement units, definition, and data sources

Level	First-level indicators	Second-level indicators	Units	Definition	Source, Year	Impact
Household	Electricity use	EG_USE_ELEC_KH_PC	Electric power consumption (kWh per capita)	Electricity consumption measures the production of heat and power plants less transmission, distribution, and transformation losses and own use by heat and power plants	WDI, 2014	Positive
		Elc_Accs	Access to electricity (% of population)	Access to electricity is the percentage of the population with access to electricity. Electrification data were collected from industry, national surveys, and international sources	WDI, 2018	Positive
	Cooking and heating	Cft_Accs	Access to clean fuels and technologies for cooking (% of population)	Access to clean fuels and technologies for cooking is the proportion of the total population primarily using clean fuels and technologies for cooking. Under WHO guidelines, kerosene is excluded from clean cooking fuels	WDI, 2016	Positive
		Sta_Airp	Mortality rate attributed to household and ambient air pollution, age standardized (per 100,000 population)	The mortality rate attributed to household and ambient air pollution is the number of deaths attributable to the joint effects of household and ambient air pollution in a year per 100,000 populations. The rates are age standardized. The following diseases were included: acute respiratory infections (estimated for all ages); cerebrovascular diseases in adults (estimated above 25 years); ischemic heart diseases in adults (estimated above 25 years); chronic obstructive pulmonary disease in adults (estimated above 25 years); and lung cancer in adults (estimated above 25 years)	WHO, 2016	Negative

Table 1 (continued)

Level	First-level indicators	Second-level indicators	Units	Definition	Source, Year	Impact
	Modern energy needs	IT_CEL_SETS_P2	Mobile cellular subscriptions (per 100 people)	Mobile cellular telephone subscriptions are subscriptions to a public mobile telephone service that provide access to the PSTN using cellular technology. The indicator includes (and is split into) the number of postpaid subscriptions and the number of active prepaid accounts (i.e. that have been used during the last three months). The indicator applies to all mobile cellular subscriptions that offer voice communications. It excludes subscriptions via data cards or USB modems, subscriptions to public mobile data services, private trunked mobile radio, telepoint, radio paging, and telemetry services	WDI, 2015	Positive
		IT_NET_USER_ZS	Individuals using the internet (% of population)	Internet users are individuals who have used the internet (from any location) in the last 3 months. The internet can be used via a computer, mobile phone, personal digital assistant, games machine, digital TV, etc	WDI, 2011	Positive
Enterprise	Energy services	IT_NET_SECR_P6	Secure internet servers (per 1 million people)	The number of distinct, publicly trusted TLS/SSL certificates found in the Netcraft Secure Server Survey	WDI, 2017	Positive
		IC_ELC_TIME	Time required to get electricity (days)	The time required to obtain electricity is the number of days required to obtain a permanent electricity connection. The measure captures the median duration that the electricity utility and experts indicate is necessary in practice, rather than required by law	WDI, 2014	Negative
		EG_ELC_LOSS_ZS	Electricity transmission and distribution losses (% of output)	Electricity transmission and distribution losses include losses in transmission between sources of supply and points of distribution, including due to pilferage	WDI, 2014	Negative

Table 1 (continued)

Level	First-level indicators	Second-level indicators	Units	Definition	Source, Year	Impact
	Energy costs	Elc_Pri	Obtaining electricity: price (US cents per kWh)	The price of electricity is measured in US cents per kWh. Monthly electricity consumption is assumed, for which a bill is then computed for a warehouse based in the largest business city of the economy in March. The bill is then expressed in kWh. The index is computed based on the methodology in the DB16-20 studies	WDI, 2015	Negative
		ELC_COST	Obtaining electricity: cost (% of income per capita)	The cost is the total median cost associated with completing the procedures to connect a warehouse to electricity. It is calculated as a percentage of income per capita. All the fees and costs associated with completing the procedures to connect a warehouse to electricity are recorded, including those related to obtaining clearances from government agencies, applying for the connection, receiving inspections of both the site and the internal wiring, purchasing materials, getting the actual connection working, and paying a security deposit. Bribes are not included	WDI, 2015	Negative
Nation	Energy supply	EG_USE_PCAP_KG_OE	Energy use (kg of oil equivalent per capita)	Energy use refers to the use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport	WDI, 2013	Positive

Table 1 (continued)

Level	First-level indicators	Second-level indicators	Units	Definition	Source, Year	Impact
		EG_IMP_CONS_ZS	Energy imports, net (% of energy use)	Net energy imports are estimated as energy use less production, both measured in oil equivalents. A negative value indicates that the country is a net exporter. Energy use refers to the use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport	WDI, 2013	Negative
	Energy facility	Elc_Plant	Total net installed capacity of electric power plants, kW per capita	This is the maximum active power that can be supplied continuously with all plants running at the outlet point (i.e., after taking the power supplies for the station auxiliaries and allowing for losses in transformers considered integral to the station). This assumes no restriction of interconnection to the network. It does not include overload capacity that can only be sustained for a short period (e.g., internal combustion engines momentarily running above their rated capacity). The net maximum electricity-generating capacity represents the sum of all individual plants' maximum capacities available to run continuously throughout a prolonged period of operation in a day	UNSD, 2017	Positive
	Energy facility	EG_FEC_RNEW	Renewable energy share of total final energy consumption (%)	Renewable energy consumption is the proportion of renewable energy in total final energy consumption	WDI, 2017	Positive
	Energy efficiency	NY_ADJ_DNGY_GN_ZS	Adjusted savings: energy depletion (% of GNI)	Energy depletion is the ratio of the value of the stock of energy resources to the remaining reserve lifetime. It covers coal, crude oil, and natural gas	WDI, 2016	Negative
		PEI	Primary energy intensity (MJ/ GDP)	Energy intensity is defined as the energy supplied to the economy per unit value of economic output	SDGs, 2016	Negative

Table 1 (continued)

Level	First-level indicators	Second-level indicators	Units	Definition	Source, Year	Impact
		NY_GDP_FUEL_RENT	Coal, oil and gas rents (% of GDP)	Coal, oil, and natural gas rents are the differences between the values of hard and soft coal, oil, and natural gas production at world prices and their total costs of production. This indicator is the sum of the three rents	WDI, 2012	Negative

"Positive" denotes a benefit indicator (a high value is preferred); "negative' denotes a cost indicator (small value is desirable). Data source: WDI = World Development Indicators, WHO = World Health Organization, UNSD = United Nations Statistics Division, SDGs = Sustainable Development Goals

consumption is used as an indicator of the affordability of energy for households. Also, cooking and heating comprised two indicators: the proportion of the population with access to clean fuel, and the mortality rate attributed to household and ambient air pollution; the former represents the accessibility of clean energy to households, while the latter represents the health damage suffered by households due to energy poverty (Sadath & Acharya, 2017). Modern energy needs represent further energy requirements of households and comprised two indicators: mobile cellular subscriptions and the proportion of individuals using the internet.

At the enterprise level, the first focus was on the energy services that enterprises obtain. This category comprised three indicators: secure internet servers (per 1 million people), the time required to obtain electricity—which means the number of days between the company applying for and obtaining electricity, and electric power transmission and distribution losses (% of output). These three indicators together represented the efficiency of facilities and energy services obtained by enterprises, reflecting the support of energy services for doing business. Additionally, the energy costs of enterprises in BRI countries were considered to represent the affordability of energy (Ayodele et al., 2018). Electricity cost consisted of two indicators: the price of electricity, which represents the cost of energy used by most enterprises daily, and the cost of electricity, which is the median of the total cost of electricity access for a country's enterprises calculated as a percentage of per capita income. These two indicators together represented the energy burden of enterprises.

At the national level, energy poverty was measured in three categories: energy supply, energy facilities, and energy efficiency. The parameters for energy supply were energy consumption (kg of oil equivalent per capita) and net energy imports (percentage of energy use). The former can indicate how rich a country is in terms of total energy. The latter indicates the energy endowment of a country; countries with less energy endowment tend to import energy to meet domestic energy demand. The evaluation of energy facilities and energy intensity was concerning SDG7, which measures the energy situation of various countries to ensure that everyone has access to affordable, reliable, and sustainable modern energy. The total net installed capacity of electric power plants per capita and the renewable energy share of total final energy consumption were used as indicators for energy facilities. The former refers to developing a country's energy infrastructure, while the latter refers to the advancement of its energy technology. To demonstrate energy efficiency, energy intensity refers to the amount of energy given to the economy per unit of economic output (United Nations Statistics Division, 2017). Energy depletion (% of GNI), which is the value of the stock of energy resources for the remaining reserve lifetime and includes coal, crude oil, and natural gas, was included in this category. The difference in value between hard and soft coal, oil, and natural gas and their production costs was also utilized as a metric (percentage of GDP). These two measures are used to describe two different aspects of energy loss during the production-to-consumption process. The choice of indicators for national levels is primarily intended to provide a reference for addressing the energy poverty of the population by looking at it from the perspective of the supplier. Because the existence of energy poverty among the population often derives from the supply level and capacity of the suppliers and cannot be solved solely by them individually (especially for nationals of low-income countries, as is widely the case in BRI countries), their energy poverty depends on at least two factors, i.e., the economic level of the individual and the supply level of the government. And in rich countries, fossil fuels are disproportionately consumed by poorer citizens (Berry, 2019), illustrating the extent to which national supply capacity can solve the affordability problem.

