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Multidimensional Assessment and Alleviation of Global Energy Poverty Aligned With UN SDG 7

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There are increasing concerns that energy poverty across nations is weakening the global efforts toward achieving Sustainable Development Goals (SDGs). A systematic assessment of energy poverty is, therefore, essential to track the spatiotemporal pattern of SDG 7 and monitor the global efforts in alleviating energy poverty. This article develops the first Multidimensional Energy Poverty Assessment Index (MEAI), incorporating energy availability, affordability, and efficiency applicable to quantify the spatiotemporal dynamics of energy poverty development at global, regional, and national scales. Our analyses indicate that the overall MEAI and indices in all dimensions decreased from 2001 to 2016 at a global level with energy affordability experiencing the highest decline. The MEAI at the national level declines within the same period, showing significant regional heterogeneity in terms of the sub-index. Energy efficiency in developed and less-developed regions is characterized by high carbon emissions and low energy modernization, respectively. The energy availability indices are lower in developed nations and in nations with abundant energy resources. Overall, our results highlight a sudden increase in MEAI for Central America in 2014 and a gradual decline in MEAI for East Asia during 2014–2016. A call for regional actions is critically needed to solve energy poverty from different facets.

Keywords: energy poverty, multidimensional energy poverty assessment index (MEAI), energy availability, energy affordability, energy efficiency

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INTRODUCTION

Energy poverty has received growing attention worldwide in both academic communities and political agendas in recent years. The United Nation's Sustainable Development Goal 7 (SDG 7) refers specifically to energy poverty and aims to achieve universal access to affordable, reliable, sustainable, and modern energy services by 2030. However, there is no internationally consistent definition of energy poverty. It is usually considered a situation where households are unable to adequately meet their energy needs at an affordable cost (Dobbins et al., 2019),thus thwarting efforts to achieve Sustainable Development Goals (SDGs). A lack of access to modern energy causes severe health problems, including cardiovascular, cerebrovascular, and respiratory disorders (SDG 3: Good Health and Well-Being), blunts future generation's opportunity to reach satisfactory lifestyles (SDG 10: Reduced Inequalities), results in global deforestation and climate change (SDG 13: Climate Action), and affects many of the SDGs (Chapman et al., 2019). To fight energy poverty with sound policies and measures, a systematic and comprehensive assessment of energy poverty is of necessity for human sustainability.

TABLE 1 | Indicators selected for each of the dimensions.

Dimensions	Indicators	Attribute
Energy availability(0.3492)	Household energy consumption per capita (0.3375)	–
	Household electricity consumption per capita (0.3430)	–
	Proportion of population with access to electricity (0.3195)	–
Energy affordability(0.3278)	GDP per capita (0.3416)	–
	Household disposable income per capita (0.3710)	–
	Cellphone ownership per 100 people (0.2874)	–
Energy efficiency(0.3230)	Proportion of population with access to clean fuels and technologies for cooking (0.1914)	–
	Ratio of biomass and waste consumption on total final household energy consumption (0.2052)	+
	Household CO_2 emissions per capita (0.2051)	+
	Ratio of non-solid commodity energy on household commodity energy (0.1903)	–
	Proportion of non-thermal electricity generation on electricity generation (0.2080)	–

Note: the numbers within parentheses were weights derived from the large-scale survey.

Energy poverty is considered a multidimensional concept, including socioeconomic challenges, environment climate concerns, and so on. Multidimensional energy poverty measurement attempts to capture various dimensions and results of energy poverty and has become the prevailing method of assessing energy poverty. Jayasinghe et al. (2021) examine the incidence, intensity, inequality, and determinants of energy poverty in Sri Lanka by constructing the Multidimensional Energy Poverty Index (MEPI). Gafa and Egbendewe (2021) proposed a new multidimensional measure to evaluate the levels and determinants of energy poverty in rural West Africa. Halkos and Gkampoura (2021) examined energy poverty for 28 selected European countries, using a composite measurement. We found that previous studies are limited to a particular country or region, and rarely studies are found to assess global energy poverty by using multidimensional energy poverty measurement. The study by Che et al. (2021) is an attempt to assess global energy poverty with an integrated approach. However, the score for a sample country is relative closeness that is better suited to national ranking and the calculation process of this integrated approach is complicated.

Hence, based on the study by Che et al. (2021), we construct a Multidimensional Energy Poverty Assessment Index (MEAI) that not only reflects the reality of energy poverty but also is relatively simple to calculate. The MEAI takes into a set of multiple dimensions to represent the overall performance toward alleviating energy poverty. It is an aggregate index with fixed weights for sub-dimensions/indicators by their importance. With such a universal index, it makes the comparison of energy poverty possible at the national level (Xu et al., 2020).

