Mapping the scientific structure and evolution of renewable energy for sustainable development

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Received: 27 September 2021 / Accepted: 15 April 2022 / Published online: 27 April 2022
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Abstract
The integration of renewable energy and sustainable development (RE&SD) can help overcome existing obstacles and create opportunities for renewable energy deployment to achieve sustainable development goals. In view of the limited research on science mapping and visualization analyses of RE&SD, this study sought to determine the scientific structure and evolution based on longitudinal and mapping change analysis. As an entity in the knowledge base, keyword and subject were considered essential information of documents. The co-word network was generated using SciMAT to reveal the dynamic aspects of the scientific research in the five subperiods. The thematic evolutionary analysis identified two main RE&SD thematic areas, with the current research hotspots that involved technological, environmental, sustainable energy innovation, and sustainable biofuel contributions. The alluvial diagram using MapEquation revealed significant structural changes from subject data. Clusters of subjects continued to grow, and more interdisciplinary integration was undergoing. This study provides a systematic study of RE&SD research, and the future research of RE&SD may inevitably consider renewable energy investment and renewable energy perspective approaches to achieve sustainable development goals.

Keywords  Renewable energy · Sustainable development · Scientific structure · Evolution analysis · Science mapping

Introduction
Renewable energy can contribute to the three-pillar model (economic, environmental, and social aspects) of sustainable development (Wichaisri and Sopadang, 2018; Purvis et al., 2019) and offer the opportunity like energy access and security, climate change mitigation, the reduction of environmental and health impacts, and social and economic development (Owusu and Asumadu-Sarkodie, 2016; Sathaye et al., 2011; Fathollahi-Fard et al., 2022). Sustainable Development Goal 7 (SDG 7), established by the United Nations General Assembly in 2015, concerns access to affordable, reliable, modern, and sustainable energy by everyone (Cf, 2015; Bekun et al., 2021; Fathollahi-Fard et al., 2021). In this respect, the intimate connection between renewable energy and sustainable development comes out, and the importance of renewable energy for sustainable development has been highlighted (Omer, 2008; Bekun et al., 2019). Research on the strategies and paths of renewable energy for sustainable development has blossomed over the past few years (Danish et al., 2020; Buchmayr et al., 2021; Bekun et al., 2020). As global carbon neutrality continues to advance and the global energy transition is accelerating, a systematic review and closer integration of insights are needed to determine the structure and evolution of renewable energy for achieving the 2030 Sustainable Development Goals.

Science mapping and visualization analyses have been widely used nowadays to analyze the research trends and evolutionary patterns of different research themes in the field of renewable energy, such as sources, supply and demand, low-carbon energy technology, and wastewater (Jabeen et al., 2021; Gan et al., 2020; Yu et al., 2016; Hou and Wang, 2021; Zheng et al., 2017), as well as the field of sustainable development, such as trends and future directions, sustainable technology development, and
enterprise aspects (Wichaisri and Sopadang, 2018; García-Berná et al., 2019; Prashar et al., 2020). However, there are few related studies on renewable energy for sustainable development, given that previous studies have focused on renewable energy or sustainable development, respectively. Considering the integrity and complexity of renewable energy for sustainable development, it is necessary to conduct a scientific structure and evolution analysis based on current science mapping (Cobo et al., 2012; Orimoloye et al., 2021) and network visualization methods (Van Eck and Waltman, 2014; Moosavi et al., 2021).

The present study aims to reveal the scientific structure and evolution in the field of renewable energy for sustainable development (RE&SD) through science mapping and visualization analysis approaches. Keyword and subject were selected as entities for the above analysis. In creating the main scientific structure of RE&SD, we follow the methods proposed by Cobo et al. (2012) and Rosvall and Bergstrom (2010). Therefore, a co-word network was generated using SciMAT to reveal the conceptual evolution of RE&SD, and a longitudinal framework was applied to explore the structure and dynamic aspects of the related scientific research (Cobo et al., 2012, 2011). An alluvial diagram of the subject using the MapEquation was employed to provide visual insights into changes in the structure of RE&SD. This study provides researchers and policymakers with a systematic study and discussion on the scientific structure, evolution, and changes in the field of RE&SD.

This paper is organized as follows. The “Materials and methods” section introduces the methodology used and builds a data analysis system for network visualization based on longitudinal and mapping change analysis. The “Results and discussion” section presents the results of themes visualization and alluvial diagram analysis, as well as discussions of evolution. The “Trends and future research directions” section presents emerging trends and future research directions. Conclusions are given in the “Conclusion and policy recommendation” section.

Materials and methods

Knowledge structure and significant structural changes can be determined by discovering a scientific field and delimiting research areas (Cobo et al., 2012; Rosvall and Bergstrom, 2010). In this study, a data analysis system (DAS) for scientific visualization is built to analyze the research status and structural changes of RE&SD based on science mapping and visualization methods.

