Energy, Sustainability and Society

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Sustainability indices for energy utilization using a multi-criteria decision model

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Abstract

Background: Energy and water availability are considered vital for a country's development. An exhaustive review of literature has been undertaken on indicators for sustainable energy development. In addition to energy and water, the resources of the country namely land availability, human capital, and nation's wealth were also found to be vital for sustainable energy development of any country. These resources have to be optimally used for sustainable energy development which is measured in terms of technical, economic, social, environmental, and institutional indices.

Methods: In this research, a multi-criteria decision model was used to measure sustainable energy development efficiency. The natural resource of the country was considered as the input criteria, while the indices were used as the output criteria. This research is unique in finding if the country's resources are being utilized in an efficient manner for sustainable development using the multi-criteria fuzzy-analytical hierarchical processing—data envelopment analysis model.

Results: From the fuzzy analytical hierarchical processing, it was found that experts were of the opinion that water availability and energy reserves were the most important parameters among the input resources, while environmental and social indices were opined to be the most important parameters among the output indices. Data envelopment analysis model was carried out using assurance region Charnes, Cooper, and Rhodes output-oriented method. The results revealed that Togo was the most efficient country with maximum sustainable energy development efficiency. Sensitivity analysis was also carried out to find which among the resources were sensitive with respect to energy sustainability for a specific country.

Conclusion: The analysis can help countries to benchmark themselves against the country lying in the efficient frontier and draft policies to improve their energy sustainability indices. Similar analysis and comparison can be done for other countries, since this research analysis was carried out only for 48 developing countries.

Keywords: Energy sustainability, Index, Sustainable development, Sustainability indices, Multi-criteria decision model

Background

Sustainable development can be defined as the development that caters to the needs of the present generation without compromising on its ability to meet the needs of the future generation [1]. With globalization and swift changeover taking place from an agricultural economy to an industrial economy [2] and then from an industrial economy to green economy (https://sustainabledevelopment.un.org/index.php?page=view&type=400&nr=131&menu=1515) in several fronts, the world is witnessing, on the one hand, massive consumption and large scale depletion of its natural resources while on the other hand increased environmental consciousness. Care has to be taken to ensure that such consumption does not happen at the cost of the future generation.

The rapid development in the industrial sector had tousled the planning of the resources. In both developed and developing countries, planners and policymakers are

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looking at various options for sustainable development, so that the country's resources are kept available for generations to come. Sustainable development requires judicious use of resources, technology, economic incentives, and strategic policies, at the local and national level [3].

Energy and water are considered as vital resources for a country's development. The percentage of renewable energy in the total energy scene has been declining over the years [4]. With rapid industrialization in both developed and developing countries, several energy-intensive industries have sprouted over the years [5]. Developing countries find they can very easily procure the necessary technology and the energy resources for industrialization that enabled them to quickly shift over from an agricultural economy to an industrial economy. However, it is important to note that such a transition should happen keeping sustainability in focus. In addition to energy, water is yet another resource which every country has to judiciously utilize. The development of any country is found to be directly proportional to that country's endowment of water and energy resources [6]. In addition to water and energy resources, the land is yet another vital input for energy sustainability since energy is a land-use intensive sector [7]. It is the role of policymakers to make use of the available land in an efficient manner for sustainable development. The human capital is another resource available within its national boundaries which need to be optimally utilized, since energy sustainability depends on the manpower available to support the energy activities [8]. Several researchers have established the causality relationship between national income and energy [9], and hence national income has been considered as an input criterion for energy sustainability. All of these resources have to be used in an optimal manner to meet the needs of the present generation for enhancing energy sustainability without jeopardizing the requirements of future generations.

In this paper, a framework is proposed that considers how to utilize the available resources within a country, namely energy, water, land, human capital, and national wealth in an effective manner so that it can target for higher sustainable energy development. It gives an indication of how a country can judiciously use its limited resources to achieve the desired output. While choosing the energy resources for a country, it is essential to consider the consequences of the same which will be reflected in the output indices selected for sustainable energy development. The sectors wherein course corrections need to be taken are also presented, using a multi-criteria multi-evaluation methodology. Using this framework, the policymakers can strategize their energy portfolio so that they become sustainable in the long run.

Indicators for sustainable development

Researchers have proposed various indices and metrics to find whether a country is progressing in a sustainable manner. A good framework of indicators will help policymakers to understand where the country is headed and how to provide for alternate solutions. The framework needs to present the inter-linkages and tradeoffs. Several indicators have been put forth by researchers since the Brundtland report was published in 1987 [3, 10–12].

Latin American Energy Organization (OLADE), Economic Commission for Latin America and the Caribbean (ECLAC), and the German Technical Cooperation Agency (GTZ) proposed eight indicators [13]. Millennium Development Goals' (MDG) Indicator Program proposed 60 indicators [14]. International Atomic Energy Agency (IAEA) proposed 30 indicators for Energy Indicators for Sustainable Development (EISD) [3, 15]. Collection of data for these numerous indicators is arduous. Further deciphering and inferring information from these numerous indicators, which sometimes are in different units, becomes cumbersome. Though this wide spectrum of dashboard indicators has its own advantages, it was found that composite indicators were relatively easier to measure and compare across multiple dimensions. Some examples include the Energy for Development Index (EDI), Environmental Sustainability Index (ESI), and Environmental Performance Index (EPI).

The Energy for Development Index (EDI) [16] is a composite index that measures development in terms of energy use. The components include commercial energy consumption per capita, commercial energy share in total energy use, and percentage of the population having access to electricity. The Environmental Sustainability Index (ESI) jointly developed by Yale and Columbia universities, World Economic Forum, and European Commission Joint Research Centre is another example of a composite indicator that summarized the index from 21 indicators to measure environmental sustainability [17]. Environmental Performance Index (EPI) was also developed by the same group with 25 performance indicators. Thus, composite indicators were found to be very comprehensive and robust covering various aspects. Also, the performance of these indicators could be easily compared across dimensions, sectors, and countries. However, all these indicators calculate the status of the measure, namely environmental sustainability and do not provide a mechanism to identify how to achieve a higher level of sustainability.

Composite sustainable indicators for assessing city/region/country

Having established the importance of composite indicators, a review of the literature was undertaken to find how composite indicators can be used to assess a city/region/country's sustainability.

Siemens Green City Index (http://sg.siemens.com/city_of_the_future/_docs/gci_report_summary.pdf) evaluated more than 120 cities around the world (27 cities in the USA and Canada, 12 cities in Germany, 30 cities in Europe, 17 cities in Latin America, 22 cities in Asia, 7 cities in Australia and New Zealand, and around 15 cities in Africa) using 30 indicators (16 quantitative and 14 qualitative) which included energy, waste, land use, water, air quality, environmental governance, and carbon dioxide (CO_2) emissions. The indices have been used without any categorization as to whether they are input or outcome parameters. It is necessary to find whether the input resources available in a country are being optimally transformed into the required output to ensure sustainability. In an indirect way, Bossel [18] has addressed this aspect. He has presented indicators for sustainable development for a state, country, and globally, in terms of an orientor, namely existence, effectiveness, freedom of action, security, adaptability, coexistence, and psychological needs. He has identified subsystem performance for each, in terms of human, support, and natural and has related it to the total system. Impact on the environment because of personal demands to meet sustainable footprint is found under coexistence dimension.

For measuring sustainability in the urban context, researchers [19–21] have used four indices, namely social, economic, community, and cultural (human). Zhang [22] has developed 22 urban sustainability indicators presented in Table 10 in Appendix which was developed in the context of urban China. The researchers have found the indicators in terms of ratio assigning weights for each. The indicators highlight to what extent urban sustainability has been achieved. As technological innovations are being witnessed across several disciplines, it is emerging as one of the important indices that have to be sustainable. In this paper, in addition to other dimensions, technical sustainability in terms of renewable energy generation and non-renewable energy substitution is measured. Dijk and Mingshun [23] using the 22 indicators developed by Zhang [22] measured urban sustainability index (USI) in four Chinese cities. Andriantiatsaholiniaina et al. [24] measured sustainable development using environmental, economic, social, political, and cultural indices.

Lee and Huang [25] based on the "3E11" structure of environment, equity (social equity), economy, and institution (politics) [26–31] proposed 51 indicators (Table 11 in Appendix). An institutional dimensional indicator has been newly proposed along with the other three indicating its growing importance. The researchers have carried a longitudinal study to measure Taipei's sustainability over a period of 11 years. Trigg et al. [32] have included a new parameter, namely quality of life, in addition to resilience and environmental performance to measure sustainability. They have compared and ranked 15 Australian cities.

On the same lines, to assess sustainability among cities, Zhou et al. [33] identified 33 indicators for low-carbon eco-city planning in China. Kostevšek et al. [34] developed 20 indicators across energy, economy, and social aspects to assess the district heating system of Ormoz Municipality in Slovenia. Martinez [35] has used energy, economic, environmental, and social indicators (Table 12 in Appendix) to assess the energy and sustainable development in cities by taking Bogota as a case study. The indices used for measuring sustainable development focuses on energy sustainability with special reference to environmental emission. When cities become sustainable, the expectation is, it will automatically lead to a country's sustainability. However, this may not be true because of the urban-rural divide in terms of resource availability. The 17 sustainable development goals set by the United Nations are as follows: (i) No Poverty, (ii) Zero Hunger, (iii) Good Health, and Well-being; (iv) Quality Education, (v) Gender Equality, (vi) Clean Water, and Sanitation; (vii) Affordable and Clean Energy; (viii) Decent Work and Economic Growth; (ix) Industry, Innovation, and Infrastructure; (x) Reducing Inequality, (xi) Sustainable Cities, and Communities; (xii) Responsible Consumption and Production; (xiii) Climate Action, (xiv) Life Below Water, (xv) Life On Land, (xvi) Peace, Justice, and Strong Institutions; and (xvii) Partnerships for the Goals. Unless concerted efforts are taken towards achieving these goals, development will take place only in segregated pockets. Sustainable development measurement must be from a holistic perspective wherein every aspect of the economy is covered and which in consequence will lead to global sustainability.

Strunz et al [36] in their meta-analysis have clearly brought out that the resource input is a major challenge; the global community needs to address first for achieving sustainability followed by the risks associated on the sink side, namely the outcome side in terms of climate change and biodiversity loss resulting from human activity. The authors suggest that a positive framework has to be proposed rather than issuing ecological collapse warnings because such activities are found to be psychologically ineffective since they result only in fear and lack of action. Any new mechanism being ventured into should ensure there is a proper balance between the resource availability and its consumption for the ecosystem to be sustainable.

Kılkış [37] has developed a composite index, namely Sustainable Development of Energy, Water and Environment Systems (SDEWES) City Sustainability Index (Table 13 in Appendix). This is a comprehensive index drawing inferences from various research work. The index is used to benchmark cities using various themes:

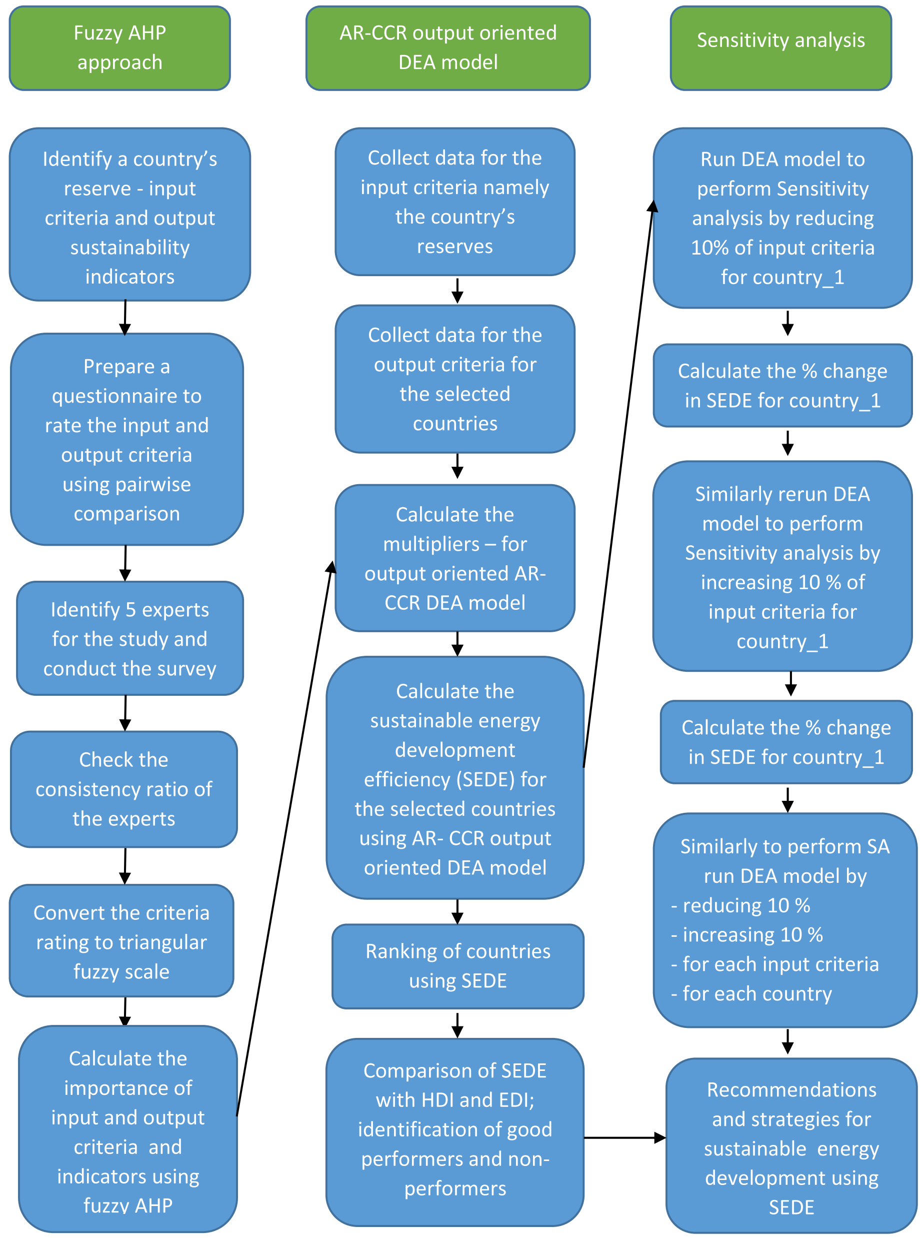

Fig. 1 Research plan

Table 1 Rating scale for rating importance of criteria

Intensity of importance	Definition	Explanation
1	Equal importance	Two indicators contribute equally to sustainable development
2	Weak importance of one over another	Experience and judgment slightly favor one indicator over another
3	Moderate importance of one over another	Experience and judgment moderately favor one indicator over another
4	Very strong importance	The indicator is strongly favored over another
5	Extremely strong importance	The evidence favoring one over another is of the highest possible order of affirmation

Table 2 Triangular fuzzy (TFN) scale and its inverse TFN scale for the linguistic pairwise comparison scale

	Rating scale	Triangular fuzzy numbers			Triangular fuzzy reciprocal numbers		
Just equal		1	1	1	1	1	1
Equal importance	1	1/2	1/1	3/2	2/3	1/1	2/1
Weak importance of one over another	2	1/1	3/2	2/1	1/2	2/3	1/1
Moderate importance of one over another	3	3/2	2/1	5/2	2/5	1/2	2/3
Very strong importance	4	2/1	5/2	3/1	1/3	2/5	1/2
Extremely strong importance	5	5/2	3/1	7/2	2/7	1/3	2/5

(i) energy consumption and climate, (ii) penetration of energy and carbon dioxide saving measures, (iii) renewable energy potential and utilization, (iv) water and environmental quality, (v) carbon dioxide emissions and industrial profile, (vi) city planning and social welfare, and (vii) research and development, innovation, and sustainability policy. It is found that the index stresses on energy, water, and emission. Though the index considers several aspects, there is a need to study sustainability from a country's perspective. Also, the resources of the country available across the nation have to be accounted for while measuring the sustainability of a country.

