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Modelling the growth dynamics of sustainable renewable energy – Flourishing green financing

Jatin Trivedi [a], Dipanwita Chakraborty [b,c], Haitham Nobanee [d,e,f,*]

[a] National Institute of Securities Markets, India
[b] Jagan Institute of Management Studies, Sector 5, Rohini, New Delhi, India
[c] Indian Institute of Technology Kharagpur, Kharagpur, India
[d] College of Business, Abu Dhabi University, Abu Dhabi, 59911, United Arab Emirates
[e] Oxford Centre for Islamic Studies, University of Oxford, Oxford, OX3 0EE, UK
[f] Faculty of Humanities & Social Sciences, University of Liverpool, Liverpool, L69 3BX, UK

A R T I C L E I N F O

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A B S T R A C T

This study investigates global energy production and consumption trends amid the backdrop of rising global temperatures. Utilizing data from the World Bank, we analyze renewable energy (RE) production and consumption in 51 countries, encompassing 38 OECD nations, 18 non-OECD countries, and 31 IEA member states. Employing dynamic hierarchical clustering analysis (HCA) with various linkage methods, including single-linkage, combined-linkage, and Ward linkage, we identify patterns in RE source growth. Our findings offer valuable insights for green finance and private investors, enabling them to develop essential infrastructure to bolster economic sustainability. Furthermore, our results underscore the significance of exploring RE growth and its associated clusters to inform energy policies and investment opportunities. We emphasize the necessity of adopting green and sustainable energy policies, fostering RE sharing, and making informed decisions to maximize natural resource utilization. Additionally, we stress the importance of structuring both short- and long-term global corporate green financing strategies and policies to facilitate the transition toward sustainable energy solutions.

1. Introduction

Sustainable energy, or ‘green energy’, refers to renewable energy (RE) sources that protect the environment, providing hope for future generations. However, approximately 80% of world energy consumption remains dependent on fossil fuels to run global commerce. As a gateway to global warming, the consumption of oil, gas, coal, and nuclear energy harms the environment, resulting in continuous heatwaves as well as other environmental events. Globalisation and non-renewable energy (non-RE) consumption jointly boost emissions in the long run (Yuping et al., 2021) and require energy management and policy (Dong et al., 2021). Toward that end, non-RE use can be controlled, modelled, and predicted (García-Martín et al., 2019). Fossil fuels account for 85% of total carbon emissions (J. Li, 2023); hence, we are penalising the health of future generations by damaging the quality of air and water and upsetting the planet’s carbon budget. Sustainable or green energy can alter these damaging effects on the environment to protect the health of future generations. The efficient use of energy is a prerequisite for economic development (Bhuiyan et al., 2022). Sustainability finance, or green finance, is the only option that establishes permanent energy use solutions through investments in RE production and consumption to control CO2 emissions (Ping and Shah, 2023). Numerous studies have demonstrated the effects of growth in economic development, sustainability, and RE consumption controls on carbon emissions (Jiakui et al., 2023; C. Li et al., 2022; Ping and Shah, 2023; Samour et al., 2022; Taridala et al., 2023; X. Wang et al., 2021; L. Zhang et al., 2022; Zhong et al., 2022). Green finance promotes RE investment efficiency for long-term sustainability (B. Wang and Zhao, 2022).

Therefore, achieving ecological sustainability has become a global challenge. In the past few years, the drive toward globalisation has paid little attention to the environment, resulting in habitat destruction, air pollution, water pollution, global warming, heatwaves, deforestation,

* Corresponding author. College of Business, Abu Dhabi University, Abu Dhabi, 59911, United Arab Emirates.
E-mail addresses: contact.tjatin@gmail.com (J. Trivedi), biswasdipanwita88@gmail.com (D. Chakraborty), nobanee@gmail.com, haitham.nobanee@adu.ac.ae, haitham.nobanee@oxcis.ac.uk, haitham.nobanee@liverpool.ac.uk (H. Nobanee).

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and the depletion of natural resources (Jakob, 2022; Malone, 2014; Pozio, 2020, 2022; Sahoo et al., 2023; Sillmann et al., 2021; Y. Zhang et al., 2020). To achieve sustainability, green finance investments have sought to create green and sustainable energy solutions to protect the environment from nitrogen dioxide (NO2) emissions. NO2 is produced by the combustion of coal, gas and oil from transportation and industrial waste, affecting the quality of air, water, and weather. Fig. 1 illustrates the changes in the human NO2 and carbon dioxide (CO2) footprints from 2010 to 2020. The figure illustrates the estimated impact on the global environment in 2045 based on the scale of the current (2023) NO2 and CO2 footprints, with the map shifting from multiple colours to a single colour. This suggests that air quality and pollution can be uniform across the planet with the increasing pace of carbon emissions, directly increasing the speed of global warning, which is already accelerated by the existing carbon footprint. If alternate energy solutions are not increased to control CO2 emissions, this unwanted scenario for 2045 will unfold.

RE use has the potential to transform energy consumption in transportation and industrial applications. The concepts of green finance and 'innovative finance' have emerged as viable approaches to sustainable investment, with the potential to promote economic growth and ecological well-being. The implementation of green finance policies plays a significant role in the transformation of energy policy towards sustainable and growth-oriented solutions. Thus, the RE sector has been prioritised, as evidenced by the recent, accelerated growth in the sector. This has created a connection between sustainable finance and sustainable energy. Countries that exhibit a higher rate of expansion in the domain of RE sources are more likely to garner increased foreign investment, facilitate international trade integration, and curtail their reliance on non-renewable fossil fuels (Z. Zhao et al., 2023).

The environmental condition of our planet is vulnerable to global exposure of carbon emissions. Several factors influence the environment including the environmental policy (Khalfaoui et al., 2023), geo-political risk (Chu et al., 2023), economic complexity (Doğan et al., 2022; Rafique et al., 2021), energy security also impact on energy efficiency (Chu et al., 2023; Payne et al., 2023). Several interesting studies also identified impact of environmental subsidy and practice on environmental monitoring (Zhang et al., 2023; Zhang, 2023; Zhang et al., 2023). The heterogeneity structure of country such as population in urban-rural region, income structure impacts directly on energy consumption (Zhang et al., 2023). Energy plays vital role in economic growth. The type of energy consumption makes the difference on environment. Dogan et al. (2020) finds that consumption of renewable energy remained more effective than non-renewable energy on the sample of European region countries. Also, emerging economies that focus on export diversification influence on energy demand (Shahzad et al., 2021). While some countries have launched carbon emission trading platform as part of economic policy which contributes sustainable economic growth and tackles environmental problems (Zhang et al., 2023). Our objective is to model the dynamic growth clustering of green energy, which is considered a promising avenue for sustainable financial investments. Based on a thorough review of the literature in the field of energy, we found no studies using hierarchical clustering analysis (HCA) to model the expansion of RE across all listed countries in