The data in this paper were mainly collected from the World Bank database (WDI, 2020), Doing Business (DB) dataset (World Bank, 2020), World Health Organization (WHO, 2016), and Sustainable Development Goals (SDGs) (United Nations Statistics Division, 2020). Limited by the availability of data, 82 countries were selected as the sample set. Specific indicators are shown in Table 1. Since indicators could have a positive or negative impact on energy poverty, some needed to be positive. This was achieved using different approaches depending on the meaning and form of the indicators. For indicators with data in the form of percentages, adjusted savings, energy imports, coal oil and gas rents, etc., values were in the interval of 0–1; therefore, one minus the original indicator was used for positivity. For the proportional indicators, such as the mortality rate attributed to household and ambient air pollution per 100,000 populations, the positive was obtained by subtracting the index value from the denominator of the index. The remaining indicators were positive by inverting their values; for example, obtaining electricity was not a percentage indicator and did not fall in the interval of 0–1, so was positive by taking its inverse.

Determination of indicator weight using an entropy method

Common subjective methods for determining weights, such as the Delphi method, may change the weights due to subjective factors. In contrast, the entropy weight method is an objective method to determine weights and can effectively overcome this issue. The basic idea of the entropy weight method is to determine weights according to the variability of the index. Usually, the greater the entropy of information in an indicator, the greater its degree of variation and, thus, the more weight it is given (Delgado & Romero, 2016). In this study, the entropy weight method was used to determine the weight of each indicator.

A total of 18 indicators were selected for this paper:X_1, X_2,…X_k, k=18.

$$X_i = \{x_1 x_2 \dots x_n\} \tag{1}$$

First, all data were normalized as follows:

$$Y_{ij} = \frac{X_{ij} - \min(X_i)}{\max(X_i) - \min(X_i)} \tag{2}$$

where X_{ij} represents the j th observation in the i th indicator, and Y_{ij} is the normalized data. Then, the entropy information for each indicator was calculated.

$$E_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{3}$$

$p_{ij} = Y_{ij} / \sum_{i=1}^{n} Y_{ij}$; if $p_{ij} = 0$, then define $\lim_{p_{ij} \to 0} p_{ij} \ln p_{ij} = 0$.

Finally, the weight of each indicator was determined.

$$W_i = \frac{1 - E_i}{k - \sum E_i} (i = 1, 2, \dots, k) \tag{4}$$

TOPSIS method

The "Technique for Order of Preference by Similarity to Ideal Solution" (TOPSIS) was first introduced by Hwang & Yoon (1981) for solving multiple criteria decision-making (MCDM) challenges. The idea underpinning TOPSIS is that the best alternative should be the smallest distance (i.e., Euclidean distance) from the ideal solution. Specifically, the ideal optimal and inferior solution can be constructed in a sample. The degree of superiority or inferiority of an observation can be represented by its distance from the ideal optimal and inferior alternative. This method has been widely used in many types of evaluations, such as supplier selection (dos Santos et al., 2019), environmental impact assessment (Vavrek & Chovancová, 2019), etc. According to Shih et al. (2007), TOPSIS has several advantages, including the following: (1) it conforms to the logic of people's choices; (2) as a scalar, it can reflect the best and worst choices at the same time; (3) the calculation process is simple and convenient; and (4) it is easy to visualize.

On the other hand, the TOPSIS method has certain drawbacks; this method requires obtaining the extremum values of all variables to form a new dummy sample and assessing the merits of each sample accordingly. This results in the TOPSIS method being susceptible to special values.

Step 1 was data normalization to make each indicator dimensionless; this enables the comparison of metrics under a unified system. The normalized data matrix $Z_{ij}(i = 1, 2 \ldots \text{k},\ \text{k} = 10(\text{indicator}); \text{j} = 1,\ 2 \ldots n(\text{observation}))$ was calculated as follows:

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} \quad (5)$$

Step 2 was the construction of the ideal optimal and inferior alternative.

The ideal optimal alternative Z^+ consists of the maximum value of the elements in each column of Z.

$$Z^+ = \left(max\left\{z_{11}, z_{12}, \cdots, z_{1n}\right\}, max\left\{z_{21}, z_{22}, \cdots, z_{2n}\right\}, \cdots, max\left\{z_{k1}, z_{k2}, \cdots, z_{kn}\right\}\right) = \left(Z_1^+, Z_2^+, \cdots, Z_k^+\right) \quad (6)$$

The ideal most inferior alternative, Z^-, consists of the minimum value of the elements in each column of Z.

$$Z^- = \left(\min\left\{z_{11}, z_{12}, \cdots, z_{1n}\right\}, \min\left\{z_{21}, z_{22}, \cdots, z_{2n}\right\}, \cdots, \min\left\{z_{k1}, z_{k2}, \cdots, z_{kn}\right\}\right) = \left(Z_1^-, Z_2^-, \cdots, Z_k^-\right) \quad (7)$$

Step 3 was the calculation of the distance of each observation from the optimal alternative and inferior alternative, as follows:

$$D_i^+ = \sqrt{\sum_{j=1}^{k} w_j \left(Z_j^+ - z_{ij}\right)^2} \quad (8)$$

$$D_i^- = \sqrt{\sum_{j=1}^{k} w_j \left(Z_j^- - z_{ij}\right)^2} \quad (9)$$

Step 4 was the calculation of the closeness score of each observation to the optimal alternative.

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (10)$$

Here, $0 \leq C_i \leq 1, C_i \rightarrow 1$ indicates the better performance of observation i.

Step 5 was the ranking of energy poverty in each country based on the closeness score C_i. The ranking results are shown in Table 2.

To facilitate the spatial visualization of the extent of energy poverty by region and country, the results in Table 2 are also represented in Fig. 3.

Results of energy poverty performance analysis in BRI countries

Figure 3 shows the spatial distribution of energy poverty in the BRI countries. The white areas indicate countries that are not BRI countries or with missing data. The green and blue blocks indicate the country's energy poverty performance is better, that is, the further from energy poverty. Conversely, the red and orange blocks indicate more severe energy poverty in the country. All BRI countries with available data are divided into four categories according to the range