METHODOLOGY

Indicator Selection and Data Sources

To get a full picture of energy poverty at national, regional, and global levels, the MEAI is designed and composed of three dimensions: energy availability, energy affordability, and energy efficiency, as shown in **Table 1**. Households lack access to modern energy due to unreliable energy supply, inadequate energy infrastructure, and tenure status or structural fabric of the building (Bouzarovski and Petrova, 2015). Low incomes keep households from affording basic levels of energy needed to attain a socially and materially necessitated level of energy services (Buzar, 2007). In addition, the inefficient use of an appliance contributes to indoor air pollution, and the combustion process of solid energy exacerbates climate change (Casillas and Kammen, 2010; Liu et al., 2016).

For each dimension, we chose as many corresponding indicators as deemed feasible from previous studies, based on data availability at the national, regional, and global levels and temporal scales. 1) Energy availability refers to a lack of access to modern energy. Household energy consumption per capita was used to measure the energy consumption. For household energy consumption, electricity is found superior to other energies because it is more efficient and could serve all energy-end uses. Therefore, household electricity consumption per capita was used to describe the access to modern clean fuels. Adequate energy supply is a precondition to access energy services. As a result, the proportion of population with access to electricity was selected as an indicator for the reliability of energy supply. 2) Energy affordability means that the energy cost is too high for householders to pay. According to the energy ladder hypothesis, GDP per capita and household disposable income per capita were used to measure the burden of energy costs. The number of household appliances reflected a household's ability to pay for modern energy and efficient equipment. Communication equipment played a key role in social life, and cellphone ownership per 100 people, therefore, was taken into account. 3) Energy efficiency considers the quality of household energy consumption from low-carbon development and modernization of energy consumption structure. The proportion of population with access to clean fuels and technologies for cooking and ratio of biomass and waste consumption on total final household energy consumption was used to explain the modernization of energy consumption structures. Household CO_2 emissions per capita, ratio of non-solid commodity energy to household commodity energy, and the proportion of non-thermal power generation on electricity generation were used to evaluate low-carbon development.

Data for "household energy consumption" were obtained from the following authoritative sources: the World Energy Balances, the Energy Balances of OECD Countries, and the Energy Balances of Non-OECD Countries. Data for "household CO_2

emissions" were from the CO_2 Emissions from Fuel Combustion. Data for "proportion of population with access to electricity," "gross domestic product" (GDP)," "household final consumption expenditure," "cellphone ownership per 100 people," "proportion of population with access to clean fuels and technologies for cooking," "proportion of non-thermal electricity generation on electricity generation," and "national population" were from the World Bank Open Data. GDP and "household final consumption expenditure" were adjusted with purchasing power parity (PPP) dollars in 2011 to remove the effect of exchange rate volatility and inflation.

Normalization of Indicator Values

The indicator values for each dimension were normalized in order to ensure comparability across dimensions. Traditional normalized approaches used annual values for the mean and standard deviation of each indicator as the criterion of normalization, which varied over time. The normalized indicator values were incomparable across time scales, and the MEAI only reflected the spatial distribution of energy poverty. However, the fixed base difference method chose the values of benchmark year indicators as the unified criterion of the annual values for 2001–2016 for the selected indicator metrics of each dimension, which objectively reflected the spatiotemporal dynamics of progress toward alleviating energy poverty at the global, regional, and national levels.

We converted negative indicators into positive indicators by using the equation$x_{ij}^{'} = -x_{ij}$and then followed the fixed base difference method to normalize the global, regional, and national data arrays for each dimension indicator. The following formula was used to normalize dimension indicator values toward meeting a dimension target at the global, regional, and national levels:

$$X_{ij}^{l} = \frac{V_{ij}^{t} - V_{ij,min}^{t_0}}{V_{ij,max}^{t_0} - V_{ij,min}^{t_0}} \times 100, \tag{1}$$

where V_{ij}^{t} was the original data value of each dimension indicator at time t, $V_{ij,max}^{t_0}/V_{ij,min}^{t_0}$represented the maximum/minimum original data values at time t_0(the benchmark year) for the worst/best performance, and $X_{ij}^{l}$was the normalized individual value for a given dimension indicator. A lower normalized dimension index indicated better performance toward alleviating the dimension. All normalized values greater than 100 meant that the indicators at time t were significantly worse than those at time t_0, and all normalized values less than 0 meant that the indicators at time t were significantly better than those at time t_0. We normalized the data across global, regional, and national levels simultaneously so that the dimension indices were comparable across regions and nations.

Weight of Indicator

The weights of indicators had a significant impact on the MEAI. Our study period was 16 years. The indicator weights were differentiated annually by using the objective weighting approaches, which were not suitable to conduct dynamic research. Hence, we weighted all dimensions and indicators within each dimension, respectively, by using a large-scale survey. Corresponding scores were based on the Likert scale, where (4,5]—very important; (3,4]—important; (2,3]—fair; (1,2]—unimportant; and (0,1]—very unimportant.