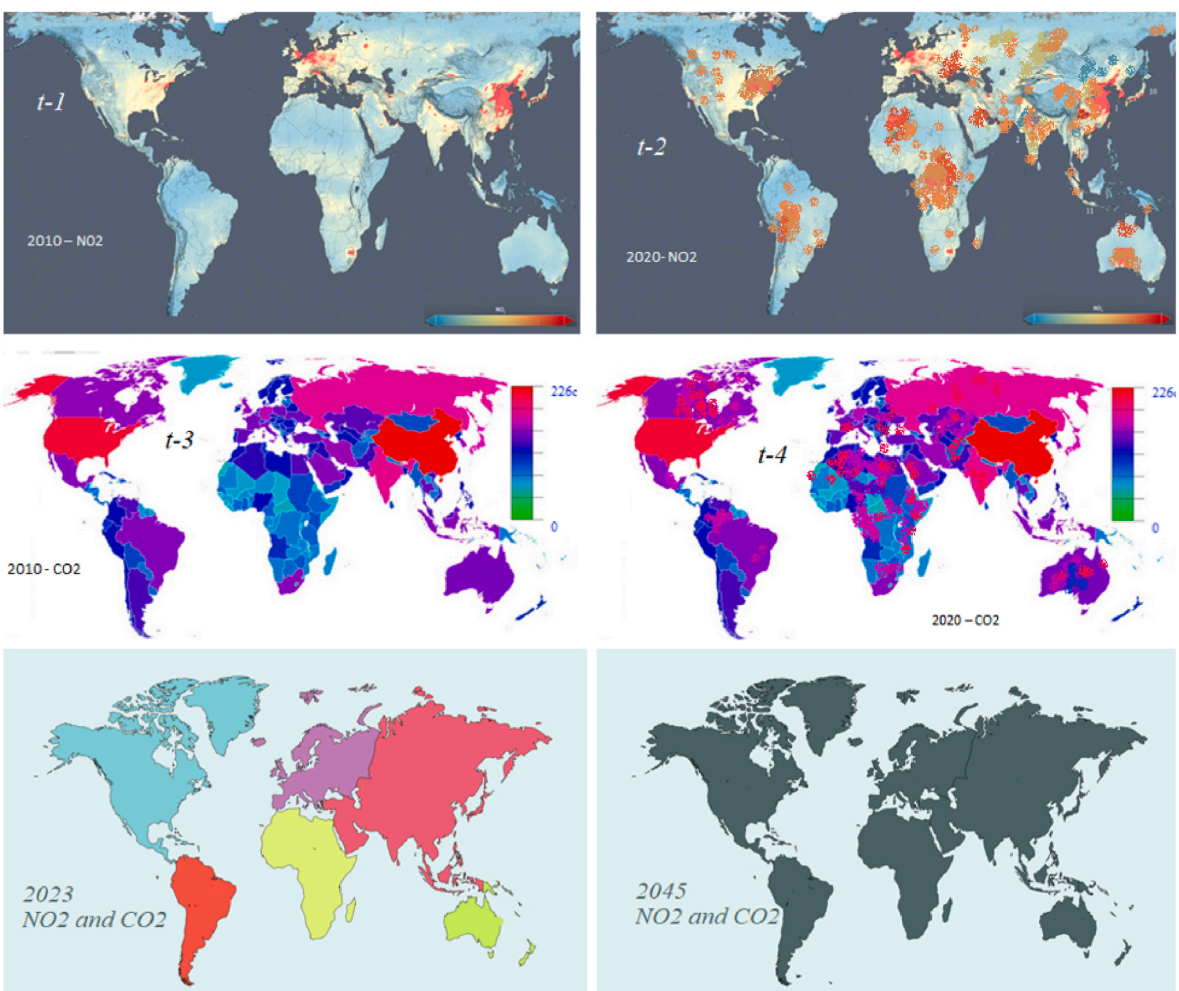

Fig. 1. Nitrogen and Carbon Footprints (t = 2010 to t = 2020). Source: Author's illustration; *t-1, t-2, t-3* and *t-4* represent 10-year period differences.

the World Bank data while also incorporating a managerial perspective. Modelling growth clusters (2010–2020) to capture growth aggressiveness across a sample of countries worldwide is currently constrained by limited data selection. Therefore, our objective is to engage in both a conceptual and empirical discussion with direct implications for long-term solutions and to present a potential avenue for identifying the optimal platform for global green finance investment.

The significance of this study for governmental bodies, policymakers, and investors in green finance can be attributed to two key factors. First, it highlights the dynamic pace of growth, enhanced environmental performance, and reduced reliance on fossil fuels, all of which contribute to long-term sustainable economic growth. Second, this study underscores the importance of liberal merger policies, opportunities for energy trade, adherence to carbon-free energy guidelines, and support for the development of liberalised and sustainable energy policies. The rapid expansion of business presents a multitude of opportunities for various industries, including global mergers, increased investments from environmentally conscious financial backers, and foreign direct investment (FDI) through sustainable investments that offer long-term and favourable returns.

The remainder of this paper is organised as follows. Section 2 presents the literature review. Section 3, details the data and methodology. Section 4 presents the discussion, conceptual model, and results. Finally, Section 5 concludes the paper with policy and strategic recommendations.

2. Literature review

2.1. RE sources production and consumption

Migrating to sustainable green energy source development is a big leap toward achieving the United Nation's Sustainable Development Goals (SDGs) and a promising future. Green recovery influences both economic and environmental growth. RE growth and production have increased dramatically worldwide. Previous studies have shown a higher intensity of RE growth across Latin America (Pablo-Romero et al., 2022). In Ghana, an RE master plan for estimated investment was established to achieve RE targets by 2030 (Aboagye et al., 2021). RE has positive effects on climate change (Olabi and Abdelkareem, 2022), and provides a sustainable environment in countries which consume more RE than non-RE (Güney, 2019). Because early acceptance is better, only RE can restrict greenhouse gas emissions (Olabi and Abdelkareem, 2022). Nonetheless, it is important to critically review energy technologies considered as RE. Levenda et al. (2021) indicated that many types of energy are classified as RE despite their harmful effects, which has implications for human health and the livelihood of those already vulnerable to climate change conditions. Typically, the production and consumption of RE is emphasised more toward countries that heavily depend on fossil fuel consumption, such as China, Germany, the United States, Australia, and Indonesia (Vakulchuk et al., 2020). Thus, the European Member States (EMS) reorganised the Renewable Energy Directive II (RED II), redefining the framework for Renewable Energy Communities (REC), and authorising the sharing of RE among member communities in 2021. This reform empowers the right to exchange RE from one EMS to another, creating potential private investment and finance opportunities. Private investors and global financiers of RE sources can drive the exponential growth of sustainable energy and emissions control within the region. The policy framework for such dynamic green energy socialisation requires technological solutions, open decision-making, and spatial planning (Hoicka et al., 2021).

RE is recognised as a source of political power, political influence, and a small part of the democratic energy movement (Burke and Stephens, 2018). Recent weather disasters and increasingly intense heat waves have awakened global concern regarding the increase in carbon emissions, directing policymakers to consider sustainable energy solutions (Shrestha et al., 2022). Country-specific RE policies (Solaymani, 2021) support and provide information for private investors and FDI, targeting a 100% renewable energy system (Breyer et al., 2022).

Carbon neutrality has become a priority on the global agenda for this century. Countries in the Middle East and North Africa have increased their investment in RE sources (Kong et al., 2022). Several other nations have also prioritised RE sources for sustainable growth. The United Kingdom, Ireland, Luxembourg, Korea, the Netherlands, and other countries have increased their capital investments to expand RE sources.

2.2. Evidence of RE consumption and inclusive growth during COVID-19

The adoption of a structured policy framework generates a balance between domestic renewable energy consumption and inclusive growth. Production and consumption of RE sources contribute positively to a nation's inclusive growth. Several studies have found evidence of such interrelationships which remained positive during the COVID–19 pandemic period. For instance, Cui et al. (2022) considered the same time-range data in this study for 40 countries and found a positive relationship between RE consumption and inclusive growth for sustainable and balanced economic development.COVID–19's impact on the social and economic environment went beyond a global health crisis, leading policymakers to remain attentive to understanding robust sustainability resistance which can pave the way for resilience to future pandemics. During the COVID-19 pandemic, global actions, such as lockdown and innovative curbs to gain control over the virus's transmission, faced significant objections and ultimately reflected more on ourselves rather than COVID. Considering the pandemic's impact and conditions promoted a solution to build smarter and greener cities and countries that can sustain against such crises (Longsheng and Shah, 2022). Several studies have demonstrated a significant role for the consumption of RE, which also captures job creation, employment through several new channels, and prospective opportunities for inclusive finance (Ahmed, 2020; Bhatnagar and Sharma, 2022; Ghouse et al., 2022; Groh et al., 2022; Rahman and Alam, 2022).

2.3. Growth consumption of RE, sustainable green finance and policy

The UN's Intergovernmental Panel on Climate Change (IPCC) continuously tracks the human footprint on climate change. The IPCC's Assessment Report 6 (AR6) provides a 'risk' framework for the irreversible impact on climate change and ecosystems, the human carbon footprint, impact on communities and regions, and biodiversity and suggests remedial actions to reduce the consequences. The IPCC's AR6 climate change to climate resilience development illustration is represented in Fig. 2, referring to an ecosystem-based approach for the transition to reducing climate and ecosystem risk on the health of the planetary ecosystem.

Transition to the use of RE positively impacts fossil fuel consumption and carbon emissions, as well as the production of clean energy and new technologies (Garrett-Peltier, 2017; Ouyang and Lin, 2014). Green finance has a positive impact on RE for sustainable development and is negatively associated with carbon emissions (Ge et al., 2022; Hemanand et al., 2022; Ibrahim, 2022; Zhou and Li, 2022). Environmental degradation requires immediate control due to the irreversible damage of carbon emissions. Therefore, a balanced energy liberalisation policy for RE sources can pause and limit the spread of the human carbon footprint. A liberalised policy framework for RE requires support for private investors and financers regarding green bonds, green finance sources, and equality with democratic transparency to benefit current and future societies.