A data envelopment analysis (DEA) that considers inputs and outputs to measure the frontier efficiency of a decision unit was used by Yang et al. [38] to measure urban sustainability in 22 regions in Taiwan. Resources in terms of food, water, gasoline, and electricity have been considered as inputs, while gross domestic product and employment have been considered as desirable outputs, and garbage, sewage, and sulfur-oxides have been considered as undesirable outputs in the determination of urban sustainability. This research is novel in the sense that researchers have proposed a mechanism for improving urban sustainability using DEA technique by considering input resources, namely food, water, gasoline, and electricity. Taking a cue from this, it was proposed to use data envelopment analysis in this present research to identify how energy sustainability can be enhanced with the available input resources within a country. Also, the review indicated that the sustainability of a country is very much dependent on the country's inherent resources to achieve energy sustainability. Hence, in this research, energy, water, land, human capital, and national wealth have been considered as the input resources to obtain the desired sustainable energy development. In addition to social, economic, and environmental dimensions, the importance of the technical dimension was found to be

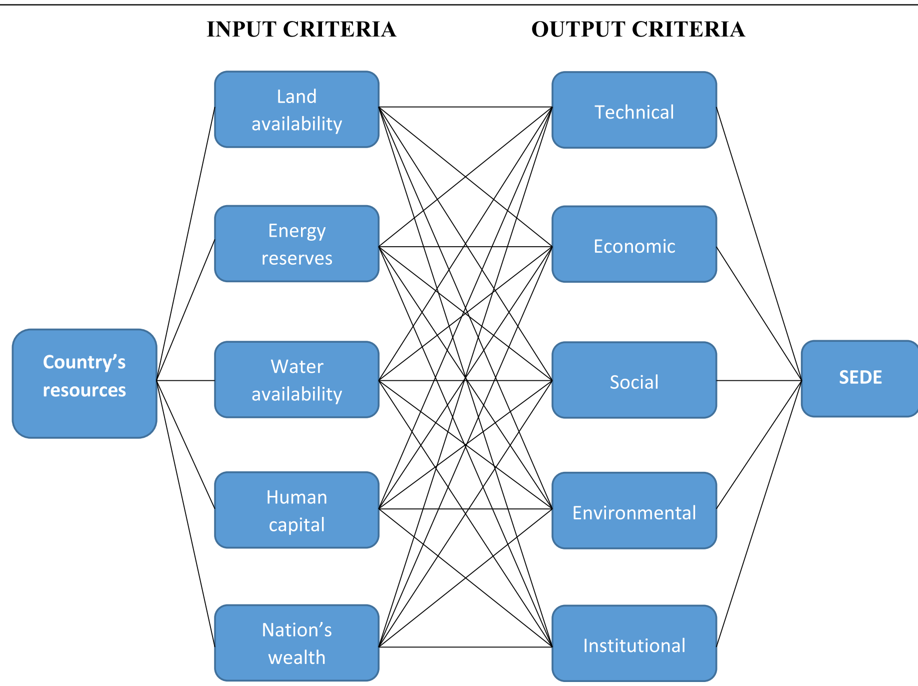

Fig. 2 Hierarchical structure of input and output criteria used in DEA

Table 3 Country's reserves

	Country	Land availability (km^2)	Energy reserves (toe)	Water availability (km^3)	Human capital (numbers)	National wealth (GDP per capita)
A1	Iran	1,745,150	28,849,882,132	137	24,639,491	6247.69166
A2	Argentina	2,780,400	638,822,734.5	814	18,474,862	9428.502541
A3	Libya	1,759,540	6,487,981,067	0.7	2,334,799	11,631.71901
A4	Algeria	2,381,740	1,956,489,474	11.67	10,861,377	4386.038896
A5	Venezuela	912,050	41,166,872,931	1,233	13,008,004	13,961.94516
A6	Jordan	89,320	1,495,472,421	0.94	1,827,111	3786.533481
A7	Gabon	267,670	335,185,309	164	485,826	8449.938711
A8	Ecuador	256,370	1.08433E + 12	382	6,828,569	4573.247084
A9	Colombia	1,141,750	4,192,381,163	2132	22,718,441	6037.12981
A10	Angola	1,246,700	1,415,972,331	148	9,233,513	3544.026552
A11	Brazil	8,515,770	5,517,029,046	8233	97,400,070	10,538.77828
A12	Egypt	1,001,450	615,679,529	57.3	27,333,918	2524.381342
A13	Costa Rica	51,100	536,630.638	112.4	2,083,466	7911.7952
A14	Yemen	527,970	405,405,405.4	2.1	5,229,818	1249.033678
A15	Uruguay	176,220	310,718.5684	122	1,695,723	11,112.45603
A16	Cuba	109,890	17,051,627.28	38.12	5,204,889	5550.705973
A17	Panama	75,420	87,126.4	148	1,678,436	7772.005022
A18	Paraguay	406,750	1,394,349.478	337	2,907,659	3996.056321
A19	Tunisia	163,610	57,844,521.82	4.6	3,723,954	4044.629689
A20	Nigeria	923,770	5,053,899,577	950	47,480,739	2178.898759
A21	Mongolia	1,564,120	9,230,802,760	34.8	1,151,716	2533.175737
A22	Peru	1,285,220	115,953,542.5	1913	15,958,608	4695.675167
A23	Thailand	513,120	67,897,478.86	457.2	39,188,148	4743.690472
A24	Zambia	752,610	2,218,992.8	107.5	5,515,365	1365.402344
A25	Bolivia	1,098,580	29,027,309.27	580	4,562,872	1933.749288
A26	Morocco	446,550	11,698,494.35	30.7	11,354,732	2765.856154
A27	Cambodia	181,040	1,511,050	476.1	7,893,797	752.9779185
A28	Ghana	238,540	92,513,764.14	53.2	10,931,018	1247.463066
A29	Cameroon	475,440	28,622,327.2	285.5	8,322,260	1300.84144
A30	El Salvador	21,040	1,031,744.897	25.23	2,559,701	2943.876855
A31	Zimbabwe	390,760	1,094,483,425	20	6,671,584	728.5662736
A32	Philippines	300,000	57,825,278.58	479	37,641,192	2010.799316
A33	Botswana	581,730	5,135,820,541	12.24	833,681	5948.853248
A34	Indonesia	1,910,930	3,101,991,363	2019	114,924,975	2970.044131
A35	Benin	114,760	2,022,628.078	26.39	3,568,162	763.154718
A36	China	9,562,911.25	87,580,442,801	2840	779,404,706	4142.038286
A37	Vietnam	331,051.01	2,728,044,533	884.1	50,869,267	1244.037152
A38	Kenya	580,370	3,648,940	29	14,984,059	917.0247151
A39	Togo	56,790	498,778.48	14.7	2,881,260	510.0840338
A40	Honduras	112,490	1,154,546.323	95.93	3,227,286	1900.382571
A41	Sri Lanka	65,610	948,802.28	52.8	8,341,363	2615.982695
A42	Guatemala	108,890	15,181,909.59	111.3	5,475,328	2806.986762
A43	Bangladesh	148,460	758,323,126.5	1227	57,920,440	725.76626
A44	Nicaragua	130,370	498,253.88	196.6	2,415,768	1480.376529
A45	Jamaica	10,990	172,903.7382	9.4	1,344,506	4777.168936
A46	India	3,287,260	70,367,230,205	1911	469,829,385	1237.339786
A47	Senegal	196,710	394,650.48	38.8	3,867,739	1247.49782
A48	Pakistan	796,100	1,122,514,784	246.8	56,949,189	1045.207929

Table 4 Output indices

	Country	Technical	Economic	Social	Environmental	Institutional
A1	Iran	0.918	0.469	1	1	0.147
A2	Argentina	0.884	1	0.397	0.978	0.098
A3	Libya	0.784	0.79	0.346	0.877	0.391
A4	Algeria	0.842	0.365	0.412	0.993	0.35
A5	Venezuela	0.869	0.5	0.268	0.962	0.278
A6	Jordan	0.844	0.385	0.296	0.997	0.001
A7	Gabon	0.995	0.058	0.088	0.647	0.694
A8	Ecuador	0.967	0.284	0.155	0.814	0.219
A9	Colombia	0.897	0.495	0.077	0.674	0.284
A10	Angola	0.952	0.044	0.031	0.611	0.779
A11	Brazil	0.931	0.448	0.097	0.796	0.086
A12	Egypt	0.828	0.278	0.21	0.929	0.11
A13	Costa Rica	0.879	0.552	0.093	0.764	0.048
A14	Yemen	0.887	0.058	0.072	1	0.183
A15	Uruguay	0.594	0.596	0.198	0.707	0.032
A16	Cuba	0.809	0.527	0.138	0.559	0.042
A17	Panama	0.91	0.514	0.097	0.527	0.017
A18	Paraguay	0.962	0.117	0.077	0.755	0.142
A19	Tunisia	0.851	0.427	0.149	0.532	0.076
A20	Nigeria	0.992	0.001	0.008	0.842	0.192
A21	Mongolia	0.913	0.163	0.278	0.438	0.216
A22	Peru	0.989	0.359	0.061	0.493	0.086
A23	Thailand	0.875	0.486	0.076	0.475	0.053
A24	Zambia	0.918	0.004	0.013	0.91	0.082
A25	Bolivia	0.929	0.142	0.062	0.586	0.207
A26	Morocco	0.581	0.343	0.104	0.816	0.002
A27	Cambodia	0.941	0.008	0.048	0.71	0.063
A28	Ghana	0.86	0.041	0.025	0.743	0.068
A29	Cameroon	0.941	0.012	0.009	0.653	0.115
A30	El Salvador	0.808	0.151	0.075	0.641	0.055
A31	Zimbabwe	0.949	0.008	0.032	0.644	0.08
A32	Philippines	0.807	0.226	0.034	0.561	0.053
A33	Botswana	0.879	0.402	0.044	0.288	0.04
A34	Indonesia	0.895	0.135	0.079	0.373	0.158
A35	Benin	0.865	0.018	0.074	0.626	0.05
A36	China	0.843	0.501	0.1	0.091	0.083
A37	Vietnam	0.966	0.078	0.059	0.361	0.108
A38	Kenya	0.633	0.004	0.014	0.809	0.074
A39	Togo	0.591	0.008	0.016	0.841	0.074
A40	Honduras	0.86	0.103	0.031	0.455	0.043
A41	Sri Lanka	0.813	0.098	0.02	0.503	0.048
A42	Guatemala	0.837	0.093	0.03	0.462	0.054
A43	Bangladesh	0.839	0.051	0.029	0.483	0.075
A44	Nicaragua	0.763	0.068	0.021	0.5	0.048
A45	Jamaica	0.636	0.271	0.072	0.38	0.013
A46	India	0.832	0.131	0.048	0.232	0.066
A47	Senegal	0.77	0.046	0.021	0.418	0.037
A48	Pakistan	0.245	0.058	0.088	0.49	0.067

Source: [55]

growing, and its sustainability has to be accounted for and ensured. Similarly, the role of institutions is gaining importance in its contribution to sustainability. A unique contribution of this research is to analyze how energy sustainability can be enhanced in the five dimensions, namely economic, social, environmental, technical, and institutional using data envelopment analysis.

Table 5 Pairwise comparison of input and output criteria—expert 1

Input	L	E	W	H	N	Output	T	EC	S	EN	I
L	1	1/3	1/2	1	1/2	T	1	2	1/2	1/2	2
E	3	1	1//2	1/3	1/2	EC	1/2	1	1/2	1/3	2
W	2	2	1	1	1/2	S	2	2	1	2	2
H	1	3	1	1	1	EN	2	3	1/2	1	2
N	2	2	2	1	1	T	1/2	1/2	1/2	1/2	1

Sustainable energy indicators

Though there are several indicators being published to measure energy sustainability, it was found that these indicators concentrate only on certain aspects, for example, renewable energy sources [39–41] or country [42–44]. It is found that the resources available in a country have not been considered in the determination of energy sustainability. Singh et al. [10] based on their review state that an integrated framework is very much needed. The review also highlighted there exists some ambiguity and gaps in the indicators proposed. There is a need for a systematic focus in developing generic sustainable energy indicators.

The major indicators, namely OLADE, ECLAC, and GTZ [13], EDI [45], EISD [3], and multidimensional energy poverty index [14] have been extensively reviewed in several of the research papers. International Atomic Energy Agency (IAEA)/International Energy Agency (IEA) [46] under the aegis of Commission on Sustainable Development (CSD) has developed 41 indicators for sustainable energy development (ISED) and has classified them in terms of the indirect driving force, direct driving force and state (Table 14 in Appendix). This was a broad framework which indicated the driving force acts as a sort of input mechanism which results in an output. Vera et al. [47] have presented how from the original 41 ISED, the IAEA [3] have developed 30 indicators after long discourse with the United Nations Department of Economic and Social Affairs (UNDESA) and International Energy Agency (IEA). The 30 Energy Indicators for Sustainable Development (EISD) grouped the 30 indicators into three major dimensions—social (4 indicators), economic (16 indicators), and environmental (10 indicators) (Table 15 in Appendix). The indicators included both basic data as well as ratios, and hence summarizing the measures for a composite sustainable index is cumbersome. The indicators captured the consequences of energy production and utilization.

Streimikiene et al. [48] have applied the EISD tool for analyzing the trends from 1990 to 2002, setting policy goals, and for monitoring the progress towards these goals in the Baltic States. They have provided recommendations for developing sustainable energy policies. Salimov [49] has calculated the EISD economic dimension for the Azerbaijan Republic from 2007 to 2016 and have studied how the indicators have changed over the years and have highlighted how these indicators have given an impetus for the strategic development of the country.