The survey began in August 2019 and lasted for 2 months. Thousand questionnaires were sent out by E-mail all over the world, and 581 valid questionnaires were collected. In the valid sample, the respondents were from China, the United States, the United Kingdom, and other countries, respectively. Authoritative experts, such as Yin Jinyue (KTH Royal Institute of Technology) and Wang Zhaohua (Beijing Institute of Technology), accounted for 4.0%; teachers and researchers from internationally renowned universities, such as the Chinese Academy of Sciences and the National University of Singapore, accounted for 51.1%; and Master's and doctoral students accounted for 32.5%. Most of the respondents were familiar with energy poverty and could score the indicators objectively. Hence, the weights of the indicators were convincing.

According to the theory of random error, the extreme scores had negative impacts on the reliability of the results. The Pauta Criterion (3δ) was used to remove extreme scores in order to minimize the potential effects of skewed data distribution on the weights of indicators. According to the actual calculation results, K was defined as 2.

$$\mu_k + 2\sigma_k > P_k > \mu_k - 2\sigma_k, \tag{2}$$

where$P_k$was the score of indicator k and $\mu_k$and$\sigma_k$were the mean value and standard deviation, respectively. The weight was based on the proportion of the average score of each dimension/indicator after the extreme scores were removed.

Calculation of the Multidimensional Energy Poverty Assessment Index and Individual Dimension Index Over Time

We calculated the MEAI at the global, regional, and national levels by using arithmetic means. The MEAI was an aggregate index that consisted of individual indices for all three dimensions and represented global, regional, or national overall progress in alleviating all dimensions over time. The individual dimension index was yielded by multiplying the indicator values within each dimension with the assigned weights.

$$X_i = \sum_{j=1}^{n_i} \omega_{ij} X_{ij}, \tag{3}$$

where$X_i$was the individual dimension index, $X_{ij}$and ω_{ij}were the values of indicator and the weight within each dimension, and $n_i$was the total number of indicators within each dimension.

We aggregated all three dimensions into one global/regional/national MEAI for each year from 2001 to 2016, which was defined as follows:

$$Z = \sum_{i=1}^{3} \omega_i X_i, \tag{4}$$

where Z was what the study called the MEAI ,and$\omega_i$was the weight of each dimension.

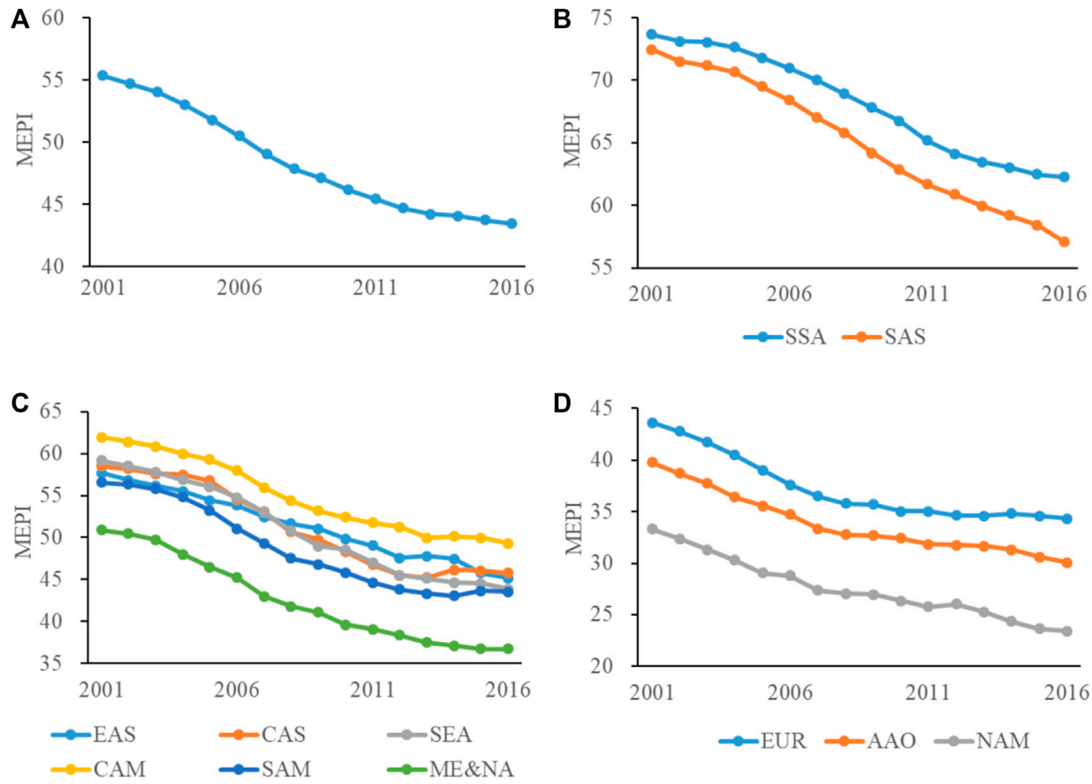

FIGURE 1 | Change in the MEAI from 2001 to 2016. **(A)** At the global level. **(B–D)** At the regional level. North America is the abbreviation for NAM, Central America for CAM, South America for SAM, Middle East and North Africa for ME&NA, sub-Saharan Africa for SSA, Europe for EUR, Central Asia for CAS, East Asia for EAS, Southeast Asia for SEA, South Asia for SAS, and Australia and Oceania for AAO.