Table 2 Score of energy poverty performance in each country

Country	C	Rank	Electric	Cooking	Modern	Service	Cost	Supply	Facility	Efficiency
Kuwait	0.480	1	0.796	0.755	1.000	0.067	0.565	0.634	0.566	0.208
Qatar	0.450	2	0.755	0.747	0.985	0.048	0.455	0.863	0.504	0.197
Singapore	0.436	3	0.453	0.766	1.000	0.944	0.161	0.181	0.366	0.473
Trinidad and Tobago	0.414	4	0.365	0.624	0.992	0.071	0.495	0.546	0.284	0.084
Luxembourg	0.385	5	0.710	0.873	1.000	0.711	0.110	0.263	0.456	0.504
Bahrain	0.306	6	1.000	0.859	1.000	0.051	0.148	0.422	0.568	0.125
Brunei Darussalam	0.288	7	0.526	0.591	1.000	0.083	0.137	0.605	0.354	0.316
Estonia	0.275	8	0.347	0.809	0.928	0.484	0.043	0.203	0.371	0.190
Bulgaria	0.271	9	0.247	0.530	0.884	0.530	0.042	0.109	0.286	0.214
Panama	0.269	10	0.124	0.496	0.888	0.130	0.360	0.041	0.207	0.680
Israel	0.268	11	0.341	0.730	1.000	0.123	0.329	0.112	0.322	0.404
United Arab Emirates	0.268	12	0.567	0.875	0.985	0.126	0.180	0.424	0.454	0.232
Angola	0.258	13	0.026	0.030	0.470	0.028	0.098	0.510	0.320	0.397
Saudi Arabia	0.244	14	0.481	0.560	0.959	0.063	0.185	0.414	0.366	0.215
Uruguay	0.222	15	0.169	0.584	0.979	0.093	0.270	0.069	0.433	0.444
Oman	0.220	16	0.333	0.556	0.951	0.069	0.162	0.409	0.276	0.193
Slovenia	0.218	17	0.347	0.693	0.961	0.347	0.046	0.139	0.324	0.288
New Zealand	0.214	18	0.462	0.802	1.000	0.259	0.062	0.189	0.387	0.253
Austria	0.210	19	0.429	0.843	1.000	0.225	0.054	0.154	0.518	0.392
Azerbaijan	0.185	20	0.130	0.534	0.955	0.048	0.070	0.386	0.133	0.351
Poland	0.184	21	0.211	0.679	1.000	0.112	0.203	0.123	0.203	0.320
Malaysia	0.179	22	0.244	0.672	0.962	0.164	0.160	0.158	0.180	0.286
Cyprus	0.175	23	0.195	0.618	1.000	0.288	0.031	0.062	0.259	0.423
Malta	0.175	24	0.257	0.708	1.000	0.238	0.016	0.066	0.268	1.000
Lithuania	0.170	25	0.204	0.694	1.000	0.219	0.096	0.092	0.299	0.365
Algeria	0.170	26	0.097	0.212	0.925	0.022	0.174	0.279	0.077	0.329
Gabon	0.168	27	0.086	0.287	0.787	0.025	0.012	0.319	0.421	0.172
Portugal	0.167	28	0.245	0.585	1.000	0.217	0.061	0.081	0.378	0.430
Croatia	0.163	29	0.199	0.600	0.926	0.251	0.021	0.092	0.286	0.350
Kazakhstan	0.162	30	0.291	0.575	0.952	0.053	0.088	0.284	0.225	0.136
Russian Federation	0.161	31	0.341	0.566	0.982	0.064	0.035	0.276	0.299	0.137
Latvia	0.159	32	0.189	0.734	0.952	0.203	0.019	0.095	0.381	0.355
Hungary	0.156	33	0.211	0.683	1.000	0.226	0.045	0.097	0.180	0.316
Chile	0.148	34	0.207	0.573	0.921	0.159	0.091	0.092	0.288	0.350
Iraq	0.144	35	0.096	0.127	0.976	0.049	0.055	0.306	0.140	0.337
Romania	0.144	36	0.147	0.443	0.856	0.205	0.046	0.101	0.257	0.454
Ethiopia	0.142	37	0.024	0.002	0.016	0.043	0.097	0.095	0.433	0.132
Mongolia	0.141	38	0.121	0.184	0.417	0.060	0.064	0.305	0.081	0.200
Italy	0.140	39	0.261	0.607	1.000	0.133	0.028	0.100	0.331	0.472
Zambia	0.139	40	0.039	0.132	0.148	0.035	0.102	0.094	0.426	0.165
Nigeria	0.135	41	0.035	0.166	0.031	0.027	0.022	0.188	0.414	0.198
Greece	0.135	42	0.264	0.556	0.942	0.106	0.068	0.090	0.318	0.382
South Africa	0.131	43	0.220	0.430	0.845	0.158	0.041	0.157	0.169	0.157
Philippines	0.124	44	0.074	0.339	0.421	0.103	0.137	0.056	0.155	0.459
Cameroon	0.122	45	0.041	0.094	0.215	0.067	0.011	0.121	0.402	0.260

Table 2 (continued)

Country	C	Rank	Electric	Cooking	Modern	Service	Cost	Supply	Facility	Efficiency
Zimbabwe	0.121	46	0.035	0.140	0.277	0.038	0.029	0.090	0.420	0.115
Thailand	0.119	47	0.145	0.335	0.739	0.118	0.094	0.095	0.212	0.240
Ecuador	0.118	48	0.098	0.328	0.955	0.057	0.054	0.214	0.139	0.396
Nepal	0.116	49	0.065	0.161	0.262	0.060	0.028	0.086	0.393	0.159
Montenegro	0.116	50	0.242	0.446	0.688	0.028	0.041	0.098	0.361	0.325
Niger	0.115	51	0.000	0.007	0.000	0.033	0.008	0.103	0.401	0.192
Suriname	0.114	52	0.193	0.387	0.894	0.037	0.063	0.147	0.207	0.528
Indonesia	0.114	53	0.080	0.230	0.576	0.057	0.027	0.208	0.221	0.404
Mozambique	0.113	54	0.025	0.084	0.018	0.055	0.061	0.151	0.332	0.106
Sudan	0.112	55	0.038	0.186	0.401	0.061	0.066	0.108	0.336	0.286
Myanmar	0.110	56	0.043	0.082	0.168	0.041	0.029	0.137	0.337	0.480
Serbia	0.110	57	0.226	0.452	0.760	0.101	0.022	0.110	0.223	0.210
Kenya	0.105	58	0.050	0.120	0.117	0.027	0.011	0.083	0.377	0.165
Togo	0.104	59	0.030	0.064	0.049	0.044	0.012	0.081	0.373	0.117
Albania	0.104	60	0.135	0.531	0.770	0.022	0.044	0.092	0.271	0.491
Costa Rica	0.104	61	0.119	0.473	0.933	0.082	0.024	0.062	0.262	0.494
Ukraine	0.099	62	0.185	0.366	0.956	0.068	0.030	0.124	0.199	0.117
Georgia	0.098	63	0.152	0.386	0.774	0.073	0.052	0.052	0.268	0.221
Peru	0.098	64	0.094	0.402	0.746	0.064	0.026	0.120	0.196	0.541
Bosnia and Herzegovina	0.098	65	0.186	0.466	0.627	0.050	0.027	0.100	0.260	0.178
Belarus	0.097	66	0.197	0.445	0.981	0.053	0.026	0.109	0.184	0.193
Sri Lanka	0.096	67	0.074	0.221	0.249	0.040	0.010	0.056	0.289	0.725
Tajikistan	0.095	68	0.102	0.185	0.800	0.039	0.065	0.066	0.292	0.241
Cambodia	0.094	69	0.064	0.197	0.161	0.021	0.015	0.069	0.341	0.221
Armenia	0.094	70	0.120	0.370	0.968	0.023	0.072	0.044	0.248	0.248
North Macedonia	0.093	71	0.189	0.586	0.650	0.041	0.023	0.069	0.194	0.329
Uzbekistan	0.090	72	0.108	0.196	0.919	0.047	0.069	0.137	0.067	0.153
Tunisia	0.087	73	0.100	0.448	0.991	0.066	0.040	0.078	0.116	0.363
Ghana	0.085	74	0.058	0.204	0.202	0.053	0.007	0.107	0.244	0.396
Morocco	0.083	75	0.083	0.509	0.967	0.069	0.033	0.019	0.080	0.446
Dominican Republic	0.082	76	0.106	0.397	0.902	0.051	0.016	0.028	0.140	0.591
Jordan	0.079	77	0.116	0.428	0.990	0.078	0.021	0.031	0.084	0.282
El Salvador	0.078	78	0.084	0.297	0.857	0.069	0.014	0.055	0.171	0.355
Bangladesh	0.076	79	0.060	0.105	0.161	0.017	0.044	0.084	0.198	0.461
Pakistan	0.074	80	0.051	0.098	0.422	0.022	0.013	0.077	0.251	0.303
Senegal	0.069	81	0.044	0.167	0.303	0.036	0.010	0.049	0.227	0.350
Jamaica	0.067	82	0.087	0.412	0.903	0.043	0.015	0.039	0.101	0.245

C indicates the energy poverty performance score of each country. If C tends to 1 show the better performance of a country and vice versa

of energy poverty, as represented by four different shades of blue. Each category accounts for about a quarter of the total number of countries.

As shown in Fig. 3, the most energy-poor BRI countries are mainly located in West Africa, Southeast Asia, South Asia, and East Asia. These countries have relatively underdeveloped economies and poor energy infrastructure. In some South and Southeast Asian countries, the proportion of clean modern energy use is low (Khanna et al., 2019). The least energy-poor BRI countries are mainly located in Europe and West Asia. Europe is highly industrialized, with many developed