To ensure all aspects of sustainability is taken care of, Bandura [50] developed 165 indices to assess sustainable development of which around 8 use some form of energy parameter. Patlitzianas et al. [51] have carried out a review on sustainable energy indicators and have proposed a framework based on their review. They stated that appropriateness, completeness, and flexibility should be the criteria for sustainable indicators selection. Indicators of security of energy supply, indicators of the competitive energy market, and indicators of environmental protection have been proposed. Jovanović et al. [52] have measured the energy system of Belgrade using sustainability energy indices from 3 dimensions, namely economy, social, and ecology (Table 16 in Appendix). Though varied aspects have been considered at the sub-indicator level, the importance and the unit of measure of each needs investigation. Mirza and Szirmai [53] have developed a composite index to calculate energy poverty, in other words, lack of sufficient energy among rural households in rural Pakistan. Vučićević et al. [54] have assessed the sustainability of energy use in residential buildings (Table 17 in Appendix) for considering economic, social, and environmental dimensions using multi-criteria analysis. This research considers energy sustainability from end-users'

Table 6 Consistency ratio of the experts for the criteria

Expert	CR input criteria	CR output criteria	Accepted
1	0.098938	0.059787	Yes
2	0.075312	0.033563	Yes
3	0.067906	0.096397	Yes
4	0.079985	0.094118	Yes
5	0.040228	0.036718	Yes
6	0.098136	0.322252	No
7	0.221946	0.071955	No

Table 7 Weights given by experts for input and output criteria

Experts	L	E	W	H	N	T	EC	S	EN	I
1	0.125	0.155	0.207	0.238	0.276	0.181	0.133	0.317	0.261	0.107
2	0.107	0.428	0.070	0.263	0.132	0.086	0.309	0.127	0.314	0.165
3	0.072	0.291	0.459	0.096	0.083	0.118	0.083	0.387	0.342	0.070
4	0.084	0.131	0.084	0.234	0.468	0.061	0.140	0.394	0.306	0.099
5	0.061	0.240	0.443	0.159	0.097	0.358	0.250	0.090	0.204	0.099
Average	0.090	0.249	0.253	0.198	0.211	0.161	0.183	0.263	0.285	0.108

perspective. The review highlights the following: firstly, the majority of researchers have considered sustainability in terms of three indices namely social, economic, and environmental. Secondly, the indicators were very detailed in their calculation some being numeric and some ratio, and arriving at a composite index was very challenging. Thirdly, the indicators do not link the resources of a country to energy sustainability. Any framework being proposed for determining sustainability has to ensure these concerns are addressed.

Iddrisu and Bhattacharyya [55] have formulated a composite index Sustainability Energy Development Index (SEDI) given in Table 18 in Appendix by combining five indices, namely technical, economic, social, environmental, and institutional. The SEDI has been calculated and compared across several developing countries. They have validated the index by comparing the index with HDI (Human Development Index), EDI (Energy Development Index), and EPI (Environmental Performance Index). Though energy sustainability has been calculated considering all the five indices, the link to the country's resources has not been addressed. This is vital, since for a country to become sustainable, it is necessary to check if the output delivered is in tune to the resources it is endowed with. A comprehensive composite measure for measuring sustainability index considering the country's resources is the need of the hour. This will help in comparing energy sustainability in a realistic manner across dimensions, sectors, and countries.

Using a multi-criteria Data Envelopment Analysis (DEA) methodology, it is proposed to identify how a country can progress towards sustainable development by finding a sustainable energy development efficiency (SEDE) considering the resources as the input criteria, namely land, energy, water, manpower, and national wealth and the five indices, namely technical, economic, social, environmental, and institutional as the output criteria. The results also highlight which sectors are sensitive to a certain country so that policies can be drafted keeping in mind that sector for maximizing SEDE.

Methodology

The research plan is given in Fig. 1. The research flow consists of three stages-fuzzy analytical hierarchical processing (AHP), data envelopment analysis (DEA), and sensitivity analysis.

Fuzzy AHP method

The resources, namely land availability (L), energy reserves (E), water availability (W), human capital (H), and nation's wealth (N) are considered as input criteria. Land availability (L) is defined as the land area of the country measured in terms of square kilometers (km^2). Energy reserves (ED) is defined as the total available energy reserves including all forms of energy in terms of tons of oil (toe). The water availability (W) is defined as the volume of water available within the country on an average measured in terms of cubic kilometers (km^3). The

Table 8 Assurance region multipliers

Min	Input criteria	Output criteria	Max
0.030388	L	E	0.493047
0.390306	L	W	0.390306
0.041215	L	H	0.371091
0.156685	L	N	0.326616
0.600307	E	W	0.79162
0.752649	E	H	2.04353
0.662445	E	N	5.156223
0.950771	W	H	3.404141
0.836821	W	N	0.836821
0.48844	H	N	3.801633
0.133186	T	EN	1.692353
0.315021	T	S	0.76501
0.133186	T	EV	2.001812
0.22002	T	I	1.68269
0.256185	EN	S	2.365269
0.287054	EN	EV	1.182857
1.272623	EN	I	1.651975
0.422785	S	EV	1.120496
0.69843	S	I	2.199565
1.651975	EV	I	2.104893

Table 9 Decomposition efficiency of the countries considering their sustainability criteria

	Country	Efficiency	L	E	W	H	N	T	EC	S	EN	I	Rank
A1	Iran	0.4314	0.3641	0.4456	0.1249	0.3391	1.0443	0.0279	0.1367	0.6741	0.1122	0.0491	8
A2	Argentina	0.2304	0.7963	0.0135	1.0184	0.3491	2.1637	0.0368	0.4001	0.3674	0.1507	0.0450	28
A3	Libya	0.2931	0.5124	0.1399	0.0009	0.0449	2.7139	0.0332	0.3214	0.3256	0.1374	0.1825	19
A4	Algeria	0.4493	0.7787	0.0474	0.0167	0.2343	1.1489	0.0401	0.1667	0.4352	0.1746	0.1834	6
A5	Venezuela	0.1241	0.3437	1.1485	2.0296	0.3234	4.2152	0.0477	0.2632	0.3263	0.1950	0.1679	37
A6	Jordan	0.6416	0.0414	0.0514	0.0019	0.0559	1.4079	0.0570	0.2496	0.4438	0.2489	0.0007	4
A7	Gabon	0.2523	0.1358	0.0126	0.3636	0.0163	3.4359	0.0735	0.0411	0.1443	0.1766	0.5645	22
A8	Ecuador	0.0212	0.1403	43.939	0.9133	0.2466	2.0055	0.0770	0.2171	0.2741	0.2396	0.1921	46
A9	Colombia	0.1104	0.6046	0.1644	4.9316	0.7937	2.5614	0.0691	0.3661	0.1317	0.1920	0.2410	39
A10	Angola	0.3603	0.6353	0.0534	0.3294	0.3104	1.4470	0.0302	0.0356	0.0219	0.1901	0.7222	15
A11	Brazil	0.0275	5.1903	0.2490	21.920	3.9168	5.1465	0.0826	0.3814	0.1910	0.2610	0.0840	45
A12	Egypt	0.3637	0.5374	0.0245	0.1343	0.9678	1.0854	0.0647	0.2084	0.3642	0.2682	0.0946	13
A13	Costa Rica	0.2404	0.0303	0.0000	0.2910	0.0815	3.7568	0.0758	0.4570	0.1781	0.2435	0.0456	25
A14	Yemen	0.6659	0.4144	0.0236	0.0072	0.2709	0.7856	0.1013	0.0636	0.1826	0.4222	0.2302	3
A15	Uruguay	0.2047	0.0885	0.0000	0.2678	0.0562	4.4734	0.0434	0.4183	0.3214	0.1911	0.0258	33
A16	Cuba	0.3291	0.0659	0.0008	0.0998	0.2059	2.6666	0.0706	0.4414	0.2674	0.1803	0.0404	16
A17	Panama	0.2089	0.0511	0.0000	0.4384	0.0751	4.2230	0.0898	0.4869	0.2126	0.1922	0.0185	32
A18	Paraguay	0.2249	0.3430	0.0001	1.2414	0.1618	2.6998	0.1181	0.1378	0.2098	0.3424	0.1919	30
A19	Tunisia	0.4381	0.1016	0.0027	0.0125	0.1526	2.0132	0.0769	0.3705	0.2991	0.1778	0.0757	7
A20	Nigeria	0.0944	0.9473	0.3837	4.2557	3.2126	1.7903	0.3080	0.0009	0.0227	0.3979	0.2704	41
A21	Mongolia	0.4086	0.8498	0.3713	0.0826	0.0413	1.1027	0.0722	0.1237	0.4880	0.1280	0.1881	9
A22	Peru	0.0861	1.0319	0.0069	6.7094	0.8454	3.0207	0.1156	0.4026	0.1583	0.2129	0.1107	42
A23	Thailand	0.1564	0.3686	0.0036	1.4345	1.8572	2.7300	0.0915	0.4876	0.1764	0.1835	0.0610	35
A24	Zambia	0.3177	0.8837	0.0002	0.5514	0.4273	1.2846	0.3344	0.0037	0.0433	0.5045	0.1140	18
A25	Bolivia	0.2153	0.9303	0.0018	2.1456	0.2549	1.3121	0.1145	0.1680	0.1697	0.2669	0.2809	31
A26	Morocco	0.3783	0.3328	0.0006	0.0999	0.5583	1.6515	0.0630	0.3571	0.2504	0.3271	0.0024	10
A27	Cambodia	0.2494	0.2144	0.0001	2.4633	0.6169	0.7145	0.3458	0.0075	0.1613	0.3971	0.0883	23
A28	Ghana	0.3694	0.2938	0.0084	0.2862	0.8882	1.2309	0.3197	0.0602	0.0850	0.4204	0.1146	12
A29	Cameroon	0.2354	0.6090	0.0027	1.5975	0.7033	1.3350	0.3639	0.0183	0.0318	0.3843	0.2017	26
A30	El Salvador	0.3775	0.0210	0.0001	0.1098	0.1682	2.3498	0.1171	0.2101	0.2414	0.3435	0.0878	11
A31	Zimbabwe	0.4993	0.4944	0.1025	0.1105	0.5569	0.7386	0.3725	0.0080	0.1148	0.3847	0.1198	5
A32	Philippines	0.1444	0.3200	0.0046	2.2321	2.6492	1.7186	0.2599	0.2877	0.1001	0.2750	0.0774	36
A33	Botswana	0.1805	0.5521	0.3609	0.0508	0.0522	4.5240	0.2519	0.4553	0.1153	0.1256	0.0520	34
A34	Indonesia	0.0496	1.8427	0.2215	8.5050	7.3121	2.2947	0.2605	0.1553	0.2103	0.1653	0.2086	44
A35	Benin	0.7886	0.1351	0.0002	0.1357	0.2772	0.7199	0.3151	0.0218	0.2465	0.3471	0.0695	2
A36	China	0.0160	7.2030	4.8842	9.3447	38.734	2.4998	0.0924	0.5271	0.2434	0.0369	0.1002	47
A37	Vietnam	0.0985	0.3844	0.2345	4.4842	3.8970	1.1573	0.3386	0.1081	0.1891	0.1926	0.1717	40
A38	Kenya	0.2916	0.8187	0.0004	0.1787	1.3946	1.0364	0.2770	0.0045	0.0560	0.5389	0.1236	20
A39	Togo	1.0000	0.0789	0.0001	0.0892	0.2641	0.5678	0.2450	0.0085	0.0606	0.5689	0.1171	1
A40	Honduras	0.3246	0.1528	0.0001	0.5694	0.2893	2.0688	0.3527	0.1670	0.1163	0.2840	0.0800	17
A41	Sri Lanka	0.2428	0.0918	0.0001	0.3229	0.7704	2.9339	0.3436	0.1637	0.0773	0.3235	0.0920	24
A42	Guatemala	0.2285	0.1486	0.0015	0.6636	0.4931	3.0697	0.3449	0.1515	0.1130	0.2897	0.1009	29
A43	Bangladesh	0.0721	0.2065	0.0781	7.4571	5.3167	0.8090	0.3524	0.0847	0.1114	0.3087	0.1428	43
A44	Nicaragua	0.2848	0.1961	0.0001	1.2917	0.2397	1.7839	0.3464	0.1220	0.0872	0.3455	0.0988	21

Table 9 Decomposition efficiency of the countries considering their sustainability criteria *(Continued)*

	Country	Efficiency	L	E	W	H	N	T	EC	S	EN	I	Rank
A45	Jamaica	0.2341	0.0118	0.0000	0.0442	0.0955	4.1201	0.0996	0.4075	0.2504	0.2200	0.0224	27
A46	India	0.0151	4.4608	7.0698	11.328	42.065	1.3453	0.3408	0.2121	0.1798	0.1446	0.1226	48
A47	Senegal	0.3628	0.3345	0.0000	0.2882	0.4340	1.6998	0.3953	0.0933	0.0986	0.3266	0.0861	14
A48	Pakistan	0.1178	1.0313	0.1077	1.3966	4.8674	1.0848	0.0462	0.1050	0.3683	0.3414	0.1391	38

human capital (H) is defined as the manpower available for employment (numbers). For this research purpose, the nation's wealth is defined to be the gross domestic product available per person (GDP per capita). As various units of measure have been used among the input criteria, normalization was carried out before performing DEA. The framework of this research proposes that the available resources have to be utilized optimally to achieve sustainable energy development. However, sustainable energy development is defined to have multiple criteria and maximizing each of these criteria is expected to result in overall maximum sustainable energy development.

Based on the review of literature, five indices have been considered as the output criteria, namely technical (T), economic (EC), social (S), environmental (EN), and institutional (I) that has to be maximized for achieving sustainable energy development. Since there are multiple outputs that have to be simultaneously maximized with the available input resources, a multi-criteria decision model, namely data envelopment analysis is chosen for this research. The values of these five output criteria for various countries calculated by Iddrisu and Bhattacharyya [55] are used in this research.

To obtain a higher degree of precision, fuzzy AHP has been used to determine the relative weights of the five input and five output criteria based on intuitionistic judgment and to develop a hierarchical multi-criteria decision-making (MCDM) model.

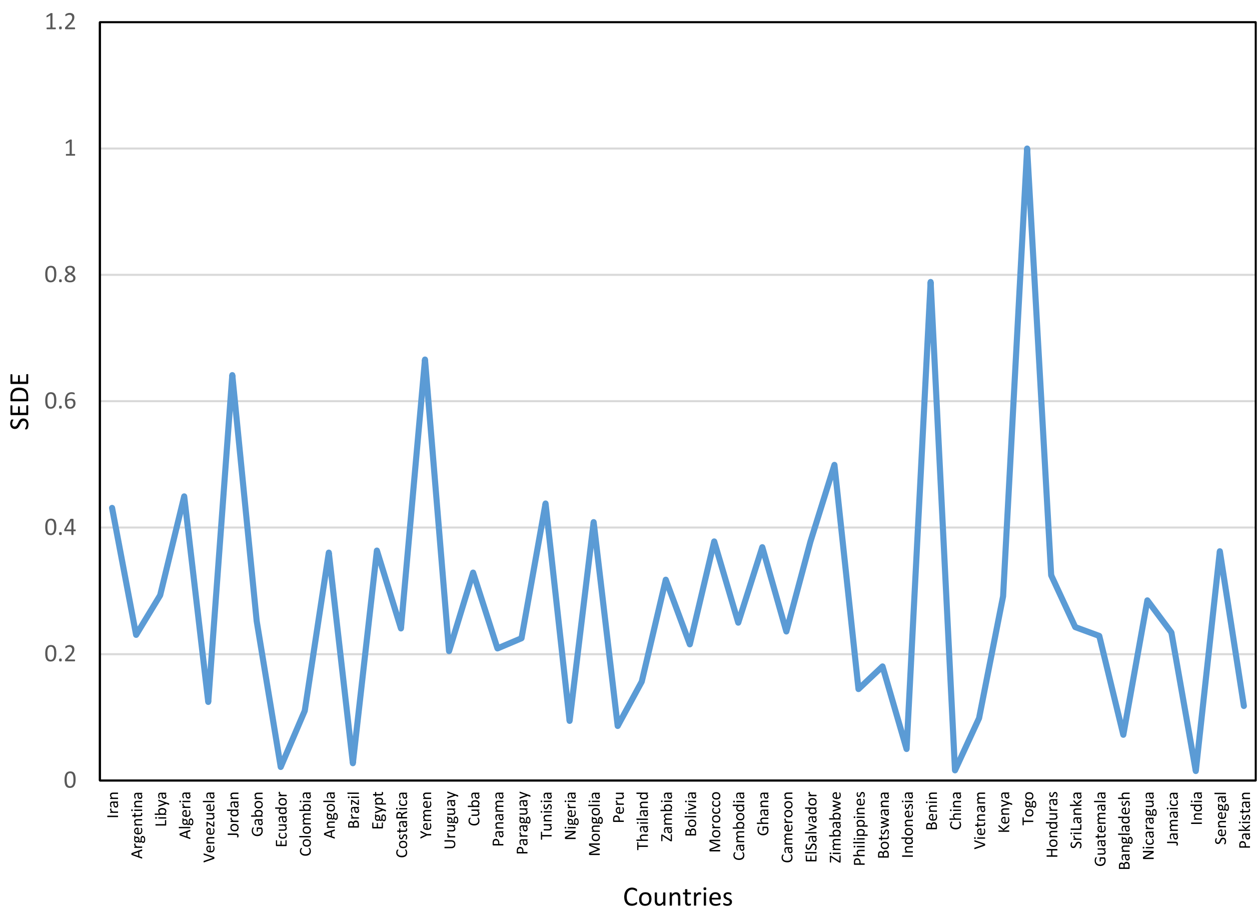

Fig. 3 SEDE of various countries from DEA

A questionnaire for pairwise comparison among the input and output criteria was designed for distributing to the experts. The criteria weights are based on the expert's opinion, and hence the selection of the experts has to be judiciously done. The number of experts chosen for the study was based on the expert's accessibility and availability. Research does not mention the number of experts essential to conduct AHP [56]. It is very important to select the expert with the right competence so that there is unanimity in the decision process. The research also highlighted that the significance of expert competence is inversely proportional to the group size whenever there is group decision-making [57]. The extant literature confirmed that smaller expert size will help in getting an effective response since there will be a concerted effort.