RESULTS AND DISCUSSIONS

Characteristics of Global Energy Poverty

We compiled annual time series data relevant to energy poverty from 2001 to 2016 for 125 countries. In total, 11 indicators were used in this assessment. These indicators allow us to calculate the three dimensions of energy poverty (including energy availability, energy affordability, and energy efficiency) and the MEAI at global, regional, and national levels. **Figure 1** shows that the MEAI at the global level decreased gradually over time, which was mainly attributed to the improvement of the energy affordability. The global MEAI decreased by approximately 27.4% from 55.3 in 2001 to 43.4 in 2016. Specifically, we found a clear distinction before and after the year 2008. The average annual decrease rate of the global MEAI after 2008 was 1.13% compared to that of 1.71% before 2008. This reveals that although global energy poverty was alleviated gradually, the financial crisis in 2008 may have had a permanent and negative impact on energy poverty alleviation. This may be because that the crisis increases unemployment and reduces household disposable income.

Figure 1 also presents the changes in the MEAI from 2001 to 2016 at the regional level. The mean value of the MEAI at the regional level declined by 22.3% between 2001 and 2016. In 2001, the MEAI ranged from 33.3 to 73.7 with a mean value of 55.2. The mean value decreased to 42.9 from 2016. East Asia's MEAI experienced a continuous decline with that of China as the largest contributor in this region. China reached full electrification in 2015, which has a significant effect in reducing the MEAI in East Asia. It is worth noticing that the MEAI in Central America suddenly increased by 2.08% from 45.2 in 2013 to 46.2 in 2014, respectively, suggesting that substantial changes in alleviating energy poverty occurred across different regions.

The mean value of the MEAI for all 125 nations is 48.5, as we can see from **Figure 2**. The national average MEAI of 66 countries is higher than the mean (48.5), accounting for 52.8% of our sample (**Figure 2**). The world is still suffering from energy poverty and, over time, all nations decreased their MEAI from 2001 to 2016 with significant spatial heterogeneity, ranging from 15.1 in Norway to 77.9 in Congo (*10*).

Figure 3 illustrates the changes in dimension indices: energy availability, energy affordability, and energy efficiency. At the global level, all dimension indices decreased over time. Energy availability and energy affordability were the key drivers for the MEAI. The three dimensions, in order of the greatest to least decline, were energy affordability, energy availability, and energy efficiency, and the decline in energy affordability was substantially higher than the others. At the regional level, the changes in energy availability from 2001 to 2016 were greater

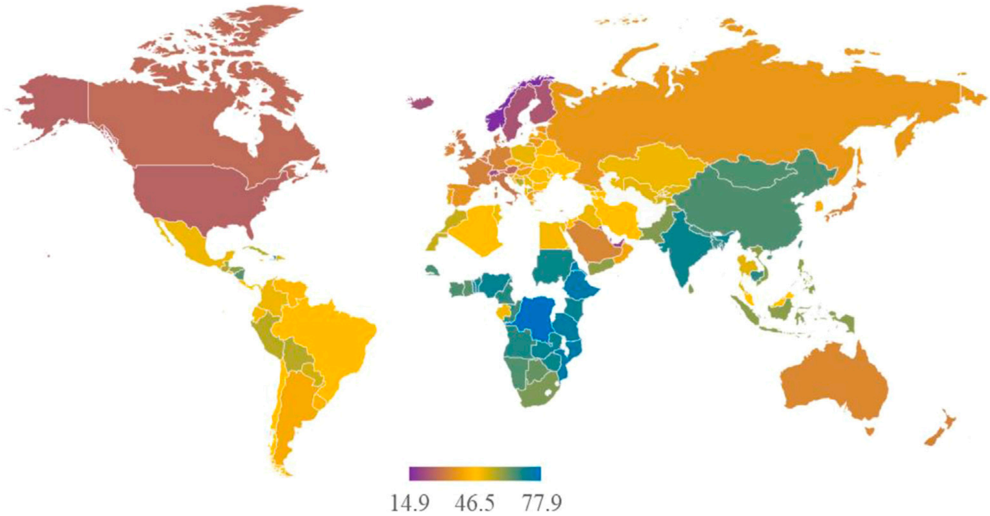

FIGURE 2 | Average MEAI between 2001 and 2016 for 125 global nations.

than zero for North America, Europe, and Australia and Oceania, and the change in energy efficiency was also greater than zero for Central Asia, implying a deterioration in energy availability and energy efficiency in these regions. The most obvious indicator responsible for such deterioration in North America, Europe, and Australia and Oceania is "household energy consumption per capita" (Sovacool and Brown, 2012; Thomson and Snell, 2013). Generally, the changes in dimension indices at the national level showed similar dynamics as those at the global and regional levels.