3. Data adoption and methodology

In the context to encourage, motivate, strategic policy framework support and promote use of green energy for healthy and sustainable environment this work requires to provide robust outcome that meets its

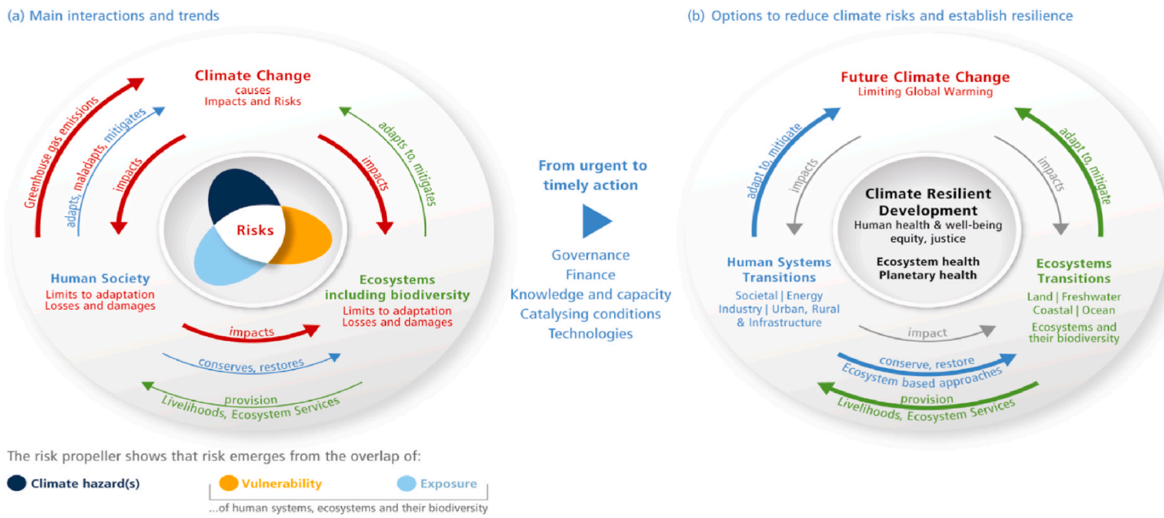

Fig. 2. Climate risk to climate resilience development – Ecosystem Transformation. Source: IPCC AR6 WGII SPM001.

primary objective. Methodology selection remained challenging as univariate series carries limited modelling capability while the primary objective needs to remain in focus. Hierarchical Clustering only identified that can explore complex growth and also satisfies the primary objectives. The method incorporates Ward linkage which is powerful techniques to capture the minimum change in the squared distance.

We sourced actual RE production and consumption data from the World Bank database for a total of 51 independent countries, 38 Organisation for Economic Cooperation and Development (OECD) countries, 18 non-OECD countries, 7 non-OECD Americas, 46 non-OECD Asia, 27 non-OECD Europe and Eurasia countries, 31 International Energy Agency (IEA) member countries, 11 IEA association countries, and world total renewable energy growth. The actual production and consumption of renewable energy were transferred to the yearly yield of RE for model building, cluster analysis, and analytical discussion. The study's year range was limited from 2010 to 2020 to deal with the large, informative dataset and construct robust and significant results. The following defines the RE yearly yield (REYY):

$$REYY = CAP - PAP$$

Where CAP indicates the current aggregate renewable energy production, and PAP indicates the previous year's aggregate production. We found it challenging to determining the leading production consumption of RE while observing the worldwide dataset, as several countries provide similar growth. Furthermore, the variations in determining identical progressive growth were found to be minor. Thus, we performed HCA to establish clustering linkages and processed the data through several runs, using the following approaches: Hausdorf linkage (2007), unweighted average linkage (UPGMA), weighted average linkage clustering (WPGMA), centroid linkage (UPGMC), Ward (1963), and minimum and maximum medoid linkages. We then classified the notions as follows:

Distance clustering:

$$DC^1 = \frac{||XC^1 - XC^N||}{\frac{1}{NC^1} + \frac{1}{NC^n}} \tag{1}$$

Similarity formation:

$$Sim(C1, C2) = Min\ Sim(Pi, Pj)\ conversing;\ Pi \in C1;\ Pj \in C2 \tag{2}$$

where C^1 represents minimum merged, XC^1 is the sum of pairwise distances for all sample RE growth and NC^1 is the size of the clusters from the first number of clusters to n number.

Maximum and minimum complete linkage:

$$\begin{aligned} &\max d(a, b, c, \ldots n); a€A, b€B, c€C\ldots.n€N; \\ &\min d(a, b, c, \ldots n); a€A, b€B, c€C\ldots.n€N; \end{aligned} \tag{3}$$

Hausdorff approach:

$$clcMAX = \max d\left(C^1, C^2, C^3 \ldots C^n\right);\min d\ \left(C^1, C^2, C^3 \ldots C^n\right)$$

where the maximum function captures the difference and establishes a complete linkage, and the minimum function captures and builds single linkage clustering.

Unweighted average, weighted average, and centroid linkage:

$$\begin{aligned} &\frac{1}{|C1|\ .\ |C2|} \frac{\sum I}{c€C1} \frac{\sum I}{c€C2} d(C1, C2); d(i \uplus j, k) \\ &= \frac{d, (i, k) + d(j, k)}{2}\ ; ||\mu C1 - \mu C2 - \mu C3||N^2 \end{aligned} \tag{4}$$

Equation (3) shows that the minimum run cleans the noise between clusters, whereas the maximum function sets the complete linkage algorithm. The similarity between (*Pi*) and (*Pj*) is defined in Equation (2), where *C*1 and *C*2 indicate equal proportions of similar clusters.

Ward linkage:

$$\begin{aligned} &|C^1|||C^2||C^3 \frac{f^{1n}}{f}||\mu C^1 - C^2 - C^3|| = \sum_{x\ €C^1 \uplus C^2 \uplus C^3} ||x = \mu C^1 \uplus C^2 \uplus C^3 \\ &- \sum_{x\ €C} ||x - \mu \uplus C\left\| - \sum_{x\ €C^2} ||x - \mu \uplus C^2 \right\| - \sum_{x\ €C^3} ||x - \mu \uplus C^3||^2 \end{aligned} \tag{5}$$

While Ward linkage, the maximum-minimum approach, and the group approach are similar, Ward linkage captures the minimum increase in the sum of the square distance from (*Pi to Pj*).

This study adopts a dynamic hierarchical model to assess RE growth performance towards sustainability using a variety of linkage methods.

HCA modelling process follows six steps process to create algorithms creation and builds dynamic linkage using renewable energy performance of selected sample countries exhibited in Fig. 3.

3.1. Managerial perspective for HCA

The motivation in selecting an HCA approach is based on its dynamic machine-learning method which allows a time-intensive algorithm to be set and provides growth distance by forming growth gap clusters. these features help identify the pattern of growth from one country to another. Such information provides greater possibilities for global investors and financiers, logistic-channel partners, land developers, and infrastructure

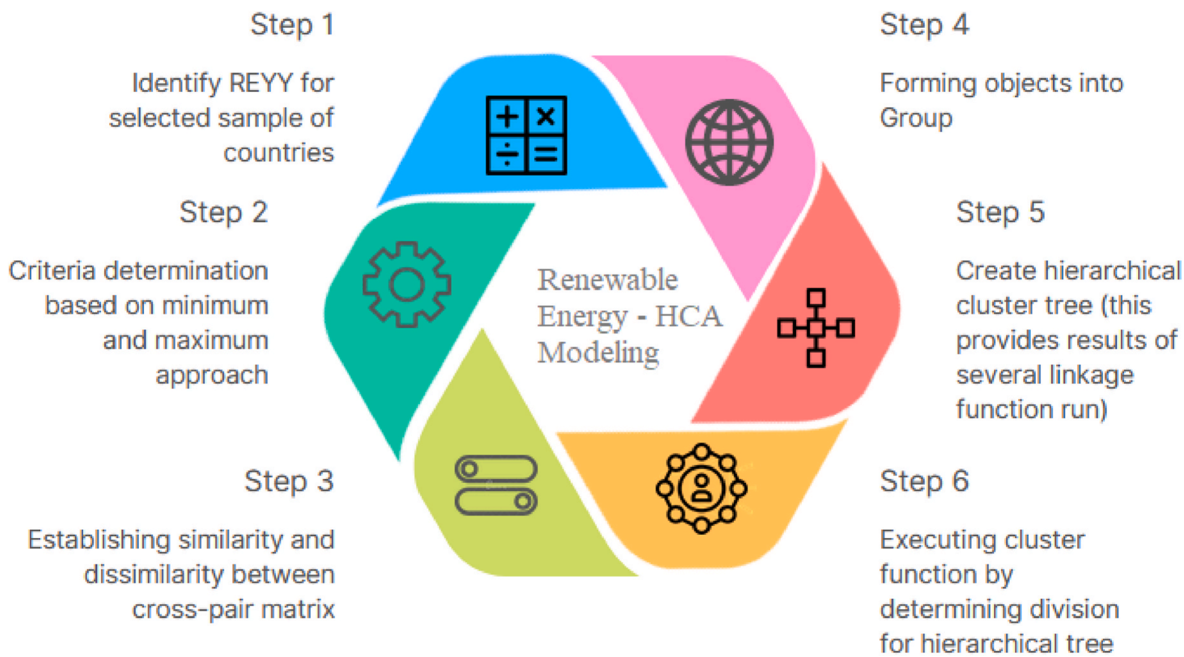

Fig. 3. Six-step model for algorithm creation to evaluate RE performance using dynamic linkage. Source: Author's illustration.