As the decision process involved an evaluation of criteria dealing with sustainable development, seven experts were chosen for the study. The expert group comprised of two government officials, two industrialists, two consultants, and one academician. All the experts chosen for this study were of Indian origin. The first expert who was a government official had a doctorate in energy management with 18 years of government service. He belonged to the Indian administrative service and has been holding various administrative positions in state-owned electricity and pollution control organizations. The second expert—who is again a government official with 22 years of government service—had done his graduation in electrical engineering and has been holding various positions in the state-owned electricity board. The third expert was a science graduate with 18 years of industrial experience working in a renewable energy organization handling solar and wind energy projects. The fourth expert had done mechanical engineering and business administration and is working in an energy organization. He is involved in sanctioning and commissioning of energy projects and has 21 years of industrial experience. The fifth expert was a consultant with 15 years of experience as a consultant. His job profile included preparing feasibility reports and drafting of project proposals in the energy sector for availing bank loans. The sixth expert was a consultant in a quasi-government organization that acts as a facilitator between industrial partners and financial

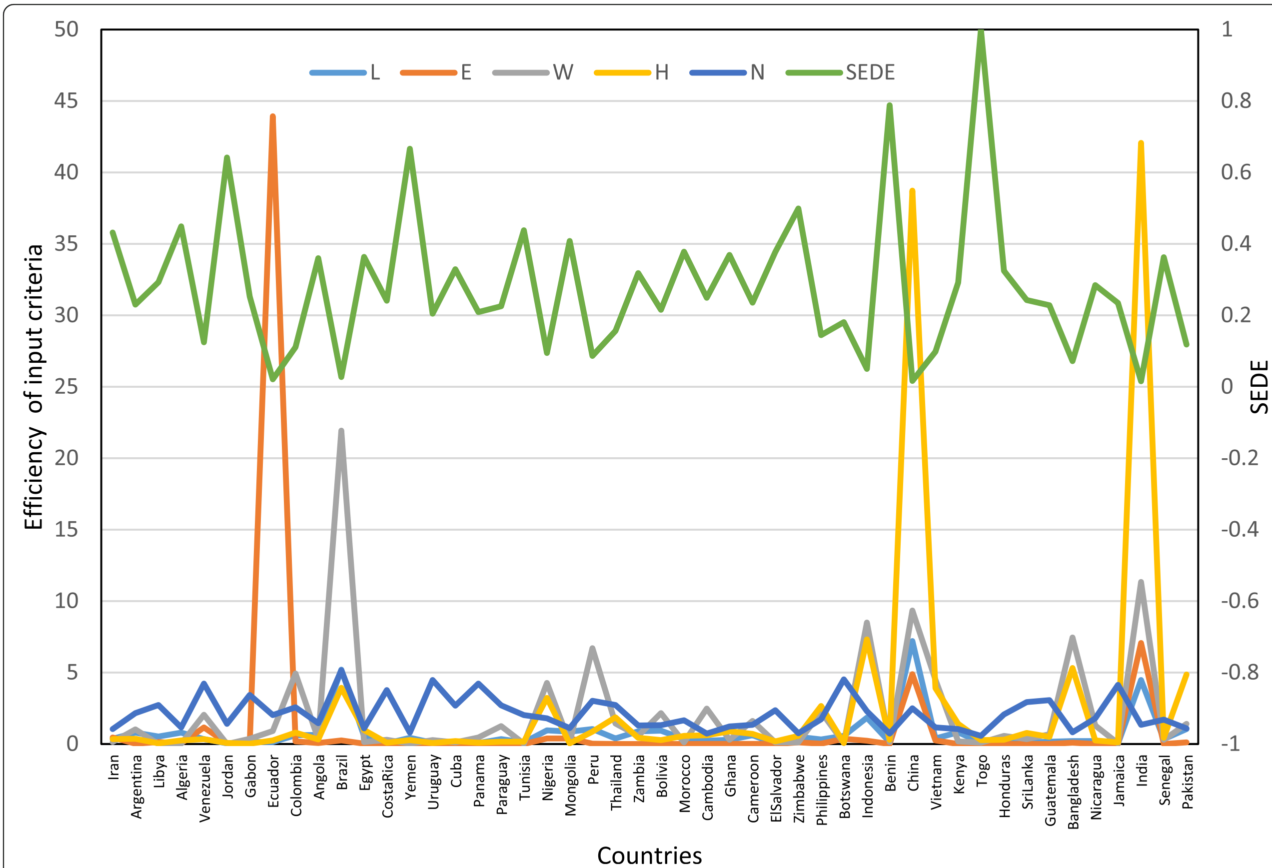

Fig. 4 Comparison of SEDE with input criteria for various countries

institutions. He was instrumental in scrutinizing the project proposals and facilitated the smooth transfer of bank loans to the industrial partners from the financial institutions. He has a total experience of 20 years as consultant handling projects in various disciplines including energy. The seventh expert was an academician with 27 years of experience. He had completed his graduation in mechanical engineering, postgraduation in thermal sciences, and a doctoral degree in energy systems. His area of expertise is energy management with special reference to renewable energy. The right choice of experts was very important for this study. It was found that the experts' years of work experience ranged from 15 to 27 years. The area of their expertise included energy and energy-related disciplines.

The experts were requested to do a pairwise comparison of the input and output criteria and rate the importance of using a rating scale (Table 1). Consistency index and consistency ratio (CR) were calculated for each expert [58, 59]. The rating of an expert was accepted if CR ≤ 0.10. The ratings given by the experts were then converted to fuzzy weights using triangular fuzzy scale (TFN) (Table 2) [60]. The weight vectors were determined and normalized to obtain relative weights [58, 59].

Sustainable energy development efficiency using DEA

Data envelopment analysis (DEA) is a multi-criteria multi-evaluation non-parametric method used to measure the relative efficiency of a set of alternatives considering input and output criteria. The fuzzy AHP weights were used as priority weights for the criteria in DEA analysis. Figure 2 shows the hierarchical structure of the DEA model. In the DEA analysis, CCR model, namely Charnes, Cooper, and Rhodes [61] model was adopted to find the relative efficiency ranging from 0 to 1. This model considered production components as constant return-to-scale. An assurance region Charnes, Cooper, and Rhodes (AR-CCR) output-oriented model was selected to avoid null output in the analysis. The relative efficiency was calculated using a country's resources as input criteria, the five indices, namely technical, economic, social, environmental, and institutional as output criteria to evaluate the sustainable energy development efficiency among the developing countries. Forty-eight countries have been chosen for the study. The input values (country's natural reserves) were collected from various sources. The energy reserves data for the 48 countries were collected from several websites ([62], http://www.economywatch.com/economic-statistics/) for each of the energy sources, namely coal, oil, fuelwood,

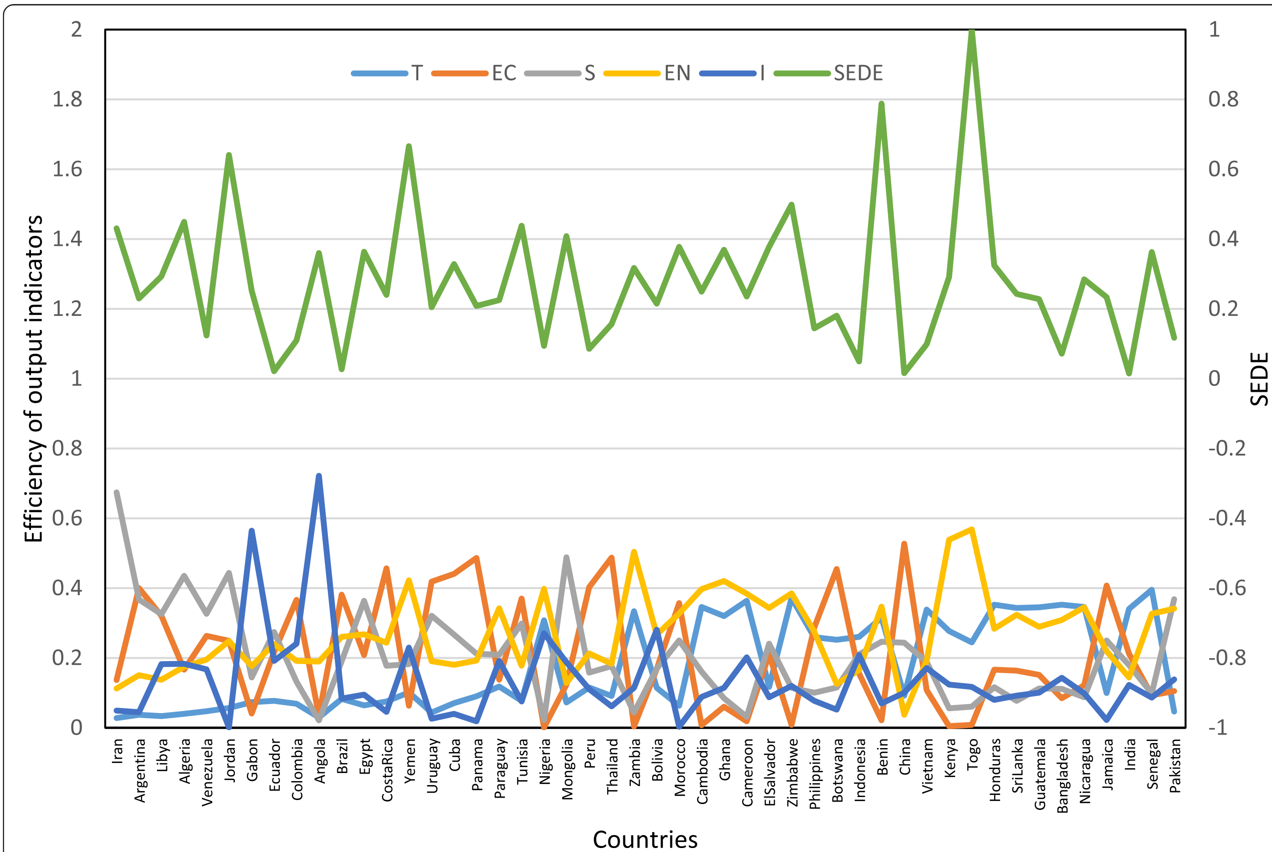

Fig. 5 Comparison of SEDE with output indicators for various countries

bagasse, natural gas, nuclear, and wind. The total energy reserves were then calculated in tons of oil equivalent (toe). The land availability (unit km^2), human capital (employable labor in numbers), and national wealth (GDP per capita constant US dollar) was collected from World Bank data [4]. The water in terms of renewable water resources (unit km^3) for the 48 countries was collected [63]. The data used as input is given in Table 3.

As already highlighted in the literature review, the researcher has found that the triple bottom approach with only economic, environmental, and social criteria for ascertaining the sustainability is insufficient. Considering this, it is found that sustainability needs to be assessed from all perspectives. For energy sustainability from the technical perspective, the proportion of renewable energy utilization as compared to primary energy should be on the increase. Also, the locally available energy should not be exploited to a large extent. In all cases, for technical energy sustainability, the conversion efficiency should be maximum. From the economic perspective, it is essential to ensure the energy intensity declines, the per capita energy consumption is efficient, and the energy being used is productively utilized by its consumers. To ensure environmental sustainability, it is essential that the emissions from the primary energy sources are kept at the base minimum. From the social perspective, the energy consumed is clean and equality is maintained across all consumers. For the institution to achieve energy sustainability, it is prerogative to ensure that energy is produced using indigenous production process for achieving self-sufficiency. Considering these as the goals for achieving energy sustainability, they are treated as the output criteria. It was found from a review that the indices used by Iddrisu and Bhattacharyya [55] given in Table 18 in Appendix were appropriate for this research, and hence it was used as the output criteria. The values of the output criteria are given in Table 4.