Mechanisms for Energy Poverty

The spatiotemporal patterns of the MEAI are the combined outcome of a number of factors, including domestic energy conditions, income level, and policy implementation. In the following section, we provide key insights on the three dimensions of the MEAI at global, regional, and national levels.

Energy availability is defined by the International Energy Agency as a lack of access to modern energy. A lower value for the energy availability index shows its contribution to the alleviation of energy poverty. At the national level, 32 of the top 40 nations, in order of the least to greatest increase for energy availability, belong to developed nations. The remaining eight nations were high-/upper-/ middle–income nations with abundant natural resources such as Kuwait, Bahrain, the United Arab Emirates, Qatar, Russia, Iran, Saudi Arabia, and Brunei. The bottom 40 nations were low-/lower- middle-income nations in Central America, South Asia, and sub-Saharan Africa. The top 40 nations have established perfect infrastructures of energy service to improve household's energy consumption levels and have gained an overall access to modern energy (Bednar and Reames, 2020). In contrary, the bottom 40 nations lack the access to adequate amounts of modern energy and rely mainly on traditional cooking fuels due to unfavorable conditions, including high energy prices, energy shortages, and inadequate energy infrastructure (Mendoza et al., 2019). At the regional level, the improvement on "household electricity consumption per capita" and "household energy consumption per capita" will have significant and positive impacts on reducing the energy availability index (see the **Figure 4**).

The energy affordability index shows to what extent households cannot afford basic levels of energy needed to attain a socially and materially necessitated level of energy services (González-Eguino, 2015). A higher value of energy affordability indicates increased difficulty in affording basic energy needs. The average index of energy affordability among nations between 2001 and 2016 ranged from −1.4 in Kuwait to 97.8 in Congo, with large variations across nations. One of the indicators for energy affordability is "cellphone ownership per 100 people," which reflects the situation of modern energy consumption and household appliance utilization (Nussbaumer et al., 2012). It has a significant positive influence on reducing the index of energy affordability, as households tend to spend more money on the modern energy consumption and efficient household appliance utilization with the increase in income. We find the change in the index values for "cellphone ownership per 100 people" among regions from 2001 to 2016 ranging from a 1.79 % decrease (Australia and Oceania) to a 93.1% decrease (sub-Saharan Africa), which plays a significant role in energy affordability improvement compared to the survey conducted in 2001 (**Figure 4**).

A higher energy efficiency level has a positive effect on reducing the final energy consumption, whereas a lower energy efficiency level poses challenges to alleviate energy poverty for all nations (Bonatz et al., 2019). In this study, energy efficiency is divided into two categories: low-carbon development and energy modernization. Low-carbon development measured by "household CO_2 emissions per capita" represent low-carbon development, "ratio of non-solid commodity energy on household commodity energy," and "proportion of non-thermal electricity generation on electricity generation." The three indicators account for over 60% of the index values of energy efficiency in North America, Europe, and Australia and Oceania. This implies that the energy efficiency issue in