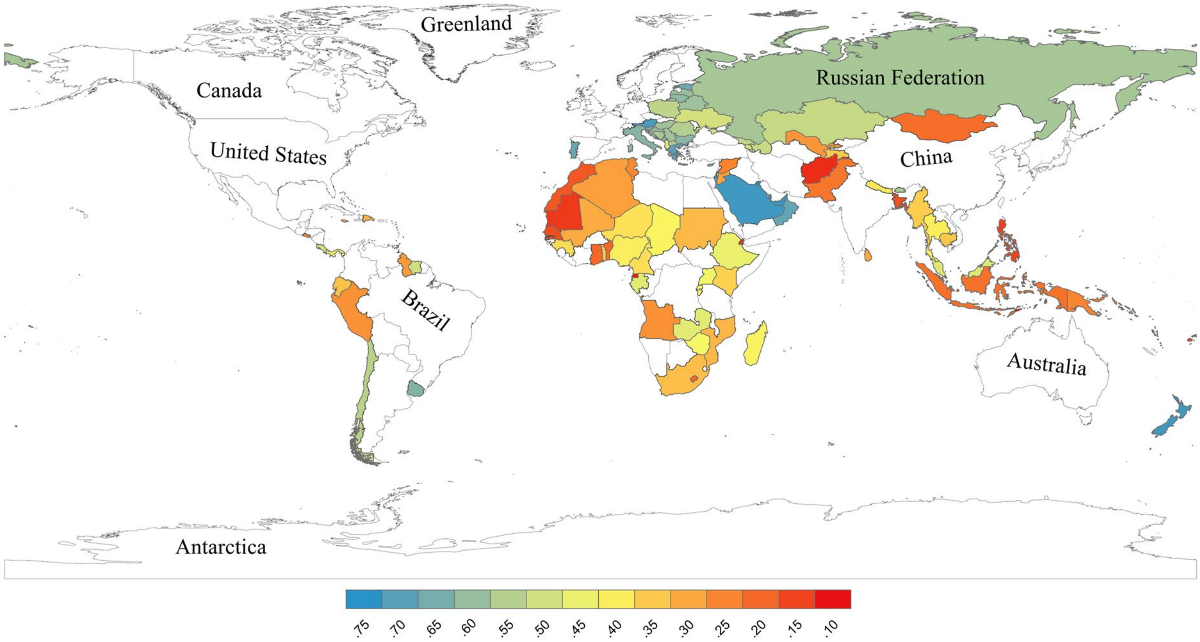


Fig. 3 Spatial distribution of energy poverty

economies and extensive energy infrastructure, and some BRI countries in the West Asia region have rich oil reserves and abundant energy resources.

Figure 4 illustrates the spatial distribution of energy poverty in Central Asia. There are three countries in this region in this study, Kazakhstan, Tajikistan, and Uzbekistan. As can be seen, two of these countries, Tajikistan and Uzbekistan, are shown in orange, which means serious energy poverty, ranking 68th and 72nd among all 82 BRI countries, respectively. Enterprise energy services and national energy supply in Tajikistan are both poor. There are only 20.0 secure web servers per million people in this country, compared to 4867 secure web servers per million people in the 82 BRI countries. On the other hand, Uzbekistan has poor energy facilities, ranking the lowest of all 82 countries. Additionally, the net installed power plant capacity per capita in this country is about 0.39 kW compared to an average of 1.09 kW for this indicator across all 82 countries, and the share of renewable energy in Uzbekistan is 2.34%, well below the average of 28.1%.

Energy poverty is polarized in West Asia, in general, as shown in Fig. 5, which shows a striking contrast in color. The figure shows that on the one hand there is a group of countries with the lowest levels of energy poverty, while on the other hand, there are two countries with more severe levels of energy poverty. Countries on the Arabian Peninsula rank well in terms of overall energy poverty performance, better than most countries. The three most energy-rich (in contrast to energy-poor) countries in this region are Kuwait, Qatar, and Bahrain; of these, Kuwait and Qatar are top-ranking of number 1 and number 2 of all BRI countries. The country with the worst energy poverty in this region is Jordan. The country has poor energy facilities, ranking 77th among all countries. The installed capacity of power plants per capita in Jordan is about 0.47 kW, while the proportion of renewable energy is about 4.55%; these values are considerably lower than the average values of 1.09 kW and 28.1%, respectively.

As shown in Fig. 6, the African region has a high number of BRI countries. Energy poverty in Africa is non-uniform, with West Africa having the severest energy poverty and Central Africa having low energy poverty. However, overall, all countries in the Africa region have warm colors, implying that energy poverty is widespread in the region. Overall, energy poverty at the household level is significant in

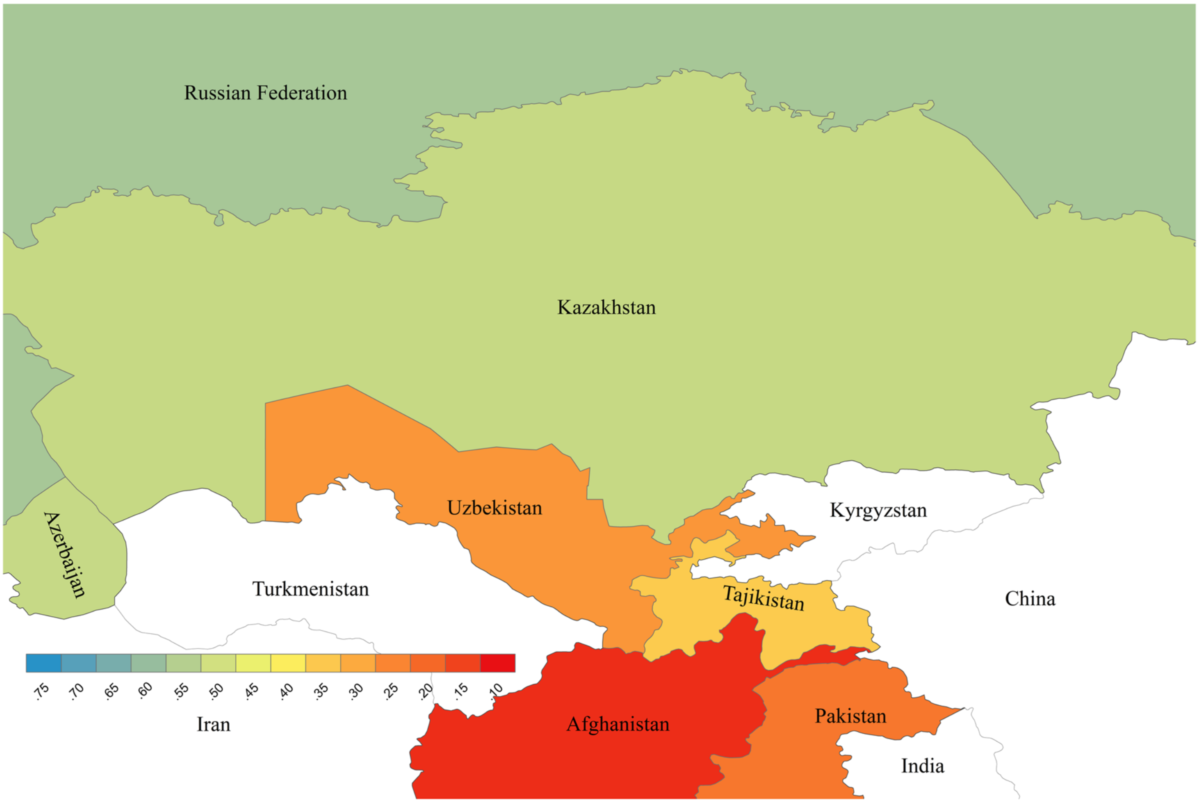


Fig. 4 Energy poverty in Central Asia

West Africa. For example, in Niger in West Africa, the per capita electricity consumption is 51.2 kWh, which is much lower than the average of 3671.3 kWh, and the percentage of the population using electricity is only 17.6% compared to the average of 90.8%. The North African, East African, and South African regions are also in the poorer half of all countries in terms of energy poverty, and there are large differences between countries. East Africa is similar to West Africa in that energy poverty is more prominent at the household level. For example, only 3.51% of the population of Ethiopia in East Africa use clean energy for cooking and heating. The four countries in the North African region vary widely, with Tunisia and Morocco being more energy poor, mainly in terms of energy supply and energy facilities. Morocco relies on imports for 90% of its energy consumption, while Tunisia has an installed power plant capacity of 0.5 kW per capita, both below-average levels.

Figure 7 shows the current state of energy poverty in Southeast Asia. Although the overall color is warm—most countries have higher levels of energy poverty in Southeast Asia—we can still see green and blue here, which means that some countries in the Southeast Asia region have less energy poverty problems, which are Singapore, Brunei, and Malaysia. Eight countries in the Southeast Asian region have widely varying levels of energy poverty. Energy poverty in Singapore, Brunei, and Malaysia are low, while the remaining five countries—Thailand, the Philippines, Indonesia, Myanmar, and Cambodia—are in the more energy-poor half of all countries. The most severe energy poverty in Southeast Asia is in Cambodia, which ranks 69th among all countries. The most prominent problems in Cambodia are in energy services, where the number of secure web servers per million people is 55, the average time for businesses to draw power is 179 days (the average is 103 days), and the power transmission loss is 23.4% (the average is 13.4%). Additionally, all five countries have higher levels of energy poverty at the household level, with most indicators being below-average values.