development. This study also provides a managerial perspective for interpreting and analysing the methodology results. For example, the hierarchy in the RE growth relationship reveals similar clusters, creating a singleton cluster that then merges with the two closest clusters to form a new one, and repeats this process until the entire RE growth data results form into one cluster. We use different distance metrics to determine how clusters are separated from each other while exhibiting growth. As a result, single, complete and average linkages are employed in this study with the following techniques, respectively: (1) Euclidian distance using $d(p,q) = \sqrt{\sum_{i=1}^{n}(q_i - p_i)^2}$, where p, q indicate two points in the Euclidean n space, and q_i and p_i are vectors of the initial point; (2) Manhattan distance technique $|x1 - x2| + y1 - y2|$, defining an analogous relationship in higher dimensional space; and (3) maximum distance using Harsdorf's technique. Moreover, the infrastructure architecture of RE sources and related development is not yet generalised, allowing prospective opportunities for high market demand; thus, FDI and other green finance investment should follow the track of such development. Since horizontal distances between the growth of RE production in two countries are integrated where two clusters join the same point, the cubic clustering criterion (CCC) was adopted to determine the summation order. Centroid triangle values were used to derive the trace values for the clusters, as follows: $G = \frac{(x_1 \times 1, x_2 \times 2.\ x_n \times n)}{n}, \frac{(y_1 \times 1, y_2 \times 2.\ y_n \times n)}{n}$.

4. Empirical results and discussion

4.1. Model summary

The model revealed some important statistics, capturing the dynamic characteristics of growth clusters. Tables 1–5 summarise the descriptive statistics of RE growth, the cubic clustering criterion, cubic centroids and distance traces, cluster leadership and joiners, and total RE growth in world RE totals, respectively.

While modelling the growth dynamics of the production and consumption of RE by selected countries, we have converted several important pieces of information into charts and plots, revealing details of the study area. Fig. 4 shows the plotted results for single linkage and combined linkage. Single linkage being formed considering the minimum distance between renewable energy clusters before merging them and forming a cluster. Whereas the combined clusters incorporate the maximum distance between the clusters before merging them. Fig. 5 shows combined linkage with the Euclidian and Manhattan approaches. Euclidian distance indicates the default distance between the clusters and represents result of the square root of the sum of the square differences. Whereas Manhattan approach measures the absolute difference of RE growth between two points against the vectors in all dimensions, also known as angular cosine similarity. Figs. 6–8 show the RE energy growth frequency distribution, the production and consumption scale as a percentage of the country's total energy consumption, and RE production growth, represented as a cluster constellation, respectively.

4.2. Need for green economic recovery

Greenhouse gases increase the aggregate planet temperature owing to electricity production, industrial production, transportation, and other commercial and residential activities comprising the human carbon footprint. Over the past 20 years, total CO2 emissions increased by 44.6%, more than 11% of which taking place between 2010 and 2020, with 5% of that increase in a single year (2020–2021). China alone contributed over 11% to the global CO2 emissions between 2020 and 2021. The United States Environmental Protection Agency (IEA) estimates that at least 16 billion tons of CO2 are produced by 25 emerging countries, accounting for over 60% of total CO2 emissions. In 2010, China and the United States produced over 8 and 5 billion tons, respectively. In the same period, the United States reduced their CO2 emissions by approximately 0.8 billion tons, whereas China increased it by approximately 2.20 billion tons. Countries such as Greenland, Mali, the Congo, and Madagascar were among the least polluting countries across the study period. In fact, many have reduced their carbon emission levels since 2010. The carbon-emission exposure scale shown in Fig. 9 indicates the lowest and highest parameters.

International transportation, including ships, planes, trucks, cars, and trains contribute the largest share of CO2 emissions due to their use of fossil fuels (gasoline, diesel, and petroleum). Electricity production is the second-largest contributor to CO2 emissions, with approximately three-quarters of electricity produced from coal and natural gases. The

Table 1
Summary of descriptive characteristics of renewable energy growth (world-countries).

Country	Mean	St.Dev.	Min.	Max.	Quart.-1	Quart.-3	Skew
Australia	345.18	44.86	284	418	309.5	379.5	0.14
Austria	424.36	21.07	379	451	419.5	440.5	-1
Belgium	155.91	16.19	132	188	149	162	0.49
Canada	2002.09	104.11	1787	2104	1950	2089	-0.99
Chile	424.91	67.3	285	503	402.5	470	-1.16
Colombia	402.82	42.95	322	446	377.5	430.5	-1.07
Costa Rica	101.18	7.72	87	110	97	109	-0.45
Czech Republic	186	23.69	145	223	173	196.5	-0.28
Finland	446.73	36.41	389	494	424.5	481.5	-0.14
France	1013.82	91.57	820	1124	966	1082.5	-0.8
Hungary	135.27	7.85	119	143	133	142	-1.12
Estonia	59.18	14.65	41	80	47.5	71.5	0.16
Greece	105.27	11.38	86	118	99.5	115	-0.67
Israel	29.55	12	15	48	21	39	0.58
Italy	1001.09	92.76	811	1091	981.5	1051.5	-1.32
Japan	1077	147.46	900	1277	947.5	1214	0.21
Korea	284.55	78.47	167	389	219	360.5	-0.14
Mexico	653.27	25.82	618	700	632.5	665.5	0.49
Poland	418.09	89.21	303	556	366	477	0.69
Spain	715.91	68.7	599	805	667.5	763	-0.72
Slovenia	46.64	2.11	44	51	45	48	0.9
Norway	553.36	37.66	487	610	532.5	579	-0.46
Luxembourg	7.27	2.53	5	13	5.5	8.5	1.29
New Zealand	317.91	24.28	278	343	295.5	335	-0.66
Lithuania	61.18	9.24	49	73	52.5	70	-0.13
Slovak Republic	74	13.86	59	100	64.5	75.5	1.05
Switzerland	241.36	12.18	214	259	239	245.5	-0.85
Republic of Turkey	694.82	218.76	472	1073	508	809.5	0.72
OECD Total	22672.36	2370.63	18962	26005	21216.5	24529	-0.11
Morocco	76.82	7.07	68	90	72	81	0.74
People's Republic of China	11167.45	2079.15	8688	14836	9476	12517.5	0.51
United States	6672.18	687.3	5512	7593	6212	7261.5	-0.05
Brazil	5169.91	314.34	4855	5787	4960	5328	1.03
Indonesia	2576.82	142.18	2351	2791	2480.5	2650	-0.26
India	7993.36	857.61	6883	9295	7303.5	8731.5	0.29
South Africa	301.18	19.32	276	336	286	313.5	0.28
Africa	15572.09	1102.1	13681	17188	14927.5	16298.5	-0.24
Middle East	129.45	22.87	108	179	113.5	133	1.38
IEA and Accession/Association countries	51260	5624.18	43968	60265	47106	55439.5	0.31
Non-OECD Americas	7479.73	396.63	7054	8174	7168	7774	0.67
Thailand	1075.73	87.95	942	1205	1012.5	1131.5	0.02
Ukraine	160.91	43.91	113	246	125.5	194	0.62
World	76095.64	7186.8	66188	87459	71029.5	81372	0.22
IEA Total	21291.64	2271.97	17829	24528	19806.5	23074	-0.05
Non-OECD Europe and Eurasia	2131	216.8	1860	2532	1990	2265.5	0.66
Non-OECD Asia (including China)	28111.27	3142.05	24383	33381	25623	30388.5	0.46
Non-OECD Total	53423.45	4838.02	47225	61454	49813	56843.5	0.37
Singapore	26.18	1.08	25	28	25	27	0.15
Egypt	199.64	15.28	186	229	189	201	1.4
Argentina	302	21.53	272	339	285	317	0.43
United Kingdom	483.27	179.22	231	754	334.5	632	0.11
Sweden	777.18	55.59	703	900	729.5	802	0.85
Portugal	236.27	17.48	197	254	227	248	-1.29
Netherlands	229.45	47.95	159	317	201	260	0.21
Latvia	101.55	12.25	83	120	94	110.5	0.09
Ireland	45.18	14.99	26	71	33	56	0.53
Germany	1776.82	209.09	1435	2065	1669	1933.5	-0.26
Denmark	159.45	16.76	139	184	143	173	0.12

Source: Author's estimation

Table 2
Cubic clustering criterion (integrated).