Data analysis system

Longitudinal analysis via science mapping (Morris and Van der Veer 2008; Börner et al., 2003; Cobo et al., 2012; Li et al., 2019) reveals the structure and dynamic aspects of scientific research. Mapping change analysis through alluvial diagrams highlights and summarizes the significant structural changes (Rosvall and Bergstrom, 2010; Diogo et al., 2021). Documents have various information associated with them, such as authors, affiliations, keywords, cited references, journals, subject, and year of publication. Each is considered an entity in the knowledge base. In this study, keyword and subject were selected as entities for knowledge structure and evolution analysis. The workflow of visualization in the scientific literature in Fig. 1 involves two parts (Cobo et al., 2012): longitudinal analysis of keyword via SciMAT and mapping change analysis of subject via the MapEquation. Keyword-based analysis can play an important role in understanding knowledge development dynamics (Gupta and Bhattacharyya, 2004), and subject-based analysis can reveal changes in the structure of RE&SD (Wang et al., 2019).

In Fig. 1, the system performed data retrieval through ISI Web of Science, identified relevant documents, and established the RE&SD database. There are many similar terms related to the objective of this study, such as renewable energy, sustainable energy, and green energy. Therefore, by using Boolean Logic techniques, the database was built according to the following search strings to ensure comprehensiveness and accuracy: “(TI = (Renewable Energ*) OR Ti = (Sustainable Energ*) OR TI = (Alternative Energ*) OR TI = (Green Energ*) OR TI = (Cleaner Energ*)) AND (TS = (Sustainable Development) OR TS = (Sustainability)).” Then, 4296 documents were identified and retrieved (on April 28, 2021). To select only the most relevant documents, all retrieved documents were reviewed and duplicate documents were removed. Therefore, 4289 related documents were finally identified for RE&SD analysis.

Mapping analysis tools

SciMAT

Co-word analysis can be conducted by SciMAT to reveal the structural and dynamic aspects of scientific research and then delimit research areas and visualize detected subfields (Callon et al., 1983; Li et al., 2021). SciMAT offers three key features that distinguish it from other scientific mapping software tools: a powerful preprocessing module for cleaning raw bibliographic data, bibliometric measures
to investigate the impact of each detected cluster or evolution area, and a wizard to configure the analysis (Cobo et al., 2012).

Science mapping analysis and research can be carried out under a longitudinal framework to show the evolution of detected clusters in successive time periods (Cobo et al., 2011). The specific process with three main modules is shown in Fig. 1. The results are represented by using strategic diagrams, and the conceptual evolution is described by thematic areas. A longitudinal co-word science mapping analysis carried out with SciMAT in the field of RE&SD research is based on four stages (Cobo et al., 2011; , 2013; Li et al., 2021):

(1) Detect research themes. An equivalence index was used to construct and normalize co-word networks of keyword co-occurrences, $e_{ij}=c_{ij}^2/c_i c_j$, where $c_{ij}$ was the number of documents in which the two keywords $i$ and $j$ co-occurred, and $c_i$ and $c_j$ were the number of documents in which each one appeared.

(2) Build the strategic diagrams. Two parameters were used in this process to plot the research themes. Centrality measured the interaction degree between a network: $c = 10 \times \sum e_{kh}$, and density measured the internal strength of the network: $d = 100(\sum e_{kh}/w)$, where $k$ and $h$ belonged to the themes and $w$ was the number of keywords in the theme.

(3) Discover the thematic areas. An inclusion index was used to detect the conceptual nexus between the research themes in different periods. A thematic evolution from theme $U$ to theme $V$ was classified if the keywords appeared in two related thematic networks.

$$\text{Inclusion Index} = \frac{\#(U \cup V)}{\min(\#U, \#V)}$$

(4) Performance analysis. H-index and total citations were used as bibliometric indicators to measure the relative contributions of each thematic area to the entire research field.

The MapEquation

Alluvial diagrams can highlight and summarize the significant structural changes to connect changing structures with the changing function of networks (Rosvall and Bergstrom, 2010). Currently, a more advanced solution is implemented using the Infomap algorithm based on the MapEquation, which can find, evaluate, and visualize the modular organization of above networks based on flow-based and information-theoretic methods. This framework can be very flexible and identify two-level, multi-level, and overlapping organizations in weighted, directed, and multiplexed networks through its search algorithm Infomap (Rosvall et al., 2009), which is a network clustering algorithm based on the map equation (Bohlin et al., 2014):