The analysis yielded an efficient frontier which was considered to be the best among the alternatives for a given set of criteria. The results helped in identifying hidden relationships existing among the multiple criteria taken together. DEA is a versatile tool since it is capable of handling multiple inputs and outputs and secondly presents the frontier alternative considering both the

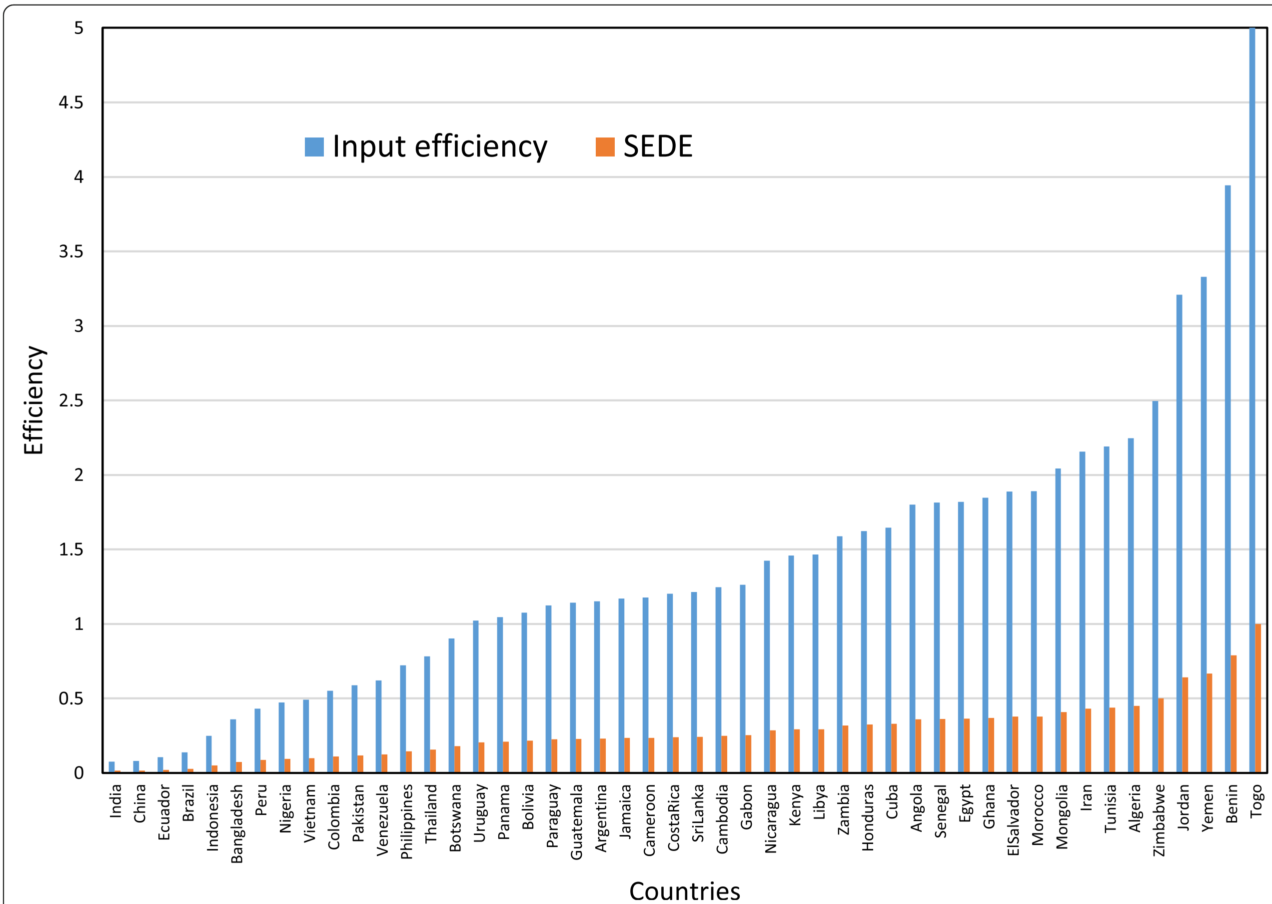

Fig. 6 Comparison between input efficiency and SEDE

input and output parameters. In this research, the DEA result posits if a country is moving in a sustainable manner by using its resources in an efficient manner to achieve the targeted outputs. The SEDE for the various countries was compared with HDI and EDI to draw further inferences.

Sensitivity analysis

A sensitivity analysis was performed on the DEA model. Since it was an output-oriented model (i.e., the output is kept as the target), the DEA analysis was run for a 10% decrease and 10% increase in each of the input criteria, namely land availability, energy reserves, water availability, human capital, and nation's wealth for each country. Sensitivity analysis is performed to find the sensitivity of each of the input criteria. Though a few of these criteria are constant, yet to study its influence on the output criteria, a sensitivity analysis was carried out. For instance, if the land (which is considered to be constant) was found to be sensitive for a country, then it is very important that policymakers take extra care to draft policies and measures for making effective use of the available land leading to increased energy efficiency. The percentage change in the sustainable energy development efficiency was calculated for each input criteria and for each country and analyzed.

Results

Fuzzy AHP

The questionnaire for carrying out a pairwise comparison of each of the input criteria as well as the output criteria was given to seven experts. The experts were asked to rate each of the criteria against the other using a table (Table 1). The ratings of the pairwise comparison for the first expert are given in Table 5. Based on the expert's ratings, the consistency ratio (CR) was calculated. The CR value for the first expert was 0.098938 for the input criteria and 0.059787 for the output criteria. Similarly, the CR value was found for the seven experts. The CR values for the seven experts are given in Table 6. It was found that the CR value for two experts was above 0.1 in either the input or output criteria, and hence the ratings were excluded. The ratings of the remaining five experts were then transformed to fuzzy weights using TFN scale (Table 2) for the first expert. The normalized non-fuzzy weights for the five input

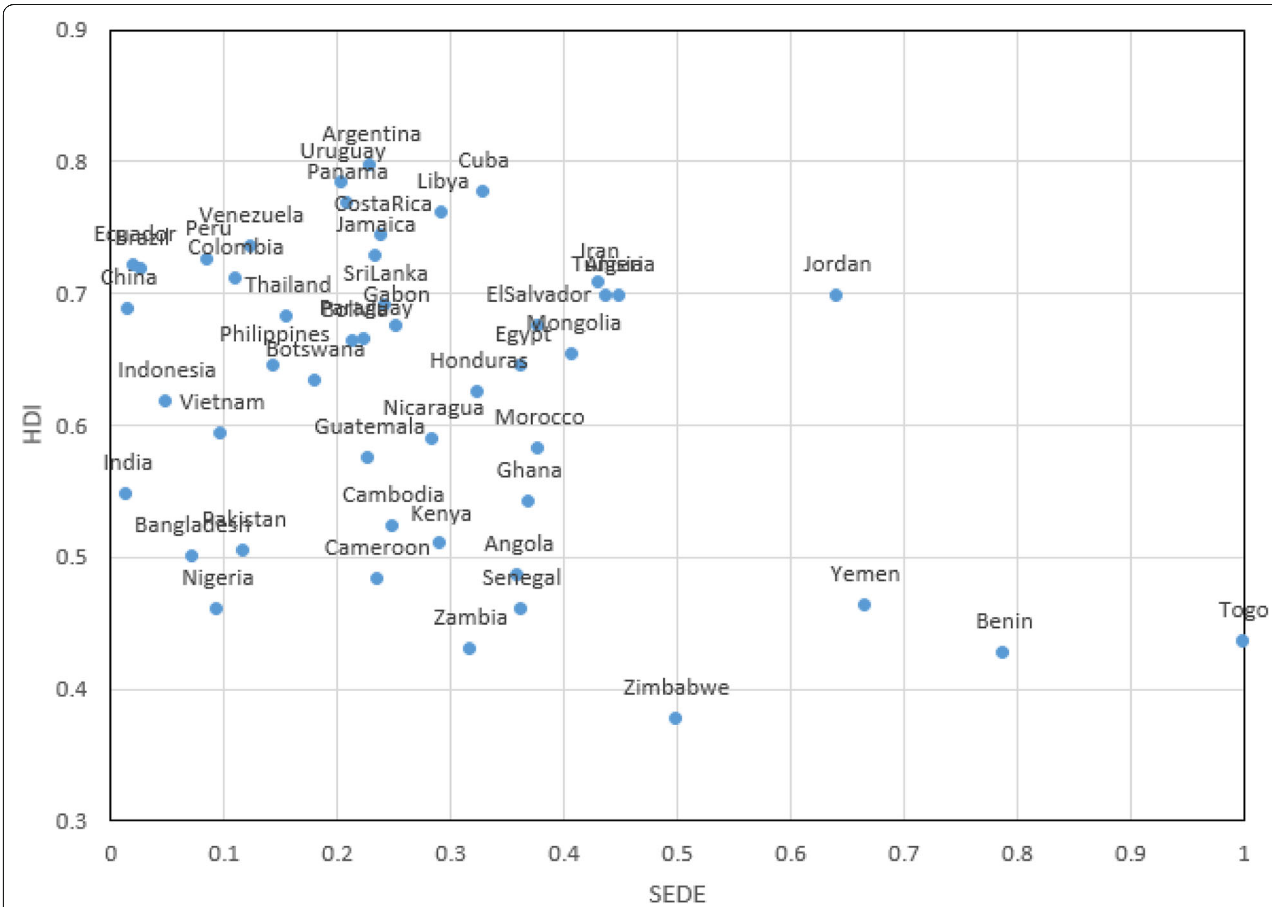

Fig. 7 Mapping of SEDE versus HDI

criteria were 0.125, 0.155, 0.207, 0.238, and 0.276 and for the output criteria 0.181, 0.133, 0.317, 0.261, and 0.107. In a similar manner, the weights for input and output criteria given by the five experts along with the average weights are given in Table 7.

From the weights, it was found that the maximum weight of 0.253 has been assigned to water availability followed by energy reserves with 0.249. This indicated that among the resources, water availability and energy reserves were important and care has to be exerted to use these reserves in a prudent manner for sustainable development. Among the output indices, it was found that an environmental index with 0.285 is the most important, followed by a social index with 0.263. Experts are of the opinion that the above indices are very important for sustainable development.

DEA using AR-CCR output-oriented model

The mean rating given by the five experts for the input and output criteria for sustainable energy development were used as multiplier constraints in the assurance region of the DEA model. The assurance region multipliers are given in Table 8. As every country would like to maximize its indices with the available resources, the DEA model was aimed at maximizing the output criteria with an output-oriented model. The DEA analysis was carried out using DEA add-in Excel. The efficiency of the selected countries and the decomposition efficiency of the criteria are given in Table 9. The DEA model revealed a country's proximity to the efficient frontier. The sustainable energy development efficiency (SEDE) was calculated using the DEA model for the 48 countries and is presented in Fig. 3. Using the SEDE score, the countries are ranked. Togo was ranked 1 and identifies as the country lying in the efficient frontier. Among the output indices, it is found that the SEDE is maximum for an environmental index with 0.5688 followed by a technical index at 0.2495. Considering the input criteria, it was found that with the available reserves, Togo has efficiently delivered the desired maximum output resulting in maximum SEDE.

Figure 4 presents a comparison between SEDE and each of the input criteria for various countries. It was clearly visible from the figure that Togo has less of input reserves, and by using that it was able to obtain the

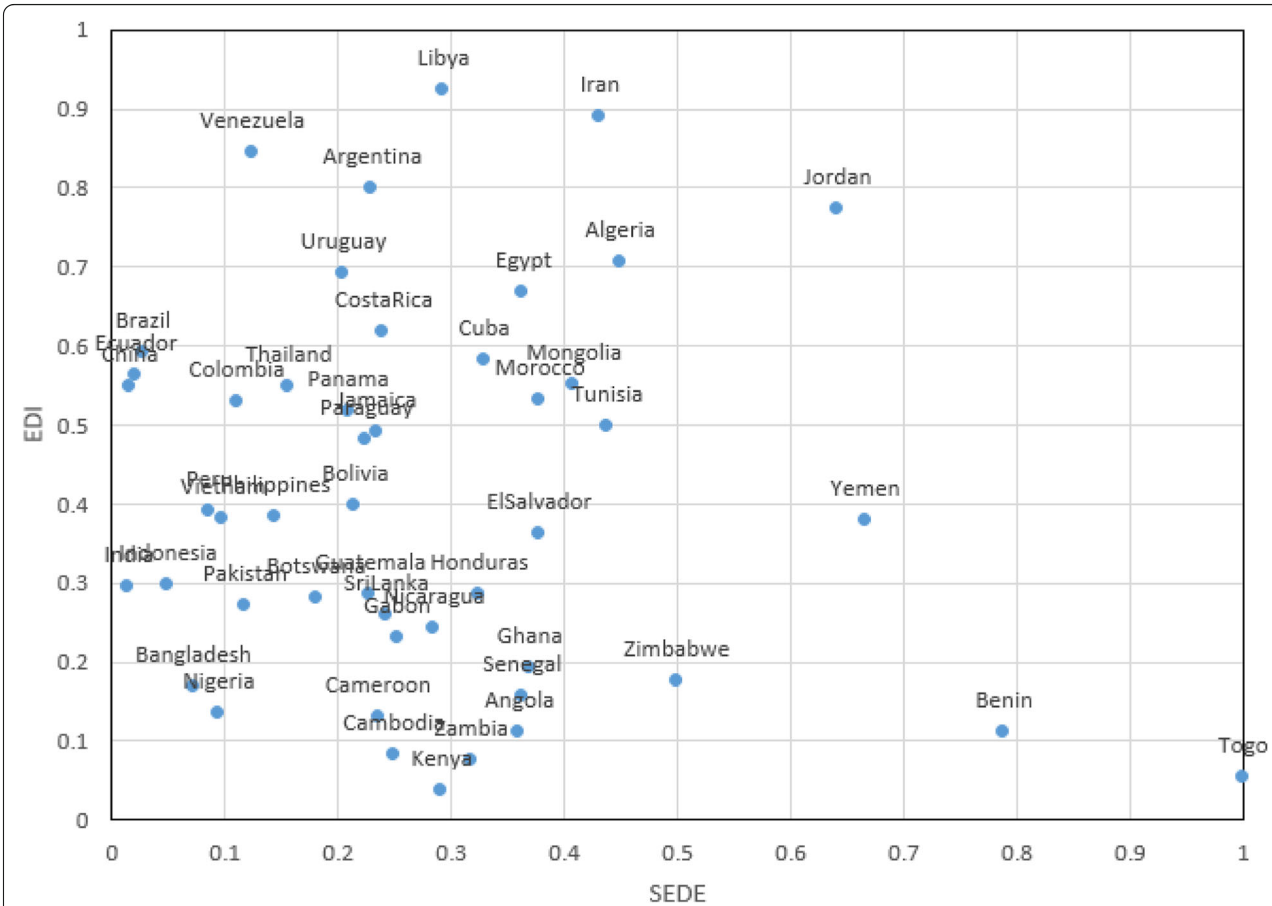

Fig. 8 Mapping of SEDE versus EDI

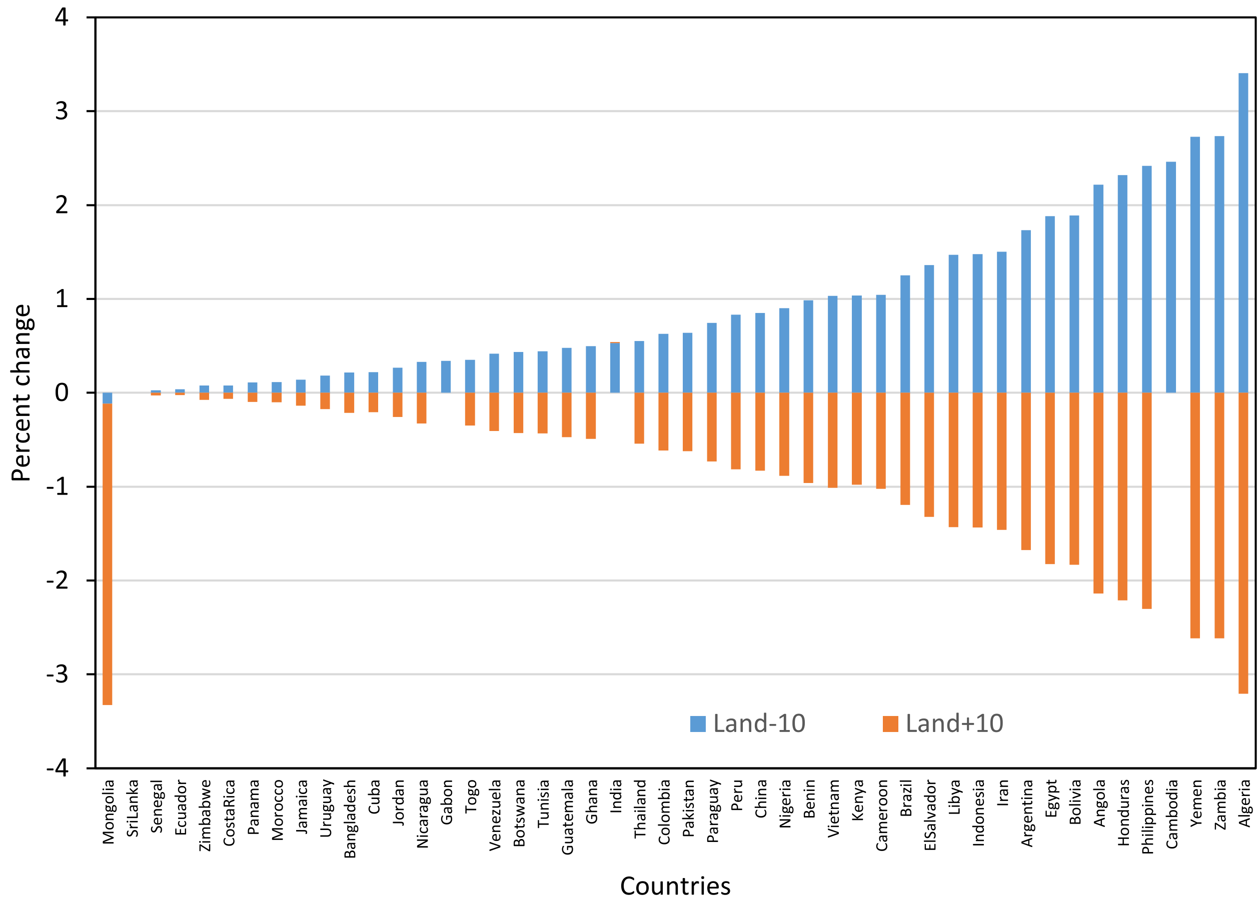

Fig. 9 Sensitivity analysis for 10% change in land availability

maximum output. Figure 5 presents a comparison between SEDE and output criteria for various countries. Though Angola has maximum effectiveness for the technical index yet considering all the output indices, Togo has the maximum SEDE.