Clusters	CCC Parametric (-1 - +4)
1	0
2	-0.08
3	2.008
4	1.792
5	1.839
6	2.245
7	3.053
8	3.03

Author's estimation.

effects of the human carbon footprint impacts climate change, increasing the pace of global warming. Thus, an immediate alternative must be sought in the form of the accelerated growth of RE production.

4.3. Model building and managerial aspects

Through HCA, a link between green recovery and RE growth was established, providing important information that explains growth clusters and the speed of RE growth. Hidden links in the sample countries were explored using single and combined linkages through Euclidian- and Manhattan-based approaches. Using HCA, this study tracked the distance traces using CCC. As shown in Table 1, the first

Table 3
Renewable energy cluster centroid and distance trace.

Trace	Centroid	Distance
Trace 0	4156.81	6.03
Trace 1	3066.27	4.06
Trace 2	2963.71	2.25
Trace 3	2899.09	1.5
Trace 4	1262.85	BV 66188
Trace 5	2963.12	4.75
Trace 6	2329.9	5.5
Trace 7	1294.93	BV 73916
Trace 8	3279.26	10.5
Trace 9	2768	Max 87459

Author's estimation.

Table 4
Growth cluster leadership summary (renewable energy; entire sample).

Number of Clusters	Distance	Leader	Joiner
30	1.4668684	4	5
29	1.6121416	18	19
28	1.7264919	11	12
27	1.9180135	14	15
26	2.1339788	16	17
25	2.2185336	27	29
24	2.2497213	9	10
23	2.3273503	1	2
22	2.3378056	7	8
21	2.4032606	13	14
20	2.4993146	22	23
19	2.5028753	26	27
18	2.6380614	30	31
17	2.8251993	4	6
16	3.0126531	20	21
15	3.0237861	26	28
14	3.2888355	16	18
13	3.3125237	3	4
12	3.31659	24	25
11	3.5294184	9	11
10	3.9784642	20	22
9	4.6799297	3	7
8	5.4357416	13	16
7	5.5426132	24	26
6	6.8942824	24	30
5	8.3010863	1	3
4	8.8435016	13	20
3	10.521924	1	9
2	19.913288	13	24
1	26.20274	1	13

Author's estimation.

screening of summary statistics provides the mean value as the growth centre, which appears to incline towards the maximum, where we notice a negative skewness. The degree of standard deviation (SD) corresponds to a constant mean annual RE growth, suggesting that a higher variation in SD sets the revised mean. The first quartile (Q1), provides information on how much RE production is expressed at the 25% level, and the upper quartile (Q3) incorporates 75% of RE growth from the sample countries. The interquartile range can be found by subtracting Q3 from Q1.

Unlike normal interpretation, the statistical summary cannot be generalised for this study because RE growth is a positive indicator which has direct influence through additional RE source creation.

Table 2 presents the CCC estimates for the number of clusters, demonstrating that the comparative measure deviation from the expected distribution within the range of -1 to +4 validates the fitness of cluster modeling at scales of 3.03 and 3.05 (8 and 7 clusters, as reflected in Table 4). This confirmation is based on the observation of the lowest distance between clusters 7 and 8. Specifically, this indicates that 24 countries, with a combined distance of 5.54, joined cluster 7, followed by 13 new joiner countries with a linkage distance of 5.43. Collectively, these 37 countries have exhibited a strong commitment to aggressively increasing their renewable energy (RE) sources. Furthermore, this finding suggests that some observations were considered as outliers initially and remained as independent clusters until later stages of the algorithm. This observation aligns with the cluster trace findings in Table 3, which are established by the centroid distance, representing the squared Euclidean distance between the mean values of each cluster.

The dynamic hierarchical clustering analysis (HCA) model has yielded robust results, uncovering hidden developments in the growth of RE sources across the sampled countries. The cluster trace summary in Table 3 groups the RE growth event log into cohesive sub-logs, resulting in the creation of the constellation tree plot model (Fig. 8). HCA segregates RE growth data into similar growth groups, providing a means to

Table 5
Growth contribution relationship in world total renewable energy.

RE producer –Countries	R - Square
Australia	0.6086
Austria	0.2175
Belgium	0.6353
Canada	0.3168
Chile	0.1935
Colombia	0.0408
Costa Rica	0.0237
Czech Republic	0.5097
Denmark	0.5421
Estonia	0.6569
Finland	0.5649
France	0.4938
Germany	0.5443
Greece	0.3668
Hungary	0.013
Iceland	0.3612
Ireland	0.7453
Israel	0.0751
Italy	0.2619
Japan	0.6587
Korea	0.5124
Latvia	0.6565
Lithuania	0.4658
Luxembourg	0.7403
Mexico	0.1466
Netherlands	0.5668
New Zealand	0.3311
Norway	0.1361
Poland	0.8703
Portugal	0.1963
Slovak Republic	0.6203
Slovenia	0.0871
Spain	0.3369
Sweden	0.4061
Switzerland	0.3348
Republic of Turkiye	0.7426
United Kingdom	0.6238
United States	0.6541
OECD Total	0.6126
Argentina	0.089
Brazil	0.8407
People's Republic of China	0.7087
Egypt	0.7815
India	0.6794
Indonesia	0.0151
Morocco	0.8008
Singapore	0.0117
South Africa	0.0465
Thailand	0.0626
Ukraine	0.6494
Non-OECD Total	0.7046
Africa	0.5659
Non-OECD Americas	0.7854
Non-OECD Asia (including China)	0.7226
Non-OECD Europe and Eurasia	0.7689
Middle East	0.7201
IEA Total	0.623
IEA and Accession/Association countries	0.6958

Author's estimation.