$$L(M) = \sum_{i=1}^{m} p_i^{ij} H(P^i)$$
The MapEquation web applications include the Map & Alluvial Generator for generating alluvial diagrams and visualizing change in structures, and the Infomap Network Navigator for exploring the hierarchical and modular organizations of real-world networks (Bohlin et al., 2014). The alluvial diagram is an emerging visualization that can reveal organizational changes with streamlines between modules of the loaded networks. Specifically, we use the MapEquation to track the flow of knowledge trajectories over time and help visualize how a trajectory at time $t$ can descend, expand, merge with other trajectories, or split into multiple new trajectories by time $t+1$ (Haller and Rigby, 2020). The method consists of four steps (Rosvall and Bergstrom, 2010; Diogo et al., 2021): (1) cluster the original network observed at each time point, (2) generate and cluster the bootstrap replication network for each time point, (3) determine the significance of clustering at each time point, and (4) generate alluvial diagrams to illustrate the changes between time points. Besides, an interactive hierarchical network, generated by Infomap Network Navigator, lays the foundation for exploring and visualizing community structure in complex networks in a fast, intuitive way (Eriksson, 2018).

Results and discussion

Longitudinal analysis

SciMAT was used for temporal analyses to clarify the evolution of the structural aspects of RE&SD. From the above established RE&SD database, 4289 documents were imported into SciMAT and keyword was chosen for the analysis. The specific process is shown in Fig. 1. Several time periods were defined to conduct the longitudinal analysis, and the same time span was basically used. The whole period (1988–2021) was divided into 1988–1994, 1995–2001, 2002–2008, 2009–2015, and 2016–2021, with 42, 99, 317, 1195, and 2643 articles, respectively. After configuring all parameters, the RE&SD theme visualizations (overlap fractions, strategic diagrams), the thematic RE&SD evolutions, and the emerging analysis were developed.

Theme visualization

Overlap fractions The overlapping-items graph can display the RE&SD research theme changes and the stability of the research field (Xie et al., 2020), which measures the number of shared keywords between the successive subperiods. Figure 2 clearly reflects the emerging and declining keywords from 1988 to 2021 in the field of RE&SD, and the inclusion index measures the weight of the thematic nexus (Cobo et al., 2011). Here, the circle represents the number of keywords in each subperiod, the horizontal arrow represents the keywords shared in two subperiods, the incoming arrow indicates the number of new keywords in this subperiod, and the outgoing arrow indicates keywords that do not exist in the next subperiod.

In each of the five research subperiods (1988–1994, 1995–2001, 2002–2008, 2009–2015, 2016–2021), the number of keywords was 23, 46, 153, 470, and 646, indicating the rapid growth trend since the twenty-first century. Compared with the first two subperiods, the number of keywords in the last three subperiods has increased significantly. The stability indices of the five subperiods were 0.39, 0.72, 0.88, and 0.96, respectively, indicating that RE&SD research has gradually formed a community with consolidated terminology and strong continuity.

Strategic diagram The themes can be divided into four quadrants according to the horizontal and vertical axes, as shown in the first graph in Fig. 3. This strategic diagram can visualize each subperiod of RE&SD themes, as measured by centrality and density. The volume of the sphere is proportional to the number of published documents obtained by each cluster (theme) (Cobo et al., 2012). With the increase of centrality, the connection with other themes becomes closer, and with the increase of the density value, the connection within the theme becomes closer (Xie et al., 2020).

The four quadrants represent (Laengle et al., 2020; Cobo et al., 2011) the following: (a) motor themes, well developed and important to the structure of the research field; (b) specialized peripheral themes, well-developed internal ties, and unimportant external ties; (c) emerging or disappearing

Fig. 2 Overlap fractions
themes, in which the development is weak and marginal; and (d) transversal and general, basic themes, important but have not yet been developed.

First subperiod (1988–1994). There were only two themes in this subperiod: RENEWABLE-ENERGY and SUSTAINABLE-DEVELOPMENT. The RENEWABLE-ENERGY theme had a high center and a general density value, while SUSTAINABLE-DEVELOPMENT had a high density and general centrality. In this subperiod, the documents and sum-citations of these two themes were relatively low (see Table 1), which shows it was still in the initial stage, and no other themes had been formed in RE&SD field.