As the DEA was run as an output-oriented model, a comparison was made between the aggregate input efficiency against SEDE for the various countries and is presented in Fig. 6. It was found that the countries which are getting maximum SEDE are those that are efficiently and conservatively using their resources. The figure clearly indicated that for a certain input of resources, there was more than a proportionate increase in sustainable energy development efficiency. This was due to the varying nature of the importance of the input criteria and the resources a country is endowed with.

A comparison was made between the SEDE and the Human Development Index (HDI), the SEDE and the Energy Development Index (EDI). The mapping of SEDE versus HDI is given in Fig.7. The figure clearly indicates that even though few countries have higher values for HDI yet they have very low values for SEDE. This indicates that such countries are not using their total resources in a holistic manner which is clearly visible in the SEDE score. Similarly, the mapping of SEDE versus EDI is plotted in Fig. 8. This figure clearly shows that countries are very good in their energy development index. But in the overall, is the resources of the country being used efficiently across all indices, it is found that there are lots of discrepancies. Few countries have got a very high EDI but the SEDE score is very low indicating inefficient use of their country's total resources.

Sensitivity analysis

The input criteria, namely land availability for Iran, were reduced by 10% and the DEA model was run. It was found that there was an increase of 1.5 % in the SEDE score. However, when the land availability was increased by 10%, it was found that SEDI decreased by 1.46%. Similarly, the DEA was run for 10% change in land availability for Argentina, and it was found that when there was a 10% decrease, SEDE increased by 1.73% while when it was increased by 10%, SEDE decreased by 1.67%. Similarly, the DEA was run by first reducing land availability by 10% for each country and then by increasing by 10% of land availability. In each case, the

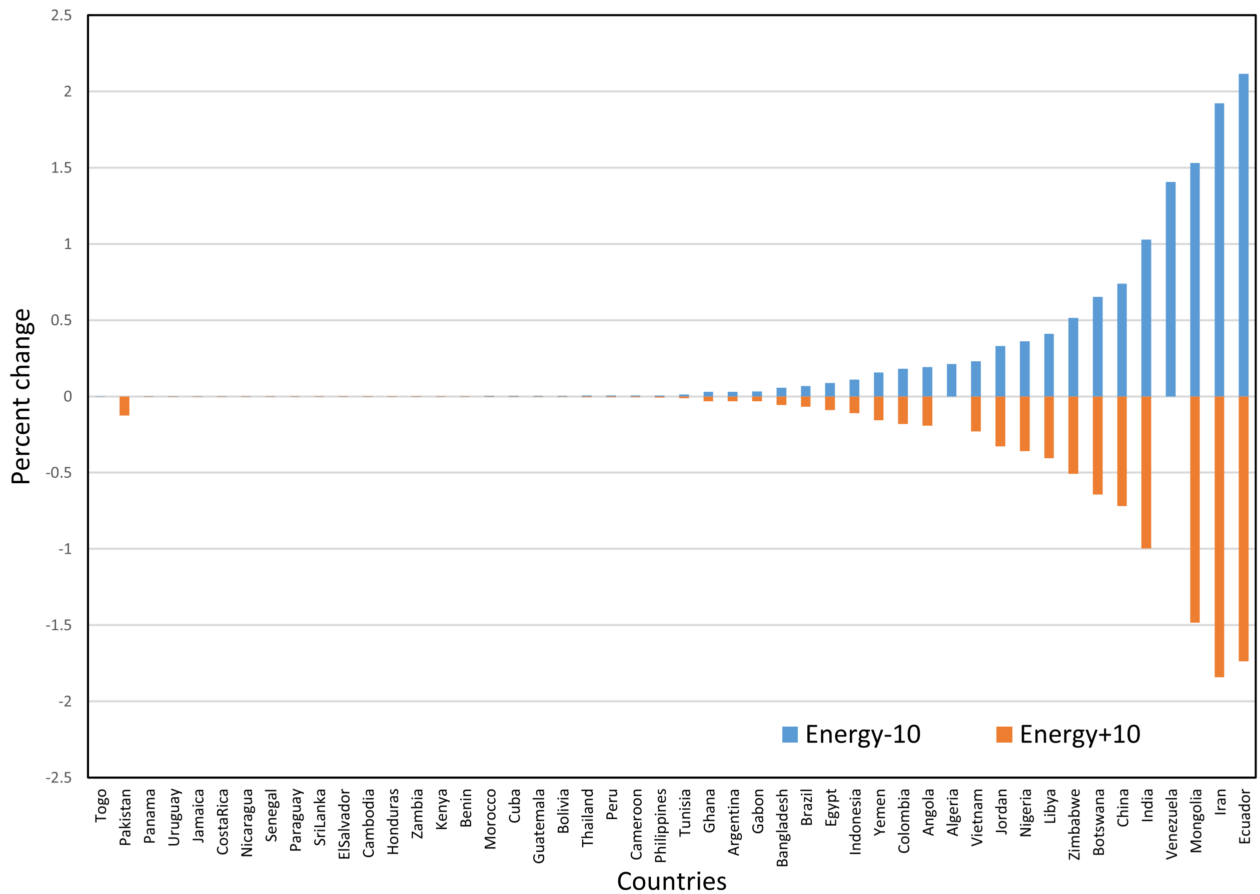

Fig. 10 Sensitivity analysis for 10% change in energy reserves

percentage change in SEDE was calculated and the values for all the countries are plotted in Fig. 9. A similar analysis was carried for each of the input criteria, and the percent change is plotted in Fig. 10 for energy reserves, Fig. 11 for water availability, Fig. 12 for human capital, and Fig. 13 for national wealth.

Discussions

The fuzzy weights given by the experts indicate that four out of five input resources are very important for sustainable development. Also, the experts have given almost equal weight for the four resources, namely water availability, energy reserves, nation's wealth, and human capital. However, of the four input criteria, water followed by the energy was given the maximum importance indicating these two resources are very vital for sustainable development. These resources have to be used in an effective manner so that higher indices are achieved for sustainable development. Among the output criteria, it was found that achieving higher environmental and social indices were very important for sustainable energy development. It was found that almost all experts have stated that environmental indices need to be carefully monitored for maximizing sustainable energy development. Three experts have indicated social indices as equally important. Experts were of mixed opinion when it comes to technical and economic indices. On the other hand, almost all experts have given the least weight for institutional indices.

As highlighted in the reports [64, 65], a country's natural resources should never become a curse. It is the responsibility of planners and policymakers to ensure the resources are being judiciously utilized for energy sustainability. In this research, the DEA analysis clearly highlights whether the country's resources are being efficiently used to obtain the desired outputs. The 5 top-ranked most efficient countries as per the order of ranking are Togo, Benin, Yemen, Jordan, and Zimbabwe. Though these countries have minimal resources, yet they are able to effectively transfer them to desired output as indicated by the higher indices in the environmental and social criteria. This is also clearly visible in Fig. 4. India is a highly populated country and is very high in human capital. But SEDE is very low for India and is ranked at 48th position. This clearly indicated that the resources are not being

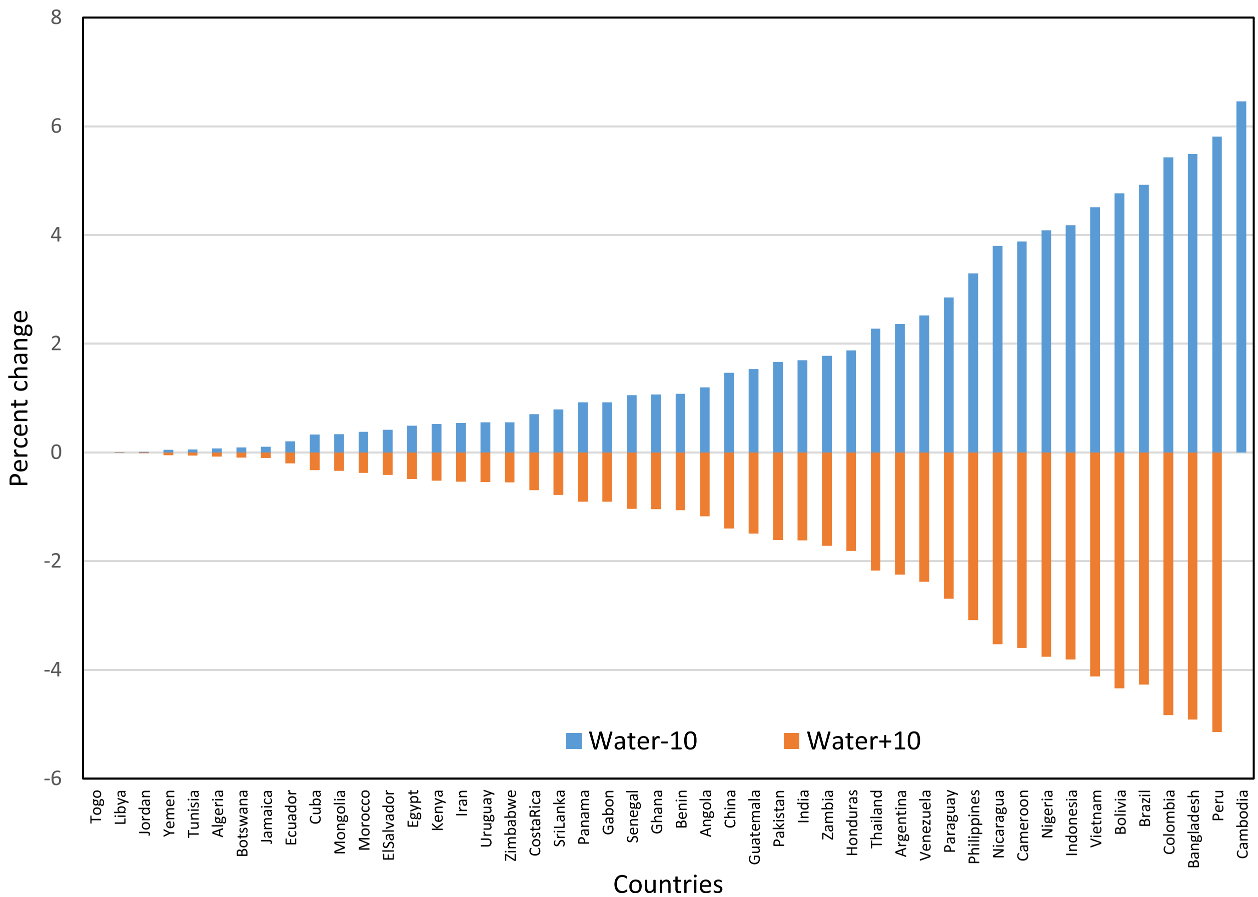

Fig. 11 Sensitivity analysis for 10% change in water availability

utilized in an efficient manner. Similarly, for China, the human capital is very high which itself becomes a burden, and the SEDE is very low at 47th position. Also, Ecuador is found to have maximum energy reserves, yet in terms of SEDE, it is ranked 46. Brazil has the maximum renewable water availability while as per SEDE it is ranked 45. This clearly indicates that it is not just sufficient to stock the resources but they need to be transformed into valuable output for achieving higher SEDE. Examining Togo which is at the frontier efficiency, it is found that the country's resources are very low. Yet with the available resources, it is able to deliver higher value in terms of the five indices which has led to maximum SEDE. Similar values are found for Benin, which also has minimal resources at its disposal. Yet with the minimal resources, it is delivering higher value in terms of output indices which has led to higher SEDE.