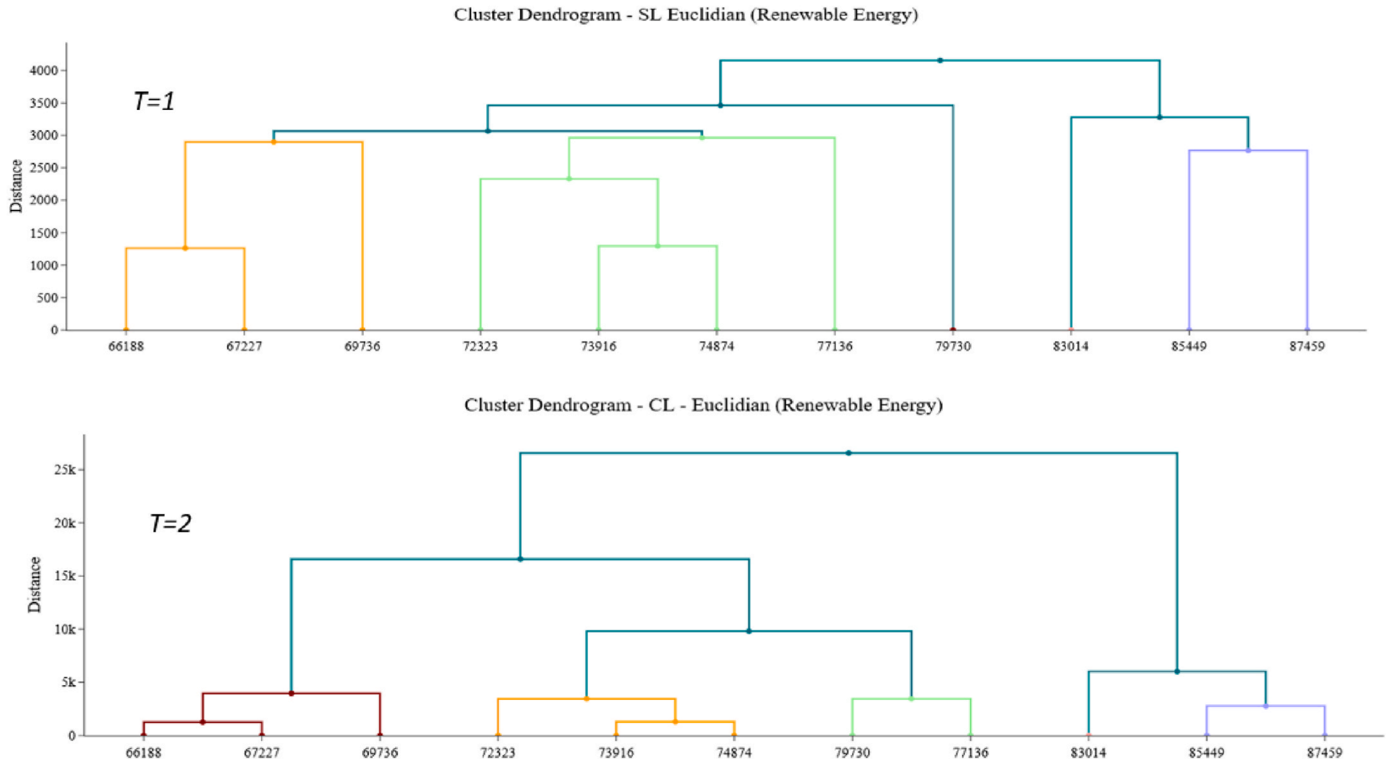

Fig. 4. Single linkage (*T = 1)* and combined linkage (*T = 2)*; Author's illustration.

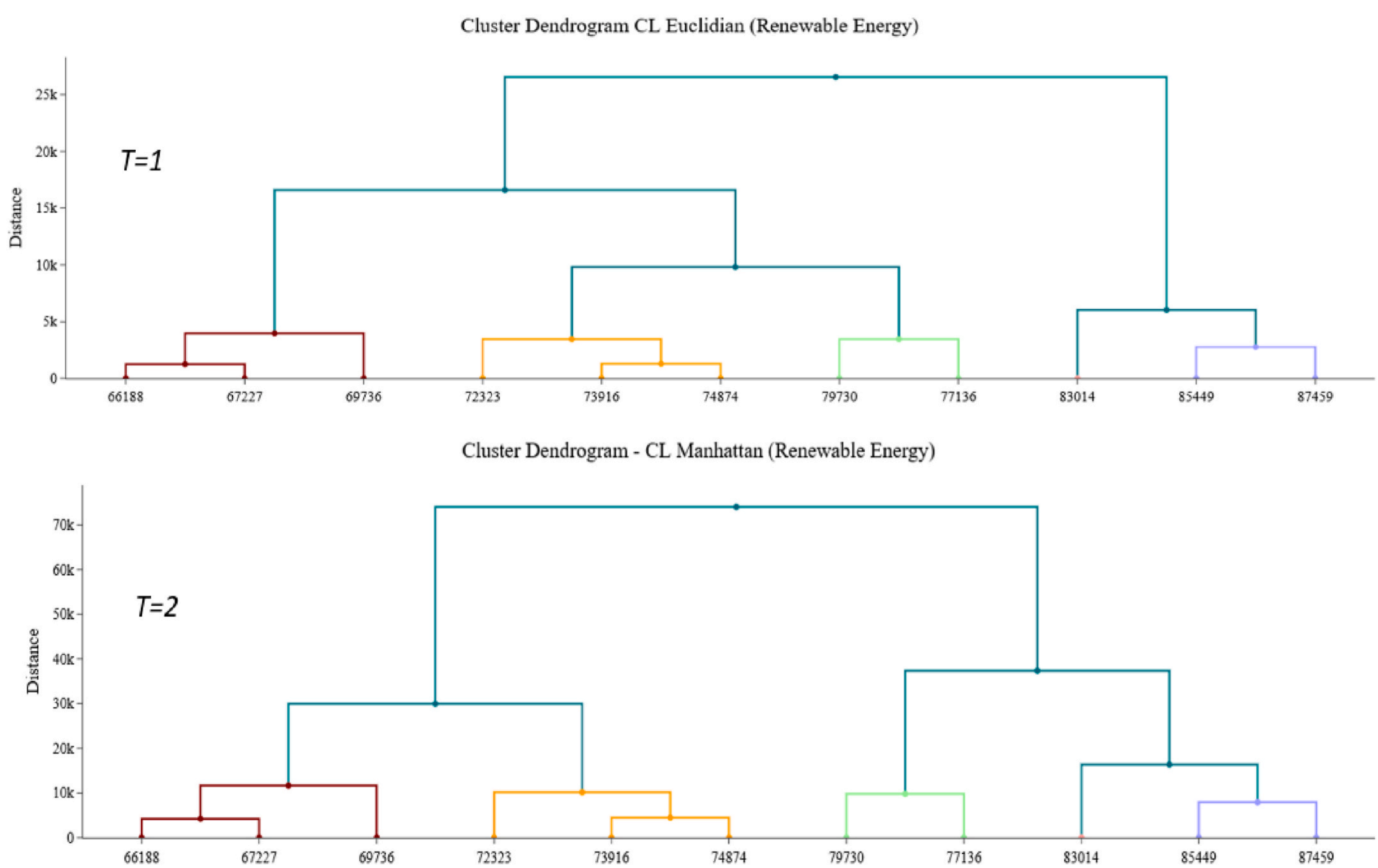

Fig. 5. Combined-linkage – Euclidean approach (*T = 1)* and Manhattan approach (*T = 2*). Author's illustration.

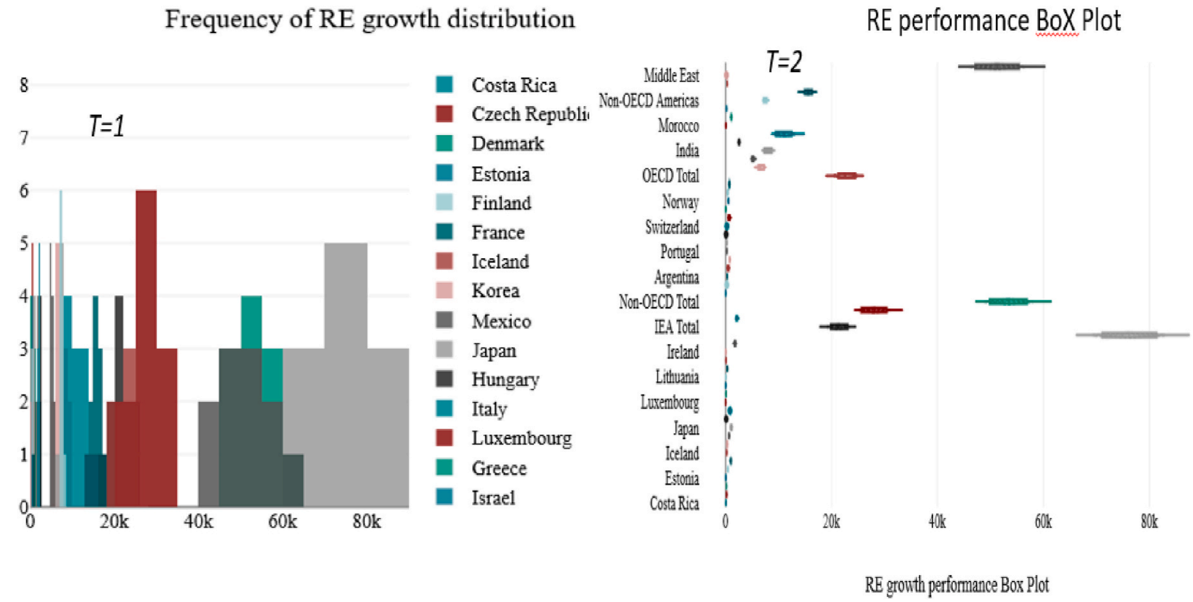

Fig. 6. Renewable Energy growth frequency distribution. Author's illustration.