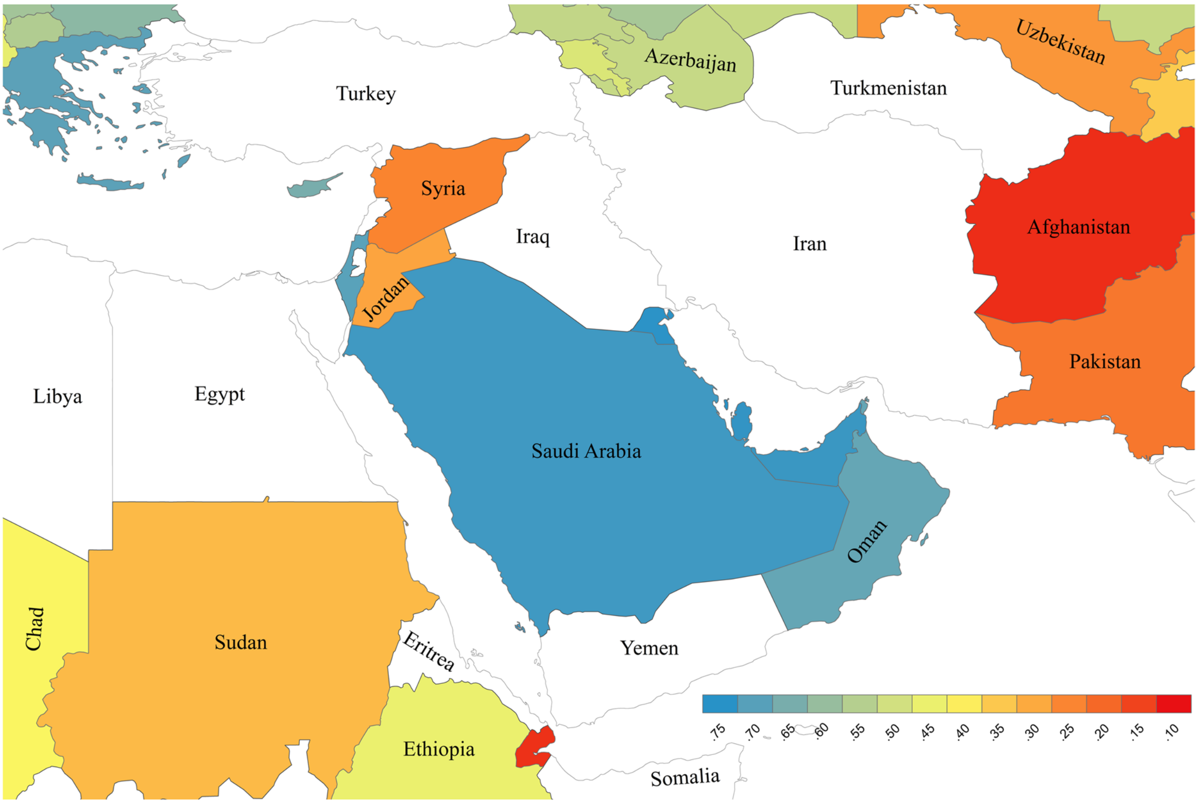


Fig. 5 Energy poverty in West Asia

Figure 8 shows the spatial distribution of energy poverty in South Asia. It is striking that this region is very "red," meaning that energy poverty is very high. Four countries in South Asia are compared, all of which are in the more energy-poor half of the countries. Energy poverty is prominent in Bangladesh and Pakistan, which are ranked 79th and 80th, respectively. In addition to poor energy services, which are common in countries with severe energy poverty, Bangladesh performed poorly in terms of modern energy needs, cooking, and heating. The percentage of the population with internet access in Bangladesh is only 4.5% compared to the average of 38.0%, and only 17.72% of the population has access to clean energy, which is one of the lowest values of all countries. Pakistan, on the other hand, has a more serious problem with the energy cost for businesses, with an electricity price of 20.8 US cents per kWh compared to an average of 14.4 US cents per kWh, and a cost of electricity extraction of 1350.5% of income per capita compared to the average of 878.2% of income per capita.

The last region is Europe, which is shown in Fig. 9. In Europe, data are obtained from 23 countries that have joined the Belt and Road Initiative with China. In the figure, the European region is shown in blue and green. These countries have low energy poverty, but there are still seven countries—Montenegro, Serbia, Albania, Ukraine, Bosnia and Herzegovina, Belarus, and North Macedonia—that are in the more energy-poor half of the countries. One of the countries with the most severe energy poverty is North Macedonia. The main problem is energy supply as the country is a net energy importer, with net energy imports accounting for 49.6% of energy consumption. Additionally, the country's per capita energy use is 1300.82 kg of standard crude oil compared to a global average of 2476.5 kg of standard crude oil.

Pakistan, Senegal, and Jamaica have the most severe energy poverty of the 82 BRI countries. These countries are in South Asia, West Africa, and the Caribbean, respectively. We use radar charts to show the current status of energy poverty in these three countries

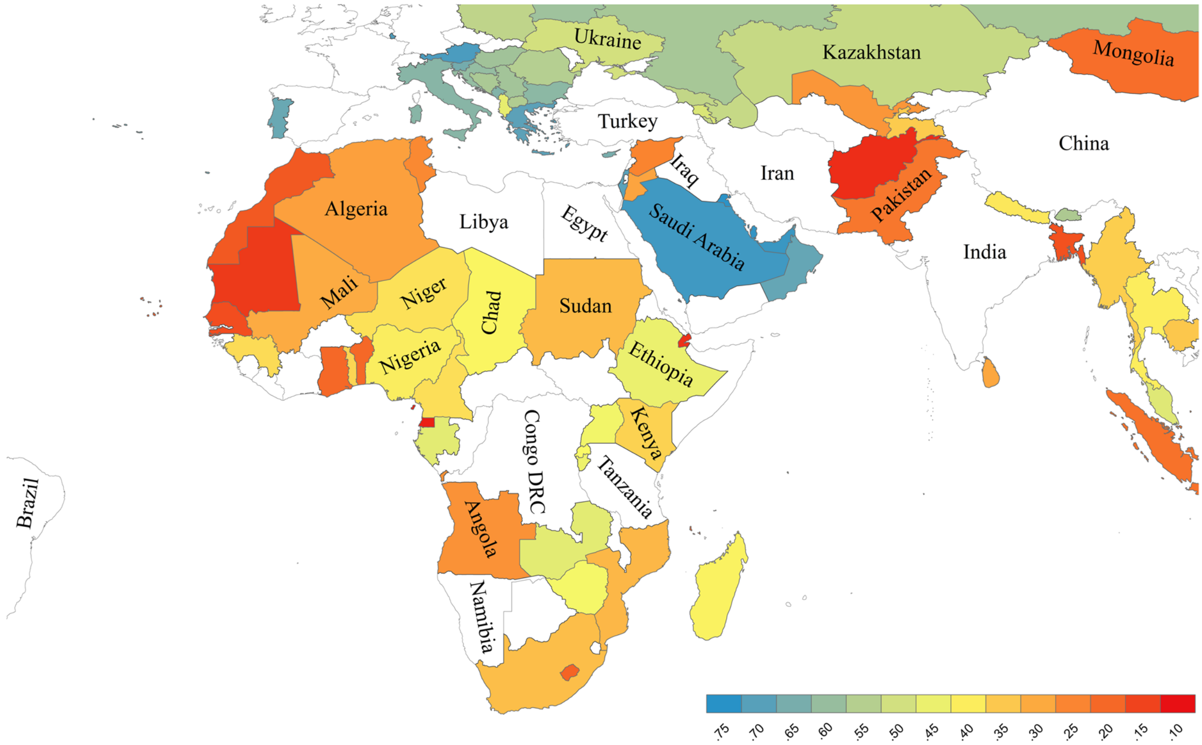


Fig. 6 Energy poverty in Africa

in different aspects, as shown in Fig. 10. It can be seen from the chart that these three countries perform better in cooking and weaker in electricity. The current status of energy poverty in Pakistan is more severe, which is consistent with the findings of many researchers (Sher et al., 2014). As previously stated, Pakistan has a more serious energy cost of business issue, with an electricity price of 20.8 US cents per kWh and an electricity extraction cost of 1350.5% of per capita income. In Senegal, the energy costs and energy supply are poor: the price of electricity is 23.1 US cents per kWh and the cost of electricity is 57.5 times the income per capita. However, the country has good energy efficiency, ranking 33rd of the 82 countries, and the coal, oil, and gas rents are only 0.01% of GDP, better than the average of 6.4%. Jamaica, the country with the worst energy poverty status of all 82 countries, has poor energy supply and energy facilities. The country is dependent on energy imports, which accounted for 82.5% of total energy use, and its installed power plant capacity per capita is only 0.36 kW, well below average. However, the country is less energy poor in cooking and heating, with a clean energy use rate of 90.5%, above the average of 74.1%.