Figure 5 highlights the contribution of the five output indices for sustainable energy development. The weights from fuzzy AHP indicated that environmental index is very important followed by a social index. Togo has scored the maximum in the environmental index which could be one of the reasons for it to lie in the efficient frontier while when it comes to the social index it is far behind. As far as the social index is concerned, it is Iran which has been scored the maximum. With regard to technical index, Togo has scored fairly well while for economic index it was almost zero with 0.0085. Benin is ranked at the second position with reference to SEDE. The reason could be it has performed fairly well with reference to environmental, social, and technical indices which are fairly important indices as perceived by the experts. Benin did not score well for economic and institutional index. Notwithstanding this, Benin scored the second position in SEDE. Algeria was found to have the maximum score for institutional index. However, since the weight assigned to the institutional index was less as per the experts' perception, and also since for all other indices it is far below in its position, it is found that the SEDE ranking for Algeria was at sixth. Comparing China and India, wherein both countries are high on human capital, it was found that their SEDE ranking was at 47th and 48th position respectively. China had scored the maximum with regard to economic index and fairly well in the social index while for all other indices it was very

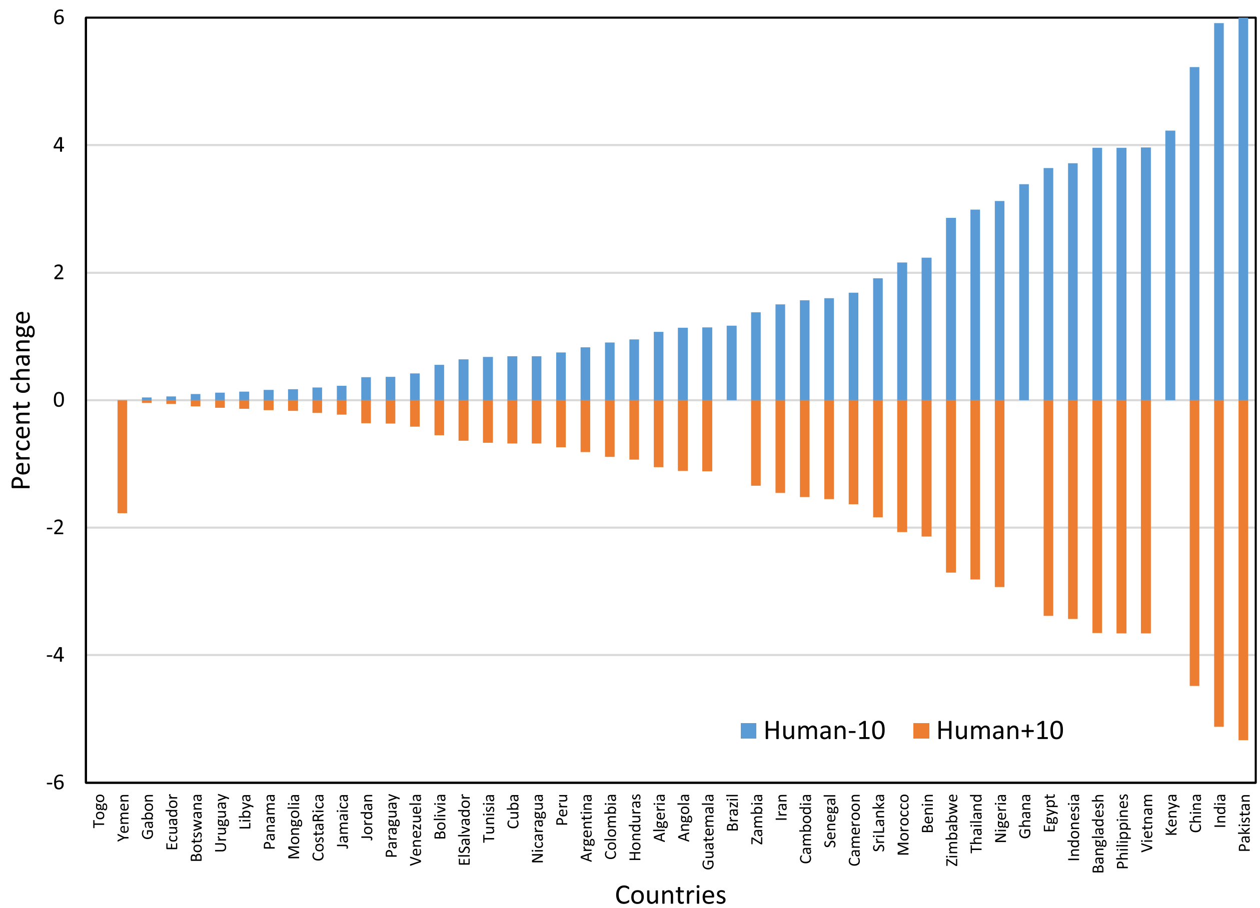

Fig. 12 Sensitivity analysis for 10% change in human capital

low. India was found to have scored maximum in the technical index while for all other indices it was very low. This indicates India needs to strengthen and make policies towards the environmental and social front so that if these two indices are increased there will be a drastic change in its SEDE position. Similarly, China also needs to take corrective action at its environmental front because it has scored the least in the environmental index, the index considered most important for SEDE by experts. The second action plan China needs to take is to find mechanisms for improving its technical and social index. This will immediately put China in a very competitive position in SEDE ranking. Comparing Figs. 4 and 5 for India, it is clearly visible that India has a remarkably large land area. However, from the results, it is seen that in spite of the land area being vast, it is not facilitating in achieving the desired outcome in terms of a maximum SEDE. As already indicated, resources should never become a liability [66, 67]. Immediate action is required for using this resource in an effective manner so as to enhance sustainability in terms of environmental and social indices for India.

The cross-examination of SEDE with HDI clearly indicates that China, Ecuador, Brazil, Venezuela, Argentina, Uruguay, and Panama have a very high HDI but a very low SEDE score. This indicates that these countries though are good in human development at a national level; they are not using their country's resources in an efficient manner. Immediate action has to be taken by these countries to ensure their resources are being used so that they can move towards overall sustainable energy development. Similarly, the mapping between SEDE and EDI clearly indicates few countries (for example, Libya, Iran, Venezuela, Argentina, Uruguay, and Egypt), which seem to be doing well with energy development, are not really progressing in a sustainable manner. Proactive measures have to be taken by the countries which are in the upper-left quadrant. For countries which are positioned in the lower-left quadrant, immediate measures have to be taken with a missionary zeal so that they are propelled to move towards the right.

Sensitivity analysis revealed the countries that were sensitive to certain indices. When there was a 10% change in

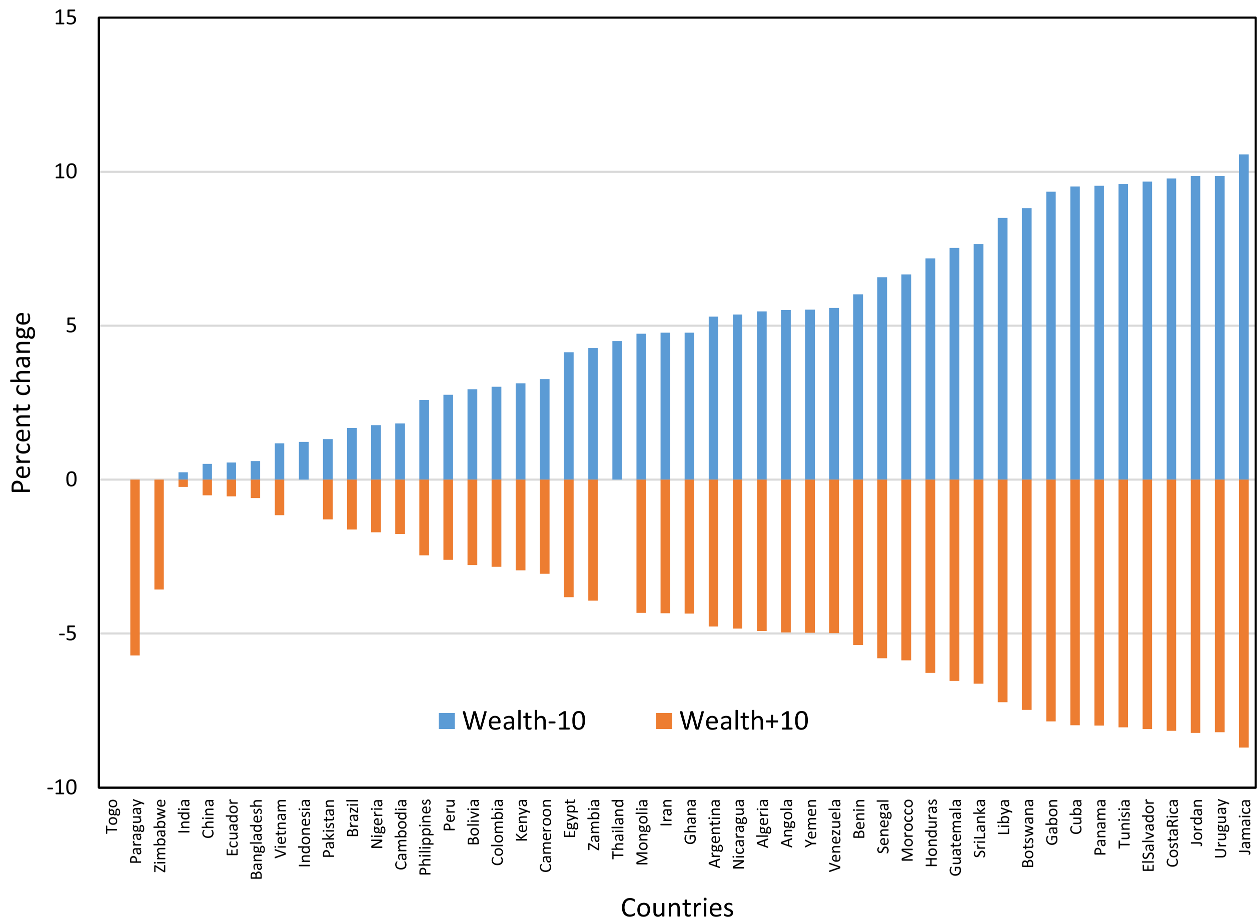

Fig. 13 Sensitivity analysis for 10% change in nation's wealth

land availability, the percent change in SEDE was considerable for Algeria, followed by Yemen, Mongolia, Zambia, Philippines, Honduras, Angola, Egypt, and Bolivia. This indicated that for improving sustainable energy development efficiency, these countries need to draft policies and take measures in these criteria, namely land availability which is sensitive for their country. For a few countries, the percent change in SEDE was very minimal, namely Sri Lanka, Senegal, Ecuador, Zimbabwe, Costa Rica, and Panama. This shows that for improving SEDE among these countries, it is not advisable to concentrate on these criteria. Similarly, for Ecuador, Iran, Mongolia, Venezuela, India, China, Botswana, and Zimbabwe are advisable to concentrate on how energy resources are being utilized, since this criterion is very sensitive for these countries towards improving SEDE. However, the figure indicated that for several countries the utilization of energy reserves in contributing to SEDE is insensitive. When it comes to water, it is seen that several countries are sensitive. The most sensitive countries are Cambodia, Peru, Bangladesh, Colombia, Brazil, Bolivia, Vietnam, Indonesia, and Nigeria. These countries have to cautiously work on the water availability, so that they might exponentially increase their SEDE score. The countries for which water availability does not cause a major impact on SEDE are Libya, Jordan, Yemen, Tunisia, Algeria, Botswana, and Jamaica. As witnessed by the nature of population explosion in the developing countries, wherein China and India are the forerunners, it becomes doubly important to use human capital in an astute manner, since the human capital which is normally considered an asset in business parlance has become a liability as seen in the SEDE score. The utmost care and prudence need to be exercised by the policymakers and planners of these nations to convert this challenge into a strength. If strategic decisions are not taken immediately, though the country is endowed with rich resources, it will not be far off before the country moves slowly towards a marked rich-poor divide. The quality of life will deteriorate and the resources will be washed off by the heavy population. The other countries that fall in this category include Pakistan, Kenya, Vietnam, Philippines, Bangladesh, Indonesia, and Egypt. Among these countries, innovative measures to transform the human capital asset into potential output indicators that will lead to a higher SEDE score need to be immediately taken, since among these countries human capital criteria are sensitive with reference to SEDE. With regard to how sensitive is the nation's wealth in contributing to SEDE, it was found that almost all countries are sensitive. Figure 13 clearly shows a funnel-shaped structure indicating a nation's wealth is a very sensitive criterion for almost all countries. The countries which are very sensitive are Jamaica, Uruguay, Jordan, Costa Rica, El Salvador, Tunisia, Panama, Cuba, and Gabon. How the nation's wealth is being utilized is a very important factor for any country and this is what the results have also corroborated. Care has to be exercised during the country's budgeting that every amount that is being spent is contributing to the sustainable development of the nation.

Conclusions

The review of literature highlighted that indicators keep evolving over time and they need to be fine-tuned to the needs of a country depending on the nature of resources a country is endowed with. A cross-sectional study by comparing indicators across countries will serve as a benchmark for a country to progress in a sustainable manner which was undertaken in this research. The indices are compared across 48 countries. The research has identified the country's resources, namely as land availability, energy reserves, water availability, human capital, and nation's wealth as the input criteria and five output indicators as technical, economic, social, environmental, and institutional. Based on the expert's judgment, it was found that water availability and energy reserves were the most important resources for sustainable development. Among the output indices, it was found that environmental and social indices were considered the most important. Using the fuzzy weights, DEA was run and it was found that Togo reached the efficient frontier. This was because with the limited resources at its disposal Togo was able to score well in the environmental index which was identified as the most important index for sustainable development. The analysis also highlighted the position of each of the remaining 47 countries against the efficient frontier and also how the country can improve its position to reach the efficient frontier. For furthering SEDE, sensitivity analysis revealed which of the input resources, each country need to judiciously use, highlighting the sensitive input resource for each country. Nation's wealth was found to be sensitive among all the countries. In the future, a longitudinal study can be undertaken to find if there is a gradual increase in the indices over the years for the countries. This analysis will indicate if the country is gradually increasing on the path of sustainable development.

Appendix

Table 10 Urban sustainability index with indicator weights [22]

Component index	Subcomponents index	Indicator
Urban status index (0.41)	Socioeconomic development index (0.50)	Per capita GDP (0.36)
		Growth rate of GDP (0.20)
		Percentage of population below the poverty line (0.30)
		Educational investment share in GDP (0.14)
	Environmental index (0.30)	Daily concentration of SO2 (0.20)
		Daily concentration of particulate matter (PM_{10}) (0.24)
		Percentage of water meeting the drinking quality standard (0.22)
		Average concentration of chemical oxygen demand (COD) (0.14)
		Area of arable land per capita (0.10)
		Per capita water resource (0.10)
	Institutional capacity index (0.20)	Citizens' satisfaction with their city
Urban coordination index (0.34)	Coordination index of economic and environmental (0.34)	Generation of waste water per 10,000 CNY (Chinese Yuan Renminbi) GDP (0.15)
		Ratio of sewage treatment (0.20)
		Generation of SO2 per 10,000 CNY GDP (0.15)
		Recycling ratio of urban wastes (0.20)
		Environmental investment share in GDP (0.30)
Urban potential index (0.25)	Ecological and environmental potential index (0.60)	Ratio of renewable resources consumption to their generation (0.20)
		Ratio of non-renewable resources consumption to their substitution (0.25)
		Ratio of degradable pollutant emission to their purification (0.25)
		Ratio of non-degradable pollutant emission to their purification (0.30)
	Welfare growth potential index (0.40)	Growth rate of basic needs index (0.60)
		Growth rate of income per capita (0.40)

Table 11 Indicators for sustainable development [25]

Theme	No	Indicator
Economic	1	Average personal income
	2	Female/male employment rate
	3	Unemployment rate
	4	Percentage of households with internet connection
	5	Percentage of public places with wireless internet connections
	6	Average daily per capita water use (liter) (excluding industrial use)
	7	Electricity consumption per person
Social	8	Urban population density
	9	Female/male life expectancy
	10	Number of households below the poverty line
	11	Wealth gap
	12	Crime rate
	13	Annual casualties from public disasters
	14	Annual number of transportation accidents
	15	Per capita attendance of art and cultural activities
	16	Average number of students per classroom
	17	Ratio of the population with a college level education
	18	Rate of expansion of urban development lands (including residential, commercial, industrial, and public facilities)
	19	Per capital floor area of private dwellings
	20	Public facility area ratio to urban land areas
	21	Per capita park and green areas
	22	Riverside park and green area per person
	23	Sewerage and waste removal efficiency
	24	Rate of sanitary sewerage to total sewerage system
	25	Car ownership rate
	26	Motorcycle ownership rate
	27	Areas covered with public transportation system
	28	Per capita pedestrian walkway index
	29	Per capita bikeway index
	30	Number of bicycle kickstands
Environmental	31	Number of bird species living naturally in the environment
	32	Number of fish species living naturally in the environment
	33	Green resource index
	34	Permeable rate in urban lands
	35	Number of days with PSI > 100
	36	Per capita CO_2 emissions
	37	Proportion of slightly polluted rivers
	38	Reservoir water quality
	39	Tap water quality
	40	Per capita daily waste production
	41	Recycling ratio for solid waste
	42	Ratio of solid waste composted to total waste production
	43	Utilization rate for renewable resources (bottom ashes)
Institutional	44	Enforcement of local environmental plans
	45	Citizen participation in major planning and decision-making
	46	Joint international cooperation regarding sustainable development (SD)
	47	Environmental and ecological budget ratio to total budget
	48	Social welfare expenditure ratio to total expenditure
	49	Government expenditure on pollution prevention and resource recycling
	50	Ratio of completed assessments to initiated assessments
	51	Appellate statistics of court cases related to environmental pollution