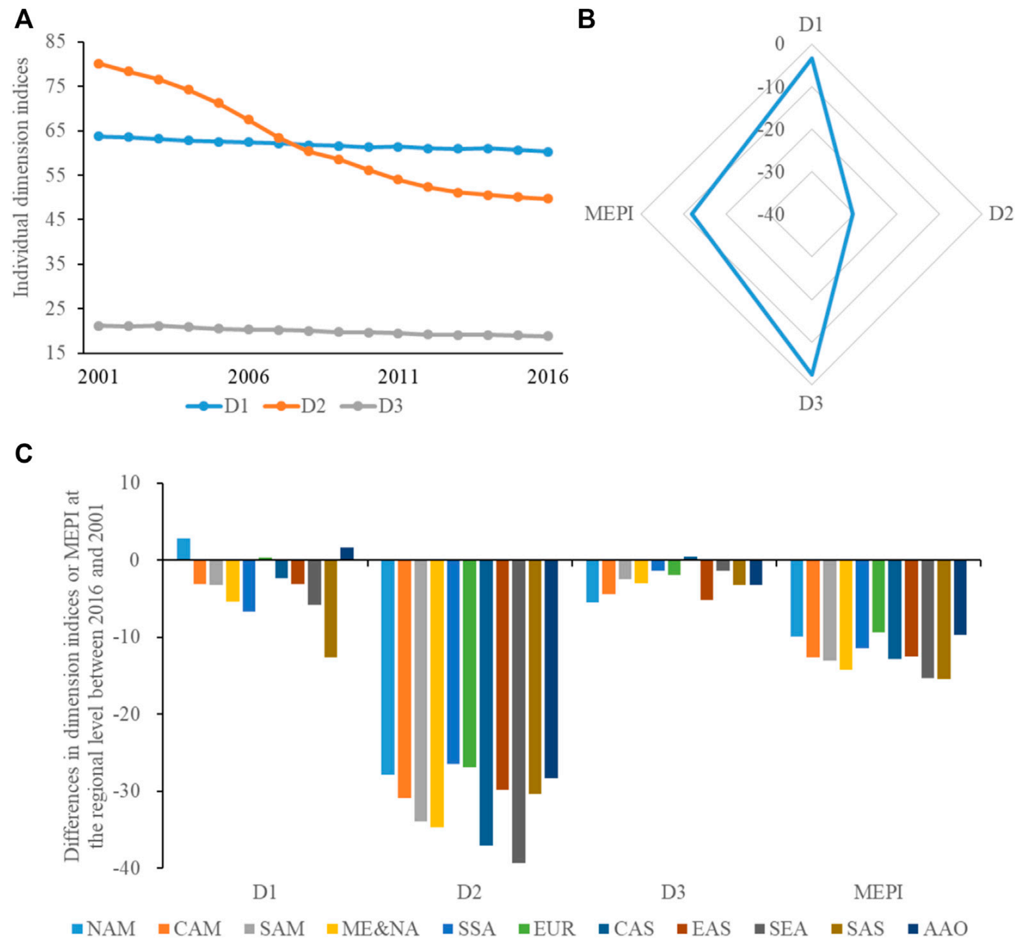

FIGURE 3 | Change in dimension indices or the MEAI. **(A)** Changes in dimension indices from 2001 to 2016 at the global level. **(B)** Differences in dimension indices between 2016 and 2001 at the global level. **(C)** Differences in dimension indices and the MEAI between 2016 and 2001 at the regional level. D1 is the abbreviation for energy availability, D2 for energy affordability, and D3 for energy efficiency. A positive value indicates an increase in the index from 2001 to 2016, whereas a negative value indicates a decrease in the index from 2001 to 2016.

the three regions is related more to carbon emissions than modernization (see **Figure 4**). The three regions are dominated by developed nations. Although these nations have reached an overall access to energy services, they still heavily depend on traditional fossil fuels to meet household energy consumption demand and lack access to adequate amounts of modern energy. In contrary, two indicators including "proportion of population with access to clean fuels and technologies for cooking" and "ratio of biomass and waste consumption on total final household energy consumption," contribute to more than 55% of the energy efficiency index value in Central America, South America, Middle East, North Africa, sub-Saharan Africa, Southeast Asia, and South Asia. Therefore, energy efficiency in these six regions concerns more on modernization (**Figure 4**). A large number of less-developed nations are clustered in the six regions, for which it is the priority to meet household basic energy requirements without considering the energy consumption structure. In East Asia, two categories of indicators, low-carbon development and energy modernization, play equal roles in constituting the energy efficiency index, implying that both carbon emissions and energy modernization are equally important for this region (**Figure 4**). This is because most nations (except Korea, Republic of China, and Japan) in East Asia are less-developed nations, and households mainly rely on energy-intensive and inefficient appliances to meet their basic energy requirements, which have a negative effect on energy modernization. Meanwhile, coal is abundant in this region, and thus final energy consumption is dominated by coal. Reducing the carbon emissions is a great challenge in this region, which is affecting the overall MEAI.

Although our results show that energy poverty has been alleviated to a large extent, evidenced by the reduction in the MEAI at global, regional, and national levels in general, the major driver for such improvement is attributed to energy affordability as the results of fast economic growth and international cooperation. The dimensional sub-index provides additional information for further action. From the perspective of energy availability, energy shortage and inadequate energy infrastructure hold back improvements on global energy consumption (Sovacool, 2012). The expansion of renewable energy technologies and the related distribution options, such as small-scale