Additionally, as shown in Fig. 11, three countries in the middle range of energy poverty are analyzed. Zambia, Nigeria, and Greece ranked near the median at 40, 41, and 42 out of the 82 countries in terms of energy poverty, respectively. Although Greece is the lowest-ranked country, it outperforms the other two countries in three areas: cooking, modern, and efficiency, which are more clearly reflected in the graph. Energy poverty is severe at the household level in Zambia and Nigeria, where the use of clean energy is 16.43% and 4.91%, respectively; both values are well below the average (74.1%). In Greece, energy poverty is low at the household and business levels but severe at the national level. The most prominent problem is the national energy supply, which ranked 57th among all countries due to its relative dependence on imports: imported energy accounted for 60.1% of the energy supply.

Among the 82 countries, the three countries with the lowest energy poverty levels are Kuwait, Qatar,

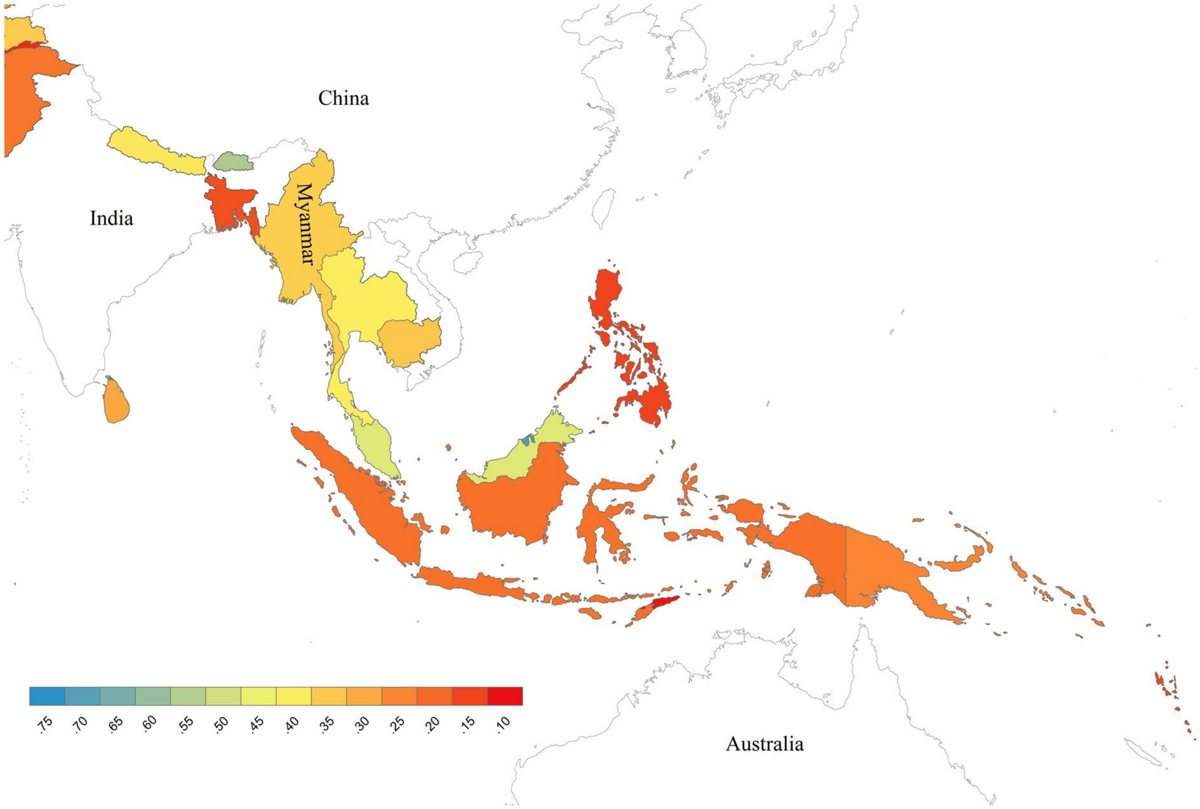


Fig. 7 Energy poverty in Southeast Asia

and Singapore. Again, the radar plots for these three countries are shown in Fig. 12. Although the "shaded area," which shows their performance, is larger in the plot, all three countries have shortcomings in certain areas. The former two are located on the Arabian Peninsula on the Persian Gulf coast. Their land area is small and the income mainly depends on oil extraction. Singapore is one of Asia's important financial, service, and shipping centers. All three countries are at the forefront of electricity use, energy facilities, and energy burden. The annual per capita electricity consumption of Kuwait, Qatar, and Singapore is 15,590.6, 14,781.6, and 8844.69 kWh, respectively, which are much higher than the average global value of 3671.2 kWh. Additionally, Singapore's enterprise energy services are among the best in all countries, with 58,690.3 secure network servers for one million people. Kuwait and Qatar are relatively less energy efficient than Singapore; their coal, oil, and gas rents are 55.1% and 31.1% of the GDP, respectively, well above average.

Discussion

Robustness of the method

A major step in our proposed integrated assessment method is entropy weights, and changes in the alternative sample may cause the weights of each indicator to change. In addition, different alternative samples may also make the assessment results based on the TOPSIS method change. These two issues imply that changes in the sample may have an impact on the final assessment results. Therefore, robustness of the proposed integrated approach is tested by changing the alternative sample.

In this study, we study 82 countries along the Belt and Road, and here, we change the population to all countries for which data are available globally, for a total of 111 countries. The results are that the countries with the least energy poverty are Iceland, Kuwait, and Qatar, which is consistent with our experience. If non-BRI countries are excluded, the least

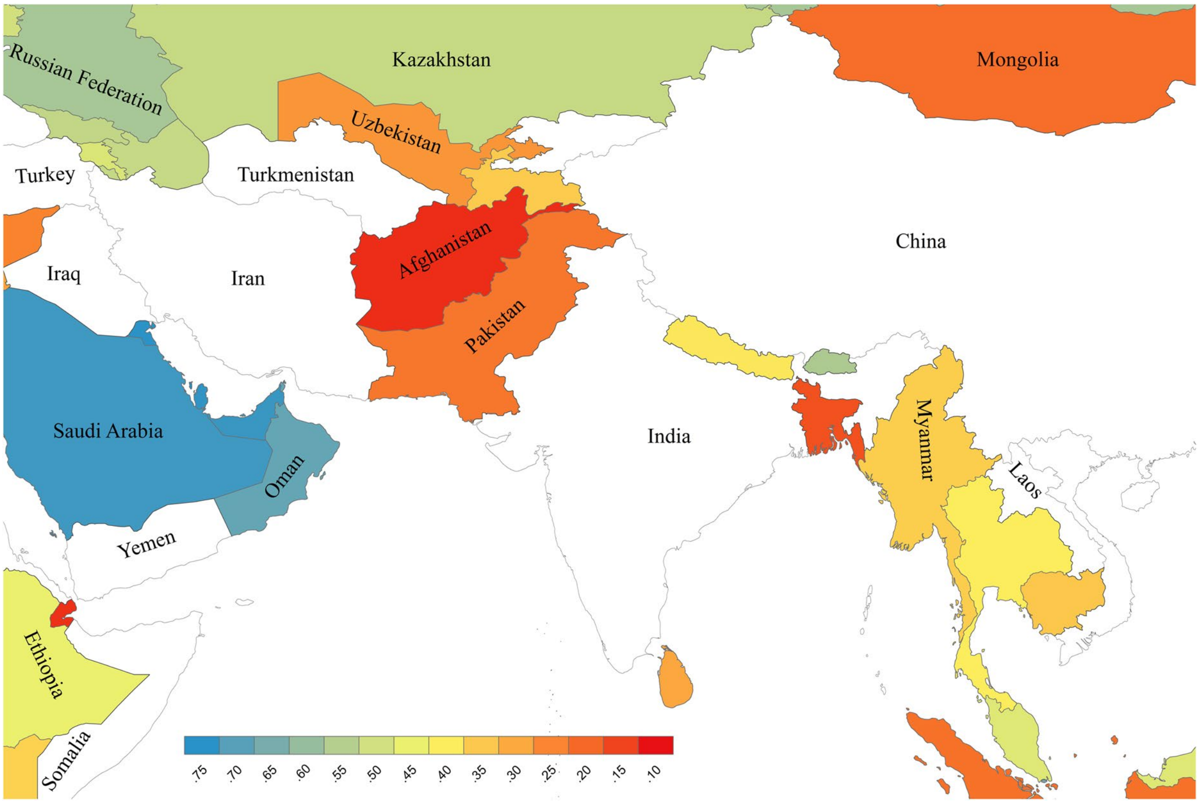


Fig. 8 Energy poverty in South Asia

energy-poor countries are Kuwait, Qatar, Trinidad and Tobago, and Singapore, while the most energy-poor countries are Jamaica, Senegal, and Pakistan, all of which are BRI countries, which is consistent with the previous findings. This demonstrates the robustness of our proposed research methodology and its applicability to different applications.