Table 12 Indicators for energy and sustainable development [35]

Factor	Variable	Intensity - measurement
Energy	Final energy consumption (tera joules) (TJ)	Final energy consumption per capita (giga joules per person)
	Electricity consumption in industrial and residential sectors (kilowatt hour) (kWh)	Electricity consumption in the residential sector per capita (kWh per person)
Economic issue	GDP (million US$2005) population	Energy intensity: final energy consumption per GDP (TJ/ million US$2005)
	Number of industries (an industrial establishment has a minimum of 10 employees and annual minimum production value of US$50,000)	Electricity consumption in the industrial sector per industry (kWh per industry)
Environmental issue	Emissions: sulfur dioxide SO_2 (ppb), particulate matter (microgram per cubic meter) (μg/m^3), CO_2 emissions (kilotons)	Energy consumption per CO_2 emissions (TJ/kilotons) CO_2 emissions per capita (tonnes/person) CO_2 emissions per GDP (tonnes/million US$2005)
Social issue	GINI, HDI, urban density (population/km^2)	

Table 13 Indicators for benchmarking cities [37]

Theme	Scope of analysis	Sample	Reference
Energy and/or CO_2 emissions	Frequency analysis of energy data	CoM signatory cities	Kona et al. [68]
	Energy consumption	198 local units in the UK	Keirstead [69]
	Carbon footprints	12 metropolitan cities	Sovacool and Brown [70]
	CO_2 emissions	Nanjing (China)	Bi et al. [71]
	Carbon footprint	21 cities (Guangdong China)	Yajie et al. [72]
	Carbon metabolism	Beijing (China)	Zhang et al. [73]
	CO_2 targets and measures	8 low carbon cities (China)	Khanna et al. [74]
	Scope of climate target setting	8 European cities	Kramers et al. [75]
Transport	Transport systems	23 European cities	Alonso et al. [76]
	ICT usage in transport	26 major world cities	Debnath et al. [77]
	Sustainable transport	Curitiba (Brazil)	Miranda et al. [78]
Waste	Waste management	3 cities (world)	Zaman and Lehmann [79]
	Urban waste management	14 Greek municipalities	Karagiannidis et al. [80]
	Sustainable waste management	5 cities (world)	Wilson et al. [81]
Water	Water treatment options	Ningbo (China)	Wu et al. [82]
Energy-water-carbon nexus	Urban water systems	4 European cities	Venkatesh et al. [83]
Socio-economic power	Socio-economic power	35 major world cities	Arribas-Bel et al. [84]
Multidisciplinary (sustainability)	Locally integrated energy sectors	Ormoz Municipality (Slovenia)	Kostevšek et al. [34]
	Low-carbon eco-cities	Not applied to any city	Zhou et al. [33]
	Environment social economic pillars	Island energy structure	Afgan et al. [85]
	Green cities (limited energy focus)	Various cities (world)	Siemens (http://sg.siemens.com/city_of_the_future/_docs/gci_report_summary.pdf)
	Environment and quality of life	Australian cities	Trigg et al. [32]
	Energy scenarios with SDEWES Index	22 Mediterranean port cities	Kılkış [37]

Table 14 ISED classified according to the indirect, direct driving force, and state [46]

Indirect driving force	Direct driving force	State
1. Population: total; urban	14. Energy use per unit of GDP	16. Energy use per capita
2. GDP per capita	15. Expenditure on energy sector: total investments, environmental control, hydrocarbon exploration and development, R&D, net energy import expenses	17. Indigenous energy production
3. End-use energy prices with and without tax/subsidy	21. Fraction of disposal income spent on fuels (total population, 20% poorest)	18. Net energy import dependence
4. Shares of sectors in GDP value added	23. Quantities of air pollutant emissions—sulfur dioxide (SO_2), nitrous oxides (NOx), particulates, CO_2, volatile organic compounds (VOC)	22. Fraction of households: heavily dependent on non-commercial energy; without electricity
5. Distance traveled per capita: total, by urban public transport mode	26. Quantities of greenhouse gas emissions	24. Ambient concentration of pollutants in urban areas: SO_2, NOx, suspended particulates, CO_2, ozone
6. Freight transport activity: total, by mode	27. Radionuclides in atmospheric radioactive discharges	25. Land area where acidification exceeds critical load
7. Floor area per capita	28. Discharges into water basins: waste/storm water, radionuclides, oil into coastal waters	30. Accumulated quantity of solid wastes to be managed
8. Manufacturing value added by selected energy intensive industries	29. Generation of solid waste	32. Quantity of accumulated radioactive wastes awaiting disposal
9. Energy intensity: manufacturing, transportation, agriculture, commercial and public services, residential sector	31. Generation of radioactive waste	34. Fatalities due to accidents with breakdown by fuel chains
10. Final energy intensity of selected energy intensive products	33. Land area taken up by energy facilities and infrastructure	37. Life time of proven fossil fuel reserves
11. Energy mix: final energy, electricity generation, and primary energy supply	35. Fraction of technically exploitable capability of hydropower currently not in use	39. Life time of proven uranium reserves
12. Energy supply efficiency: fossil fuel efficiency for electricity generation	36. Proven recoverable fossil fuel reserves	41. Rate of deforestation
13. Status of deployment of pollution abatement technologies: extent of use, average performance	38. Proven uranium reserves	
19. Income inequality	40. Intensity of use of forest resources as fuelwood	
20. Ratio of daily disposable income/private consumption per capita of 20% poorest population to the prices of electricity and major household fuels		

Table 15 List of energy indicators for sustainable development (EISD) [3]

Indicator	Theme	Subtheme	Code	Energy indicator	Components
Social	Equity	Accessibility	SOC1	Share of households (or population) without electricity or commercial energy, or heavily dependent on non-commercial energy	✓ Households (or population) without electricity or commercial energy, or heavily dependent on non-commercial energy ✓ Total number of households or population
		Affordability	SOC2	Share of household income spent on fuel and electricity	✓ Household income spent on fuel and electricity ✓ Household income (total and poorest 20% of population)
		Disparities	SOC3	Household energy use for each income group and corresponding fuel mix	✓ Energy use per household for each income group (quintiles) ✓ Household income for each income group (quintiles) ✓ Corresponding fuel mix for each income group (quintiles)
	Health	Safety	SOC4	Accident fatalities per energy produced by fuel chain	✓ Annual fatalities by fuel chain ✓ Annual energy produced
Economic	Use and production patterns	Overall use	ECO1	Energy use per capita	✓ Energy use (total primary energy supply, total final consumption and electricity use) ✓ Total population
		Overall productivity	ECO2	Energy use per unit of GDP	✓ Energy use (total primary energy supply, total final consumption and electricity use) ✓ GDP
		Supply efficiency	ECO3	Efficiency of energy conversion and distribution	✓ Losses in transformation systems including losses in electricity generation, transmission and distribution
		Production	ECO4	Reserves-to production ratio	✓ Proven recoverable reserves ✓ Total energy production
			ECO5	Resources-to production ratio	✓ Total estimated resources ✓ Total energy production
		End use	ECO6	Industrial energy intensities	✓ Energy use in industrial sector and by manufacturing branch ✓ Corresponding value added
			ECO7	Agricultural energy intensities	✓ Energy use in agricultural sector ✓ Corresponding value added
			ECO8	Service/commercial energy intensities	✓ Energy use in service/ commercial sector ✓ Corresponding value added
			ECO9	Household energy intensities	✓ Energy use in households and by key end use ✓ Number of households, floor area, persons per household, appliance ownership
			ECO10	Transport energy intensities	✓ Energy use in passenger travel and freight sectors and by mode ✓ Passenger-km travel and tonne-km freight and by mode
		Diversification (fuel mix)	ECO11	Fuel shares in energy and electricity	✓ Primary energy supply and final consumption, electricity generation and generating capacity by fuel type ✓ Total primary energy supply, total final consumption, total electricity generation and total generating capacity
			ECO12	Non-carbon energy share in energy and electricity	✓ Primary supply, electricity generation and generating capacity by non-carbon energy ✓ Total primary energy supply, total electricity generation and total generating capacity
			ECO13	Renewable energy share in energy and electricity	✓ Primary energy supply, final consumption and electricity generation and generating capacity by renewable energy ✓ Total primary energy supply, total final consumption, total electricity generation and total generating capacity
		Prices	ECO14	End-use energy prices by fuel and by sector	✓ Energy prices (with and without tax/ subsidy)

Table 15 List of energy indicators for sustainable development (EISD) [3] *(Continued)*

Indicator	Theme	Subtheme	Code	Energy indicator	Components
	Security	Imports	ECO15	Net energy import dependency	✓ Energy imports ✓ Total primary energy supply
		Strategic fuel stocks	ECO16	Stocks of critical fuels per corresponding fuel consumption	✓ Stocks of critical fuel (oil, gas, etc.) ✓ Critical fuel consumption
Environmental	Atmosphere	Climate change	ENV1	Green-house gas (GHG) emissions from energy production and use per capita and per unit of GDP	✓ GHG emissions from energy production and use ✓ Population and GDP
		Air quality	ENV2	Ambient concentrations of air pollutants in urban areas	✓ Concentrations of pollutants in air
	Water	Water quality	ENV3	Air pollutant emissions from energy systems	✓ Air pollutant emissions
	Land	Soil quality	ENV4	Contaminant discharges in liquid effluents from energy systems including oil discharges	✓ Contaminant discharges in liquid effluents
		Forest	ENV5	Soil area where acidification exceeds critical load	✓ Affected soil area ✓ Critical load
		Solid waste generation and management	ENV6	Rate of deforestation attributed to energy use	✓ Forest area at two different times
			ENV7	Ratio of solid waste generation to units of energy produced	✓ Amount of solid waste ✓ Energy produced
			ENV8	Ratio of solid waste properly disposed to total generated solid waste	✓ Amount of solid waste properly disposed of ✓ Total amount of solid waste
			ENV9	Ratio of solid radioactive waste to units of energy produced	✓ Amount of radioactive waste (cumulative for a selected period of time) ✓ Energy produced
			ENV10	Ratio of solid radioactive waste awaiting disposal to total generated solid radioactive waste	✓ Amount of radioactive waste awaiting disposal ✓ Total volume of radioactive waste

Table 16 Energy indices for sustainable development [52]

Theme	No	Sub-indicator
Economy	1	Energy cost
	2	Investment
	3	Plant efficiency
	4	Industrial, household, and commercial energy intensities
Social	5	Energy use per household
	6	Share of household income spent on fuel and electricity
	7	Number of injured per energy produced
	8	Number of working hours per energy produced
Ecology	9	CO_2 emission per energy produced
	10	CO_2 emission per capita
	11	NOx emission per energy produced
	12	NOx emission per capita

Table 17 Energy indicators for sustainable development in residential buildings [54]

Theme	Code	Sub indicator	Definition
Economic	EcI_{ec}	Electricity consumption	Total annual electricity consumption of the objects divided by the total number of objects
	EcI_{tc}	Heat consumed for space heating	Total annual heat consumption of the objects divided by the total heated area
	EcI_{hwc}	Hot water consumption	Estimated consumption of hot water per person living in the household
	EcI_{ecc}	Electricity consumed to meet household cooking needs	Average specific annual consumption of electricity used to meet household cooking needs
Social	SoI_{ls}	Living space area per person	Total area of a building divided by the total number of household members
	SoI_{ac}	Air-conditioning use	Share of buildings where air-conditioning is used
	SoI_{dw}	Dishwasher use	Share of buildings where dishwashers are used
	SoI_{ic}	Indoor comfort	Share of households that are satisfied with indoor comfort
Environmental	EnI_{at}	Air temperature	Average daily air temperature in the living room
	EnI_{rh}	Relative humidity	Average daily relative humidity in the living room
	EnI_{CO2}	CO_2 concentration	Average daily concentration of CO_2 in the living room during the winter period

Table 18 Set of indicators for sustainable energy development [55]

Dimension	Code	Indicator	Data required
Technical	TEC1	Share of depletable (non-renewable) energies in total primary energy supply (TPES)	TPES; total consumption of non-renewable energies
	TEC2	Depletion coefficient of local energy resources	Domestic production values of coal, oil, natural gas and solid fuels; proved reserves of coal, oil, natural gas; total forest area; total land area
	TEC3	Overall system conversion efficiency	Total final consumption (TFC); TPES
Economic	ECO1	Per capita consumption of commercial energies	Total commercial energy consumption; population
	ECO2	Final energy intensity	TFC; GDP in purchasing power parity (PPP)
	ECO3	Share of productive use of energy	TFC; residential energy consumption
Social	SOC1	Per capita consumption of clean energies in the residential sector	Total clean energy consumption in the residential sector; population
	SOC2	Income inequality	Gini coefficient
Environmental	ENV1	Share of "dirty fuels" in residential energy consumption	Total consumption of coal, peat, crude oil, solid fuels; residential energy consumption (REC)
	ENV2	Carbon intensity	TPES; total CO2 emissions from fuel combustion
Institutional	INS1	Overall self sufficiency	TPES; indigenous production

Abbreviations

AHP: Analytical hierarchical process; AR-CCR: Assurance region Charnes, Cooper, and Rhodes; CNY: Chinese Yuan Renminbi (currency unit); CO_2: Carbon dioxide; COD: Chemical oxygen demand; CR: Consistency ratio; DEA: Data envelopment analysis; ECLAC: Economic Commission for Latin America and the Caribbean; EDI: Energy Development Index; EISD: Energy indicators for sustainable development; EPI: Environmental Performance Index; ESI: Environmental Sustainability Index; GDP: Gross domestic product; GHG: Greenhouse gas; GTZ: German Technical Cooperation Agency; HDI: Human Development Index; HPI: Human Poverty Index; IAEA: International Atomic Energy Agency; IEA: International Energy Agency; ISED: Indicators for Sustainable Energy Development; MCDM: Multi-criteria decision making; MDG: Millennium Development Goals; NOx: Nitrous oxides; OLADE: Latin American Energy Organization; PM: Particulate matter; PPP: Purchasing power parity; REC: Residential energy consumption; SD: Sustainable development; SDEWES: Sustainable Development of Energy, Water and Environment Systems; SEDE: Sustainable energy development efficiency; SEDI: Sustainability Energy Development Index; SO_2: Sulfur dioxide; TFC: Total final consumption; TFN: Triangular fuzzy scale; TJ: Tera joules; TPES: Total primary energy supply; UN: United Nations; UNDESA: United Nations Department of Economic and Social Affairs; UNDP: United Nations Development Program; VOC: Volatile organic compounds

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Authors' contributions

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Availability of data and materials

The data used for this research will be made available upon request. Also the data is available on relevant authorities' webpages.

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Not applicable.

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Competing interests

The authors declare that they have no competing interests.

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