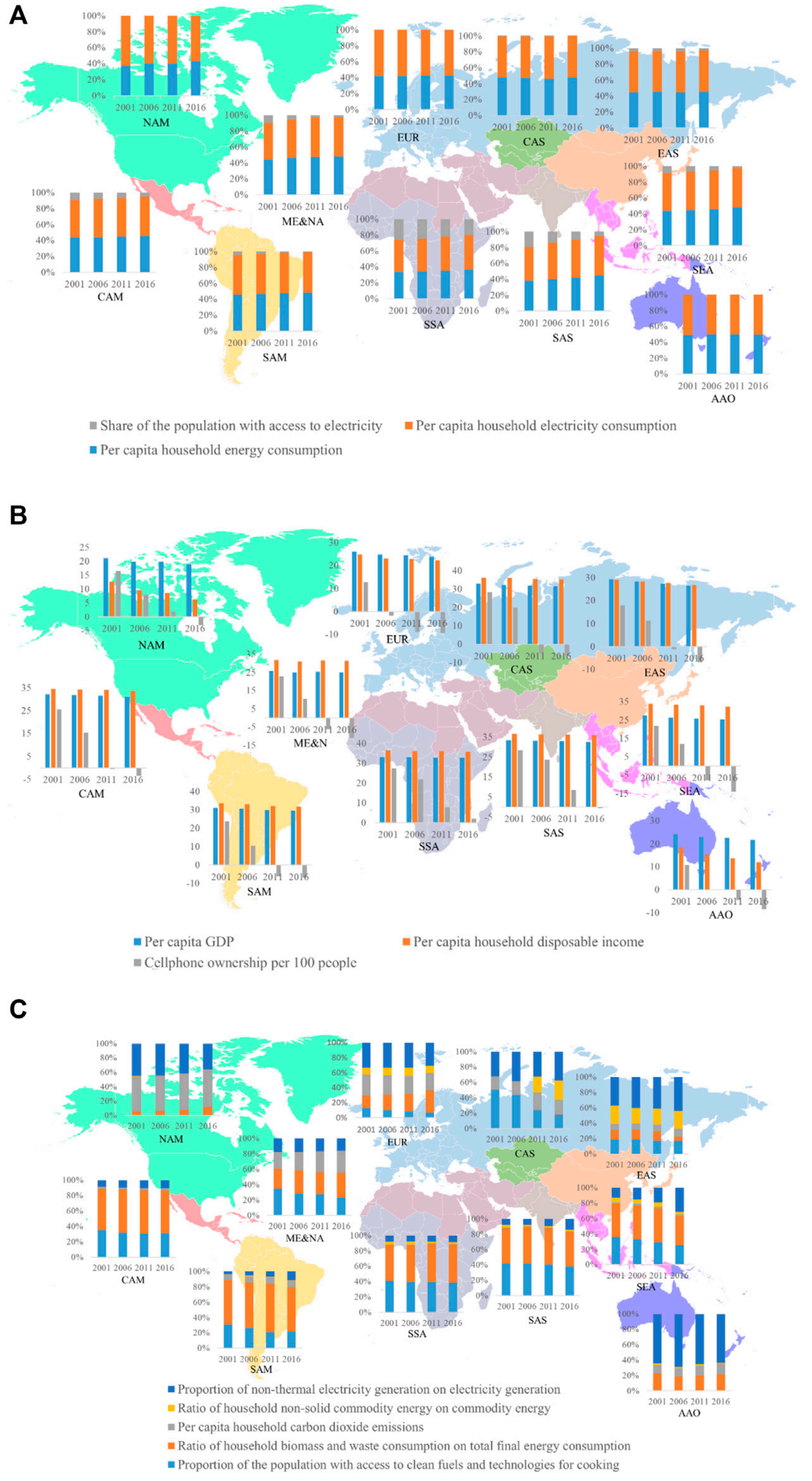

FIGURE 4 | Structure of dimension indices at the regional level in 2001, 2006, 2011, and 2016. **(A)** D1 (energy availability). **(B)** D2 (energy affordability). **(C)** D3 (energy efficiency).

photovoltaics, diesel generators, and improved cooking stoves, provide a chance to improve the access to modern energy for rural households (Yan et al., 2019). From an energy-efficient perspective, high-carbon emissions, and low-energy modernization have made energy poverty difficult to alleviate (Cameron et al., 2016). Burning solid fuels such as dung, firewood, and coal in traditional stoves for heating and cooking

TABLE 2 | Sensitivity of national ranks in 2001 in weights of indicators.

Nation	S0	S1	S2	S3	Nation	S0	S1	S2	S3	Nation	S0	S1	S2	S3
AGO	106	106	106	104	FIN	8	8	8	8	NGA	115	114	115	118
ALB	61	59	59	63	FRA	17	17	18	17	NIC	105	105	105	105
ARE	2	2	2	2	GAB	73	72	74	74	NLD	15	15	16	16
ARG	44	44	44	43	GBR	18	18	17	20	NOR	1	1	1	1
ARM	57	57	57	56	GEO	81	81	81	81	NPL	108	108	108	107
AUS	27	27	28	29	GHA	103	103	103	103	NZL	23	23	23	22
AUT	14	14	13	14	GRC	33	33	33	33	OMN	71	73	71	68
AZE	50	50	50	49	GTM	90	90	90	90	PAK	91	91	92	91
BEL	11	11	11	11	HND	93	93	93	93	PAN	77	77	77	76
BEN	118	118	118	116	HRV	39	39	39	39	PER	88	88	88	89
BGD	111	110	111	109	HTI	116	116	116	115	PHL	92	92	91	92
BGR	70	70	69	73	HUN	35	35	35	35	POL	76	76	75	79
BHR	20	20	20	19	IDN	94	94	94	94	PRT	31	31	31	31
BIH	83	83	83	85	IND	121	121	121	124	PRY	80	80	79	80
BLR	46	46	46	46	IRL	24	24	24	25	QAT	10	10	10	9
BOL	85	85	85	84	IRN	49	49	51	48	ROU	64	63	64	69
BRA	54	54	54	55	IRQ	66	65	66	60	RUS	40	40	40	41
BRN	25	25	25	24	ISL	5	5	5	5	SAU	59	66	63	58
BWA	95	96	95	95	ISR	26	26	26	27	SDN	109	109	109	108
CAN	12	13	14	12	ITA	16	16	15	15	SEN	99	99	99	98
CHE	6	6	6	6	JAM	63	62	61	65	SGP	19	19	19	18
CHL	48	48	48	50	JOR	45	45	45	45	SLV	82	82	82	82
CHN	107	107	107	117	JPN	21	21	22	21	SRB	74	74	73	78
CIV	101	101	101	100	KAZ	79	79	80	77	SVK	38	38	38	36
CMR	100	100	100	101	KEN	119	119	119	119	SVN	32	32	32	32
COD	125	125	125	125	KGZ	75	75	76	72	SWE	7	7	7	7
COG	114	115	114	112	KHM	113	113	113	111	TGO	120	120	120	120
COL	72	71	72	71	KOR	37	37	37	37	THA	84	84	84	83
CRI	53	53	53	52	KWT	3	3	3	3	TJK	78	78	78	75
CUB	67	67	68	66	LKA	96	95	96	96	TUN	69	69	70	70
CYP	30	30	30	30	LTU	42	42	42	42	TZA	122	122	122	121
CZE	36	36	36	38	LUX	4	4	4	4	UKR	60	60	62	64
DEU	22	22	21	23	LVA	43	43	43	44	URY	47	47	47	47
DNK	13	12	12	13	MAR	87	87	87	87	USA	9	9	9	10
DOM	62	61	60	62	MDA	65	64	65	61	UZB	56	56	56	57
DZA	55	55	55	54	MEX	52	52	52	53	VEN	41	41	41	40
ECU	68	68	67	67	MKD	86	86	86	88	VNM	98	98	98	102
EGY	58	58	58	59	MLT	29	29	29	26	YEM	89	89	89	86
ERI	117	117	117	114	MNG	104	104	104	106	ZAF	97	97	97	97
ESP	28	28	27	28	MOZ	124	124	124	123	ZMB	110	111	110	110
EST	34	34	34	34	MYS	51	51	49	51	ZWE	112	112	112	113
ETH	123	123	123	122	NAM	102	102	102	99	102				