Energy poverty and economic growth

In addition to assessing energy poverty across countries, this study observes the relationship between energy poverty and economic growth as well. The results of the correlation analysis show that the energy poverty level of 82 countries has a significant correlation with the logarithm of per capita GDP. The Pearson correlation coefficient and Spearman correlation coefficient between the two are 0.6804 and 0.7052, respectively; energy poverty is highly correlated with economic level. That means the more economically developed the region, the better the status of energy poverty.

To show the relationship between GDP and energy poverty more visually, we plotted a scatter plot and fitted curve of energy poverty versus the logarithm of per capita GDP. The fitted curves were obtained by simple linear regression. We constructed a simple linear regression model.

$$\mathrm{EP} = \alpha + \beta \mathrm{GDP} + \epsilon \tag{11}$$

After estimation, we get α and β, resulting in a curve: $y = \alpha + \beta x$, which is the fitted curve.

Figure 13 represents the fitted curve of the natural logarithm of energy poverty level versus GDP per capita. The gray part is the confidence interval at the 90% level. The samples below the fitted curve are more energy poor for the same level of GDP per capita. All samples are divided into four groups based on the fitted curve and the mean of the natural logarithm of GDP per capita: A, B, C, and D. Because group A has the

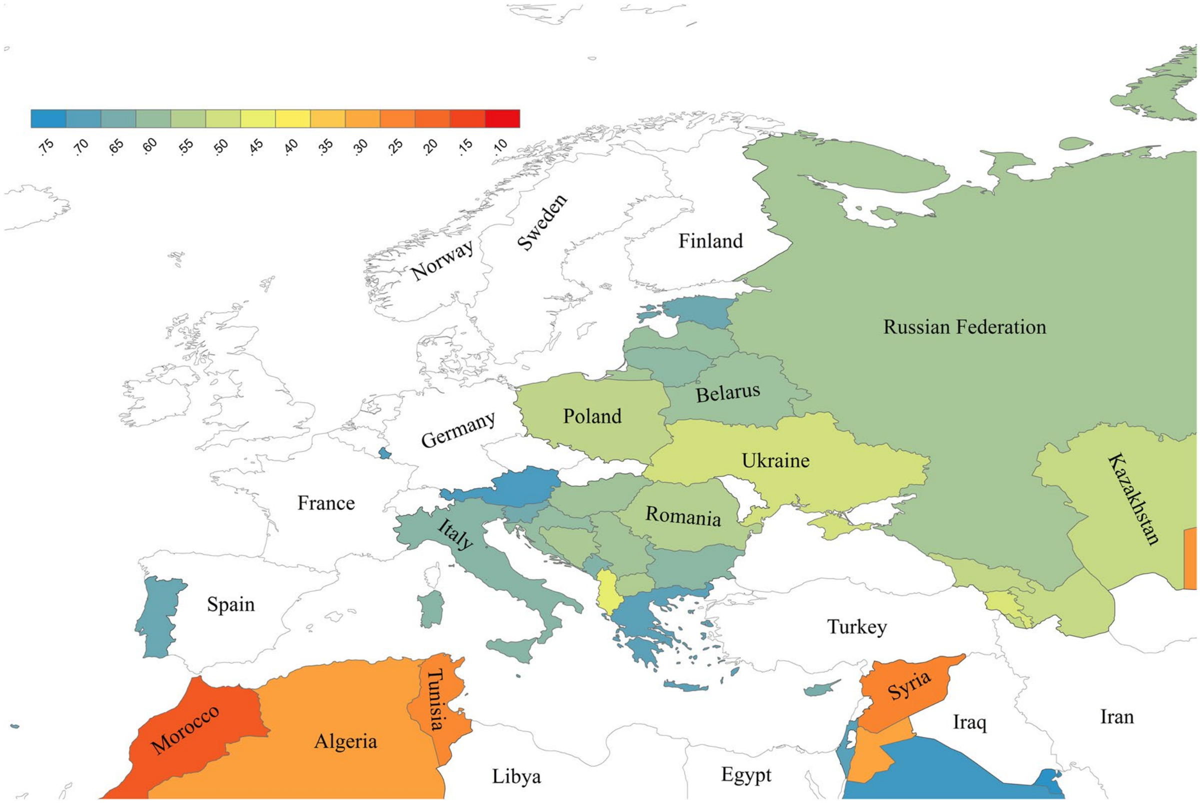
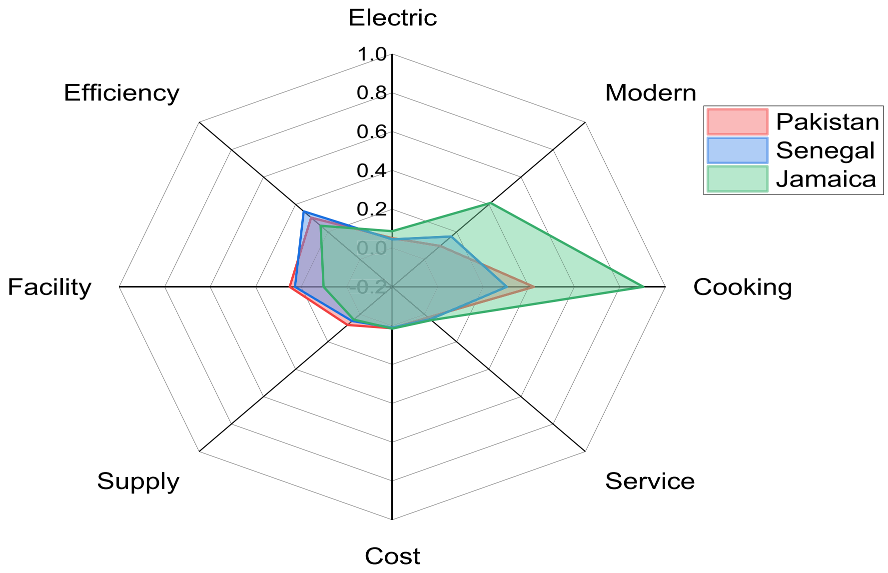