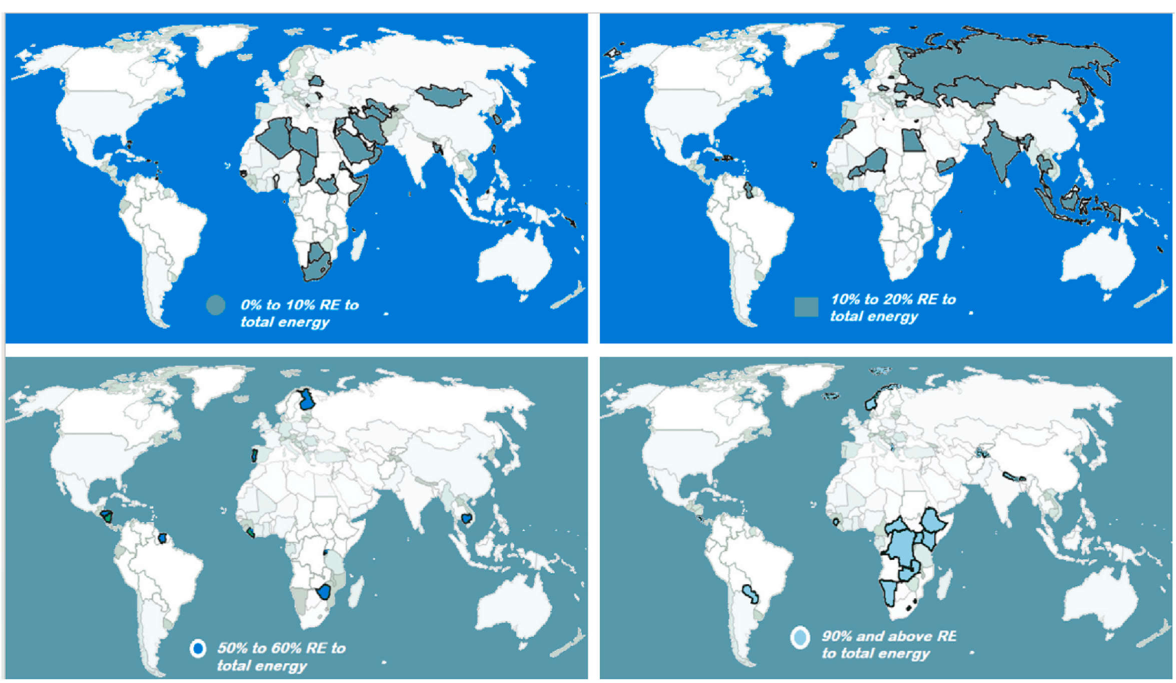

Fig. 7. Renewable energy production to total energy production and consumption. *The filled colour indicates the country with renewable energy production to total energy. Author's illustration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

measure the distance in terms of similarity and dissimilarity. This study integrates both agglomerative and divisive approaches, considering the centroid trace as the center and constructing a cluster tree in various directions. The distance matrix is populated by single, clustered, and Ward linkages. The smallest constellation line between two clusters indicates the minimum distance (single linkage), while contrasting clustered linkages capture the maximum distance, forming larger lines that define how the growth between two countries differs in scale. The Ward method allows univariate analysis of variance (ANOVA) for cluster assignments as groups replicated at different distance scales and is depicted in Figs. 4, 5 and 8.

Table 5 showcases the RE growth values relative to the proportion of total world RE demonstrated by clusters. This value is similar to the variable regression on clusters. Notably, this study has found that Turkey, Korea, Luxembourg, and Ireland have experienced a greater than 100% increase in RE sources, with the United Kingdom exhibiting an increase of over 200% since 2010. Estonia, Germany, Lithuania, Australia, China, the Slovak Republic, Chile, and Poland have shown rapid RE growth as they seek to replace fossil fuel energy with renewable sources. Emerging clusters like Colombia, Italy, Denmark, Spain, and India appear to be on a trajectory similar to the rapidly growing ones. Additionally, Greece, Latvia, Japan, and Belgium have performed exceptionally well in RE source development. Greenland and several African countries effectively controlled their CO2 emissions during the study period. Meanwhile, countries such as Singapore, Thailand, Slovenia, South Africa, Argentina, and various European nations have

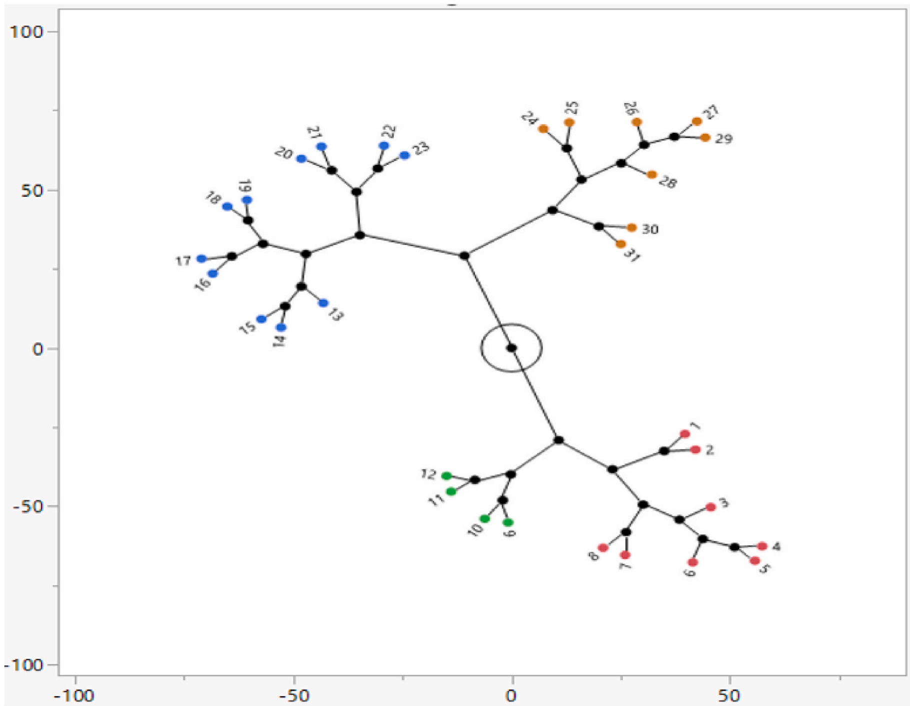

Fig. 8. Renewable energy growth cluster constellation plot. Author's illustration.

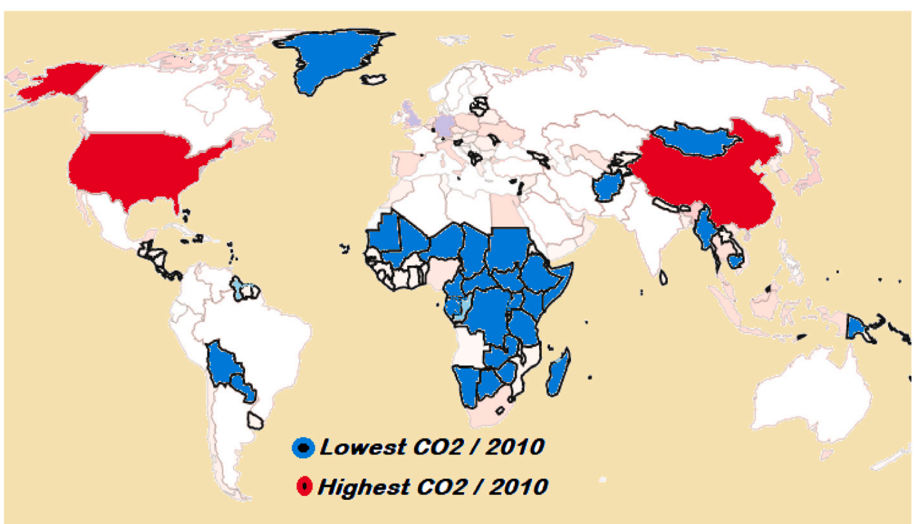

Fig. 9. Carbon dioxide emissions (CO2) – World Scale, 2010. *Annual carbon emissions are considered in the plot. Author's illustration.

maximized their utilization of RE sources to replace fossil fuel energy (coal) and mitigate CO2 emissions. The non-OECD, IEA, and Middle Eastern countries have demonstrated remarkable RE source development, with the highest annual production growth rates.

4.4. Role of sustainable and green finance

RE sources have the potential to replace a significant portion of the fossil fuel energy utilised in transportation, which is responsible for contributing at least one-fifth of overall carbon emissions. This presents a potentially advantageous opportunity for sustainable and environmentally-conscious investments and finance to, serving as reliable and promising long-term platforms. Allocating financial resources to green technology is a strategic, long-term investment that yields significant benefits for sustainability and the advancement of green economic growth.

4.5. Policy recommendation framework

A strategic energy policy with a long-term vision leads to significant and durable transformation. Over the past decade, the United States, United Kingdom, France, Germany, and Japan have collectively achieved reductions of more than 23% in their overall CO2 emissions. The G7, IEA, and OECD countries have successfully implemented measures to reduce their reliance on coal-based energy by 30% through the adoption of RE sources.