Note: S0 is the abbreviation for original rankings, S1 for Scenario 1, S2 for Scenario 2, and S3 for Scenario 3. The codes for countries refer to the World Bank Database.

contributes to global deforestation and climate change. Improving energy efficiency helps to enforce sustainable energy development, speed up the exploration of efficient household appliances, and mitigate climate change. National policymakers could consider strategies to improve energy efficiency in sub-Saharan African and South Asian nations in order to narrow the energy poverty gap between developed regions and less-developed regions.

Sensitivity analysis

We considered three scenarios to assess the sensitivity of national ranks to changes in weights of indicators in 2001. Equal weights were assigned to relative indicators, respectively, (Nussbaumer et al., 2012) and the other weights were kept constant. Altogether three scenarios were presented in the study: Scenario 1 (the equal weights of indicators within energy availability), Scenario 2 (the equal weights of indicators within energy affordability), and Scenario 3 (the equal weights of indicators within energy efficiency). We recalculated the national ranks in 2001 in three scenarios, as shown in **Table 2**. The ranks of 11 countries changed in Scenario 1, the ranks of 29 countries changed in Scenario 2, and the ranks of 77 countries changed in Scenario 3. The results show that national ranks were relatively sensitive to changes in weights of indicators, and it is important to note that the weights to indicators should be cautiously assigned.

CONCLUSION

The empirical results indicate that the overall MEAI and indices in all dimensions decreased from 2001 to 2016 at a global level with energy affordability experiencing the highest decline. The MEAI at the national level declines within the same period, showing significant regional heterogeneity in terms of the sub-index. Energy efficiency in developed and less-developed regions is characterized by high-carbon emissions and low-energy modernization, respectively. The energy availability indices are lower in developed nations and in nations with abundant energy resources. Overall, our results highlight a sudden increase in the MEAI for Central America in 2014 and a gradual decline in MEAI for East Asia during 2014–2016.

Data availability is an important criterion for selecting the dimension indicators. The lack of available data hinders researchers exploring the spatiotemporal dynamics of progress toward alleviating energy poverty. This article constructed a unique micro-level dataset from national statistical departments and international databases, providing a solid basis for developing a set of standard indicators to better evaluate the progress toward energy poverty across space and time. Policymakers continuously track and monitor energy poverty by a periodical updating of the data.

This article developed a systematic and comprehensive evaluation method of SDG 7 at global, regional, and national levels. The method outlined in our article enables us to track the spatiotemporal pattern of SDG 7 and monitor national efforts toward energy poverty alleviation. It will not only help to guide policy development and implementation but also provide reference for the next action. One direction for further research is to include qualitative indicators obtained through a participatory survey method, to reflect household's subjective feelings on energy poverty. An investigation of non-economic factors, such as educational level, cultural preferences, and dietary habits on household's energy alternatives may be helpful to reveal the complex mechanisms and consequences of energy poverty alleviation. In addition, investigations on the trade-offs and synergies between SDG 7 and the other SDGs will enrich our path toward sustainability.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XC conducted all data compilation, processing, and calculations and wrote the first draft.

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