Fig. 9 Energy poverty in Europe

Fig. 10 Energy poverty in Pakistan, Senegal, and Jamaica



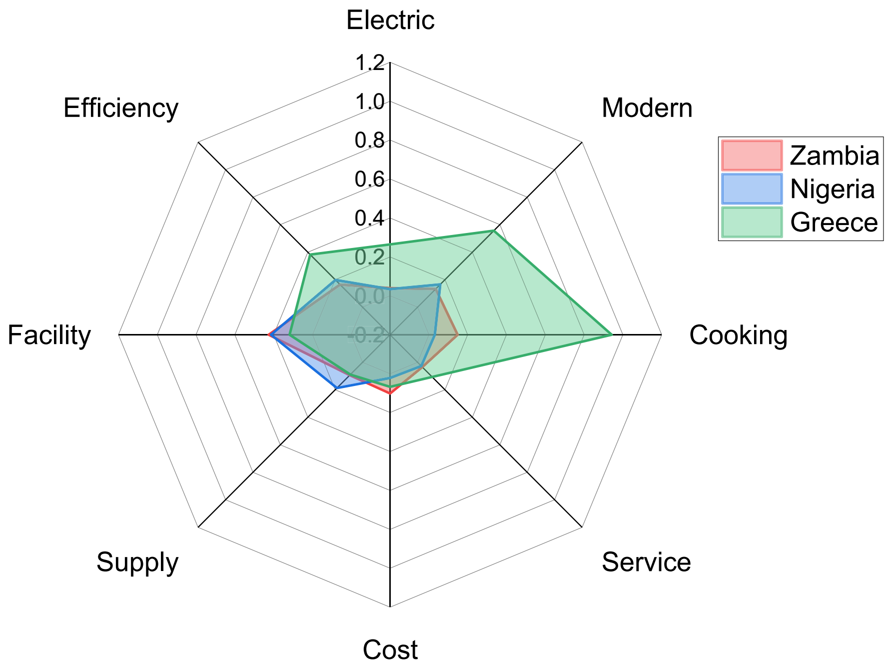


Fig. 11 Energy poverty in Zambia, Nigeria, and Greece

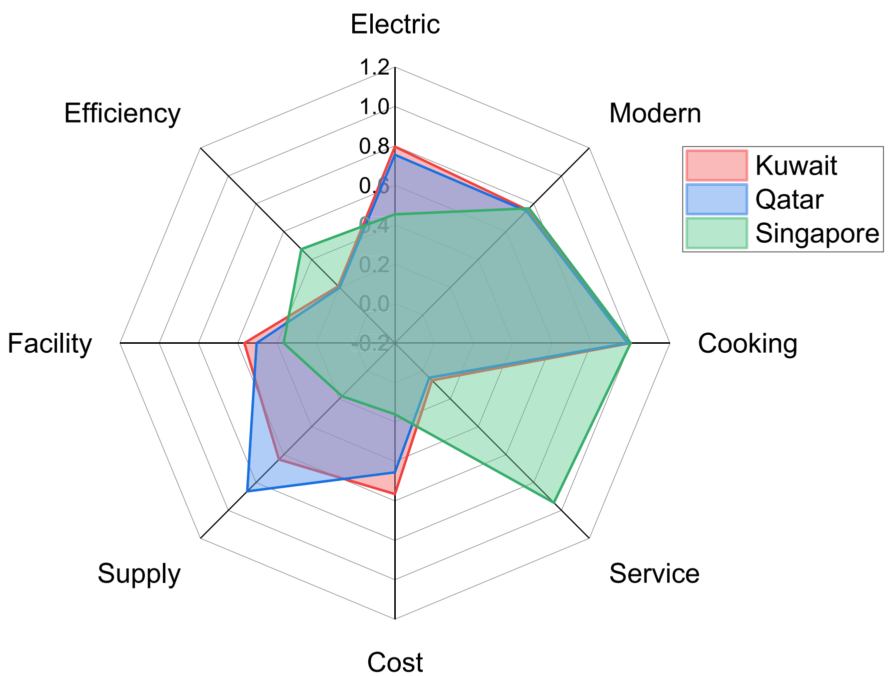


Fig. 12 Energy poverty in Kuwait, Qatar, and Singapore

most samples (25), the samples in this group have a higher level of economic and energy difficulty. As a result, the instances in group A are more noticeable. To make it easier to compare group A to other groups, we have normalized and standardized the data and then determined each indicator's mean in each group, as shown in Table 3. The mean, standard deviation, and mean standard deviation after normalization and standardization are denoted as mean, std. dev., and mean std., respectively (Table 3). Individuals who use

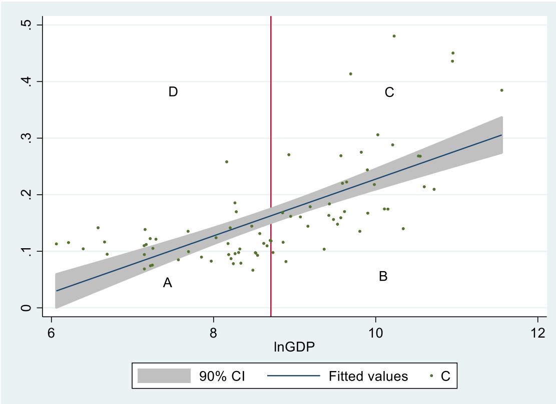


Fig. 13 The fitting curve for natural logarithms of energy poverty levels and GDP per capita

the internet, total net installed capacity of electric power plants, and electric power consumption all related to the three levels of households, enterprises, and nation, which exhibit the most variations between group A and the other groups. On the other hand, energy poverty is mainly driven by a lack of national energy infrastructure.

Conclusions

In this study, energy poverty in 82 BRI countries was evaluated. Measurement of energy poverty in each country was carried out at three levels: household, enterprise, and nation. The TOPSIS method was used to obtain a more comprehensive picture of energy poverty in the BRI countries.

In terms of regional distribution, energy poverty in West Asia and Europe was low but there were shortcomings in some categories. Energy efficiency in West Asia was generally low, with most countries in this region performing poorly in this area. Twenty-three European countries also had low energy efficiency, but the situation was as serious as in West Asia. The energy poverty in South Asia, Southeast Asia, and North Africa was pronounced. Energy poverty in South Asia and Southeast Asia was more severe at the household level, but the overall performance of Southeast Asia was better than that of South Asia.

The three countries with the lowest energy poverty were Kuwait and Qatar, and Singapore, one of Asia's major financial, service, and shipping centers. All

Table 3 Mean value of each indicator in the subgroup

Variables	Group A			Group B, C, and D		
	Mean	Std. dev	Mean std	Mean	Std. dev	Mean std
LnGDP	8.155	0.461	8.155	8.950	1.382	8.950
EG_USE_ELE ~ C	1927.398	1337.349	0.096	4436.107	4378.985	0.224
Elc_Accs	95.429	9.240	0.945	88.780	21.927	0.864
IT_CEL_SETS_P2	117.799	24.467	0.480	120.501	36.126	0.497
IT_NET_USER_ZS	28.077	14.810	0.305	42.316	26.297	0.465
Cft_Accs	72.148	26.808	0.716	74.956	34.617	0.745
Sta_Airp	89.192	47.929	0.273	75.596	69.200	0.228
IT_NET_SECR_P6	1210.723	2211.125	0.021	6471.488	11,380.230	0.110
IC_ELC_TIME	121.264	82.693	0.215	95.888	48.452	0.272
EG_ELC_LOSS_ZS	14.407	9.304	0.821	12.941	10.761	0.842
Elc_Pri	15.824	8.116	0.039	13.718	7.323	0.071
ELC_COST	965.720	1247.696	0.027	839.767	1426.273	0.121
EG_USE_PCAP_KG_OE	1176.337	763.083	0.060	3046.691	3485.794	0.169
EG_IMP_CONS_ZS	20.337	67.922	0.113	−44.760	154.215	0.207
Elc_Plant	0.629	0.425	0.132	1.289	1.124	0.274
EG_FEC_RNEW	21.192	13.484	0.236	31.135	28.954	0.347
NY_ADJ_DNGY_GN_ZS	0.814	1.735	0.948	1.941	3.333	0.876
PEI	4.842	2.136	0.308	5.462	3.115	0.292
NY_GDP_FUE ~ T	3.847	9.185	0.930	7.531	12.396	0.863

Std. dev. refers to standard deviation, and mean std. signifies mean standard deviation three countries had superior electricity use, energy cost, and energy facilities, but Kuwait and Qatar were less energy efficient than Singapore. The three countries with the most severe energy poverty among all 82 countries were Pakistan, Senegal, and Jamaica. Except for in Jamaica, where energy poverty was low for cooking and heating, energy poverty in all other categories was severe.

We found that a country's energy poverty manifests as a lack of energy infrastructure and supplies in more impoverished areas. As a result, policymakers must prioritize the development of energy infrastructure. Given that one of the BRI's key goals is to improve collaboration in infrastructure development, it is likely that the BRI will take the lead in this area. Investment in BRI countries should focus more on energy infrastructure development, resulting in a favorable impact on promoting sustainable energy use in these countries.

The contributions of this study were mainly considered as follows: firstly, it originally established an evaluation framework which was formed by 3 aspects. This analytical framework reflects not only the current state of energy poverty among households, but also the level of energy supply in a country, which is more decisive for energy poverty in low-income countries. Such a research framework more intuitively informs policy makers. Second, we try to establish a research framework that can include different countries and expand the study to countries along the Belt and Road Initiative, which can give researchers and policy makers a global view to observe the spatial distribution of energy poverty and also provide a reference for related international cooperation.

Policy implications

The integrated assessment approach proposed in this study combines the entropy weight method and TOPSIS method, which not only can accurately identify the information contained in each indicator, but also effectively overcome the issue of subjectivity in setting weights. And applying this approach to the energy poverty assessment indicator system proposed in this study can help countries to explore effective mechanisms to alleviate energy poverty. The approach is robust, and the results of the robustness tests show that the integrated approach is applicable to the assessment of energy poverty not only in BRI countries, but also in all countries worldwide.

Our findings can provide an objective reference for authorities to formulate policies to alleviate energy poverty. Countries in southern Asia and sub-Saharan Africa, where energy poverty is most severe, deserve the world's collective attention. First, energy infrastructure is the main obstacle to alleviating energy poverty. Therefore, the government needs to develop energy infrastructure to enhance energy accessibility and energy modernity in order to effectively alleviate energy poverty. Second, energy cleanliness is also an important obstacle to energy poverty alleviation, and policy makers need to pursue relevant policies that promote clean energy use, including on the supply side. And all of this requires active international cooperation.

Study limitations and future research direction

The following are some of the study limitations that can be considered: first, due to data limitations, this article does not fully cover all indicators that can be used to define energy poverty. Second, due to data limitations, this study can only look at each country's level of energy poverty in 2016, not variations in energy poverty. Third, rather than focusing on the causes of energy poverty, this study focuses on the actual situation of energy poverty in countries along the Belt and Road Initiative. In future studies, we wish to cover more indicators and more countries based on available data to compare the new findings to this study's results. In addition, we wish to discuss more related factors that affect energy poverty. To conclude, given COVID-19's current global impact, which will undoubtedly influence energy poverty in all nations, future research must integrate this worldwide crisis and examine its implications for sustainable energy use. Similarly, energy poor groups share this distress. This implies that there may be a way to address energy poverty and climate change simultaneously. And this is one of our upcoming research programs in the near future.

Funding This study is supported by "Southwestern University of Finance and Economics 2022 Special Project for Studying and Implementing the Spirit of the Central Economic Work Conference, grant no. JBK2212030."

Declarations

Conflict of interest The authors declare no competing interests.

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