To achieve green sustainability by 2040, it is recommended that frontiers and economies should prioritise decarbonised electricity production resources, with a primary focus on reducing coal-based electricity usage. The G7 countries present a viable example, seeking to achieve the decarbonisation of electricity by 2035. Countries significantly impacted by CO2 emissions, including China, the United States, India, Russia, Japan, Indonesia, Iran, Saudi Arabia, and South Korea, require the implementation of more resilient RE sources to replace their current reliance on coal-based energy. Sources, such as solar and wind power, are considered the most viable options for promoting environmentally sustainable domestic energy. The creation of green energy and green finance energy bonds can instil greater confidence in long-term investors globally. Establishing a global green energy partnership has the potential to generate infrastructure resources and foster techno-exchange partnerships, while the resultant FDI is expected to increase employment opportunities. Fig. 10 presents viable policy recommendations for both developing and developed nations to transition from fossil fuel-based energy to RE sources.

4.6. Limitations

Our study is designed to explore the speed of renewable energy sources in a large sample of countries with a perspective to understand economic and green energy adoption. HCA was found to be suitable for modelling the growth clusters on the renewable energy data retrieved from World Bank, incorporates total RE, and is subject to certain limitations. The total RE growth data does not indicate the source of renewable energy such as Wind, Solar, Hydropower, Biomass, Bioenergy, Hydroelectricity, and others. Researchers consider the total RE production and consumption. Considering the data for two decades exhibiting RE growth in each decade could be more informative. Rather, our used data set covers RE production from 2010 to 2020 despite the free accessibility of the data.

5. Conclusion and policy implications

The global environment is experiencing a steady and concerning rise in temperature, coupled with an exponential surge in energy consumption. In this scenario, renewable energy sources, often referred to as green energy, emerge as a potent and imperative alternative to fossil fuels. The proliferation of renewable energy offers nations the opportunity to amass sustainable energy resources, ultimately diminishing their reliance on fossil fuels and curbing carbon emissions. This article delves into the growth and pace of renewable energy sources, shedding light on a nation's commitment to embracing green and sustainable energy practices. The transition from fossil fuels to renewables signifies a monumental stride toward ensuring lasting sustainability for our economies and a brighter future. Notably, countries like the United States, China, the United Kingdom, Australia, and several Middle Eastern nations have harnessed solar energy to reduce carbon emissions over the past decade. Furthermore, our study identifies nations that are proactively bolstering their renewable energy capacity, reflecting their dedication to environmental sustainability. Leveraging hierarchical clustering analysis on a substantial dataset obtained from the World Bank, this research effectively delineates growth patterns within the samples and provides insightful trace analysis. The results of this analysis furnish robust and indispensable insights into economies that are conscientiously prioritizing the expansion of alternative energy sources.

. Sustainable economic growth depends on a developed and reliable energy complex. The world needs continuous energy for production expansion, households, transportation, and even for energy production. As the energy need is growing rapidly for expansions. In 2021, world fossil fuel energy consumption exceeded 176000-TW hours, 1 TW h equals 85984 tonnes of oil equivalent which is more than 80% of total energy consumption. However, renewable energy production is actively emerging, particularly wind, solar, and bioenergy, altering fossil energy. Renewable energy consumption rapidly growing exceeding 100% growth in several countries such as the United Kingdom, China, United States, Ireland, Luxemburg, etc. increasing renewable energy sources.

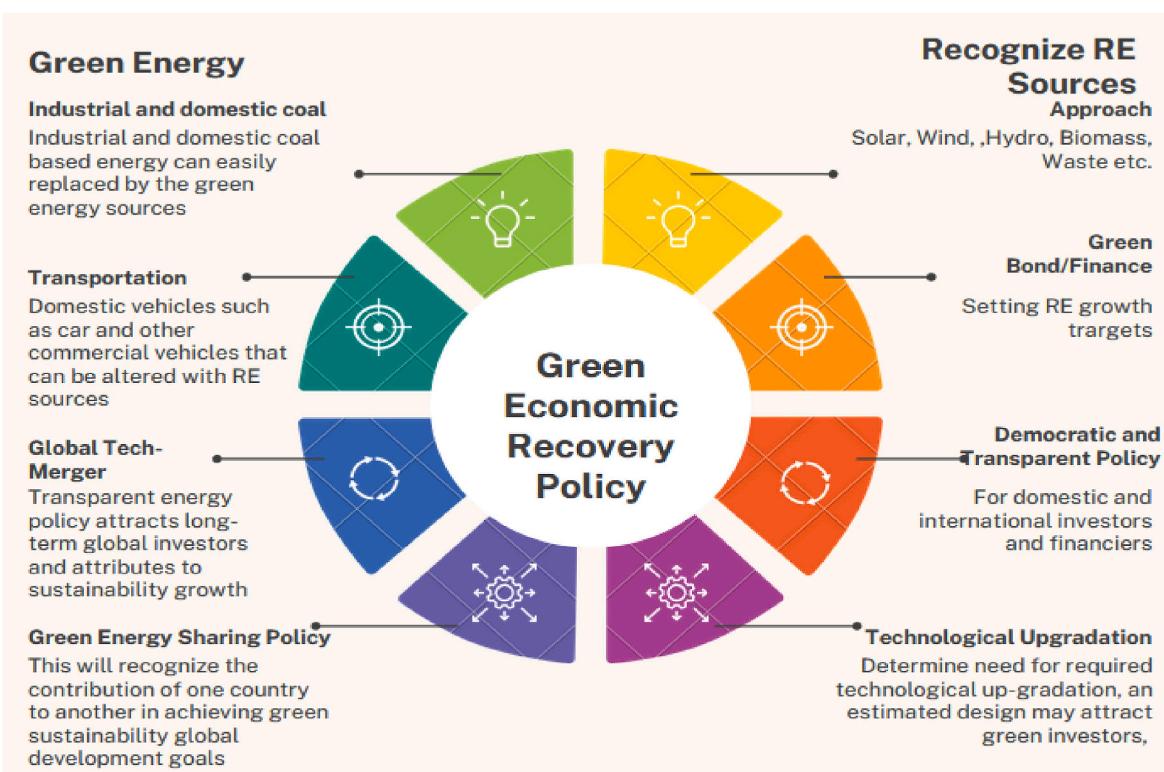

Fig. 10. Policy recommendations for emerging and developed countries. Author's illustration.

Assessment of efficiency, real prospects for green investing, and risks of economic energy policy is a progressively urgent task to thoroughly investigate. Production and consumption growth of renewable energy across selected countries are special attention concerning prospective ground for green financing that plays a win-win role. The hierarchy clustering model reveals complex growth clusters among all selected countries. The results obtained prove the emerging and rapid growth of sustainable energy to meet growing energy demands. In addition to plots and illustrative maps from the HCA model depicting the scenario on the ground, this study provides ample information to governmental bodies, international investors, financiers, and infrastructure networking companies to develop strategic decision-making policies and long-term investment schemes. Inschemes. In the European region, the adoption of a comprehensive RE framework that supplants coal-based energy has been underway. It is anticipated that other countries should follow suit as no viable alternative exists. Allocating financial resources to green technology is a strategic, long-term investment that yields significant benefits for sustainability and the advancement of green economic growth. This study does not cover carbon emission data, population data, country-wise transportation data as part of computation which could be prospective area for the future research. Finally, we propose a dynamic clustering model capturing the RE growth, growth clusters and growth pattern. We capture the silent growth in renewable energy sources that highlights the rapidly increasing the production of renewable energy. This, however, defined as prospective destinations for green financers, private investors and a visible direction for the policy makers to formulate and restructure energy policy for their sustainable bright future.

5.1. Policy recommendation

Our study obtains several policy recommendations; solar photovoltaics and wind are the finest renewable energy sources. The United States and China lead the world in solar energy production, and other countries such as the Middle East, North African, Sub-Saharan Africa, Australia, and Saudi Arabia have equal environmental conditions to increase solar and wind energy. Also, a country can formulate long-term and short-term energy policies that attract green-finance investors from the private sector. Furthermore, starting a renewable energy trading market or indicator attracts high attention towards sustainability and green energy consumption. The establishment of RE sources sets a platform for localized recruitments and promotes several other technological innovations that lead the country towards higher sustainability and private sector investors should consider promoting green financing based on the green recovery policies for green and sustainable energy. Renewable energy sources are the only solutions to protect the environment, carbon-emissions and lead toward sustainable and bright energy futures by 2050.

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CRediT authorship contribution statement

Jatin Trivedi: Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Supervision. **Dipanwita Chakraborty:** Resources, Supervision, Visualization, Writing – review & editing. **Haitham Nobanee:** Investigation, Resources, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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