![Strategic diagrams for five subperiods](image)

**Table 1** Performance measures for the first four subperiods

| Subperiods     | Theme                  | Documents count | H index | Sum citations |
|----------------|------------------------|-----------------|---------|---------------|
| 1998–1994      | SUSTAINABLE-DEVELOPMENT | 6               | 3       | 26            |
|                | RENEWABLE-ENERGY       | 4               | 2       | 19            |
| 1995–2001      | CO2-EMISSIONS          | 5               | 2       | 16            |
|                | DEVELOPMENT            | 4               | 3       | 23            |
|                | RENEWABLE-ENERGY       | 12              | 8       | 749           |
| 2002–2008      | STRATEGIES             | 6               | 6       | 1296          |
|                | SUSTAINABLE-DEVELOPMENT| 29              | 18      | 2301          |
|                | POLICY                 | 21              | 15      | 3214          |
|                | ENVIRONMENT            | 4               | 4       | 166           |
|                | POWER                  | 4               | 4       | 184           |
| 2009–2015      | RENEWABLE-ENERGY       | 285             | 65      | 19,083        |
|                | CAPACITY               | 4               | 4       | 53            |
|                | INNOVATION             | 12              | 11      | 687           |
|                | MODEL                  | 35              | 22      | 2108          |
|                | BIOFUELS               | 29              | 22      | 5687          |
|                | POWER                  | 38              | 24      | 2330          |
Second subperiod (1995–2001). Three themes appeared in this subperiod. The DEVELOPMENT motor theme, which focused on the development of technologies, resources, environment, and energy consumption, had high density and centrality value. The basic, transversal theme was RENEWABLE-ENERGY (reappearing), associated with sustainable development, having a high citation level (749). The highly developed and isolated theme, CO2-EMISSIONS, was mainly related to scenarios and life-cycle-assessment.

Third subperiod (2002–2008). As the number of publications increased, the number of themes correspondingly increased in this subperiod. Compared with the previous two subperiods, the total citations increased significantly (see Table 1). The SUSTAINABLE-DEVELOPMENT (reappearing), STRATEGIES, and POLICY motor themes, which focused on the sustainable energy policy and climate change, had high density and centrality values. ENVIRONMENT and POWER appeared as emerging themes. This subperiod mainly focused on sustainable development scenarios, policy, and renewable energy environment.

Fourth subperiod (2009–2015). The number of themes continued to grow in this subperiod, especially the theme RENEWABLE-ENERGY (reappearing) with high density and centrality. As shown in Table 1, there were 285 related documents and 19,083 sum citations. The MODEL and BIOFUELS themes had general density and centrality value, which were mainly related to city capacity, market, and transition. CAPACITY and INNOVATION were highly developed but isolated. POWER appeared as the basic, transversal theme. There were no emerging or declining themes in this subperiod.

Fifth subperiod (2016–2021). Themes in the latest subperiod increased significantly. The CO2-EMISSIONS, SYSTEMS, INNOVATION, and CLIMATE-CHANGE motor themes, which focused on the carbon emissions, ecological footprint, systems performance, opportunities, and challenges for sustainability transitions, had high density and centrality value. The LIFE-CYCLE-ASSESSMENT and SUSTAINABLE-ENERGY themes emerged and had general centrality and low density, but they had a relatively high impact index and sum of citations (see Table 2). INVESTMENT, SUSTAINABLE-DEVELOPMENT-GOALS, and ENVIRONMENT appeared as emerging themes. This subperiod revealed the diversification that was beginning to occur in RE&SD research.

Thematic evolution

The dynamic thematic RE&SD research evolutionary map in the five subperiods is shown in Fig. 4. The solid line indicates that the linked themes (clusters) share the same name, or that the name of one theme forms part of the other, the dotted line indicates that the themes are related because they share elements that are not in the name of the theme, the thickness of the line indicates the proportionality to the inclusion index, and the size of the sphere indicates the proportionality to the published documents in each theme (Cobo et al., 2011).

RENEWABLE-ENERGY and SUSTAINABLE-DEVELOPMENT were the two themes in the first subperiod. At the same time, they were also the two core keywords in the RE&SD research field. There were no subsequently disappeared themes, while the newly generated themes were CO2-EMISSIONS during 1995–2001, CAPACITY during 2009–2015, and INVESTMENT during 2016–2021. The gradual enrichment of research content and themes meant that the data flow of the nodes became more complicated from the third subperiod.

According to the principle of thematic area identification, a group of themes that evolve over several subperiods can be grouped into one thematic area. That is, if the keywords appear in two related thematic networks, a thematic evolution from theme U to theme V is classified (Cobo et al., 2011). Here, the main RE&SD thematic areas were identified. By focusing on the two key themes in the first subperiod, and the core themes in the latest subperiod, their strategic positions can be found in Table 3. This strategic position, which is either the same theme in any quadrant of the previous subperiod, or included in other related themes, helps to explore the evolution of the thematic areas.

To clearly identify and analyze the main RE&SD thematic areas, cluster networks of key and core themes were introduced in Fig. 5. As a visualization technique in SCIMAT, the interconnection between the nodes is represented in the cluster network map. The size of the node represents the number of documents, citations, or h-indices (the number of documents was selected in this study), and the thickness of the line corresponds to the strength of the correlation between the two nodes. Combine strategic positions and

| Table 2 | Performance measures for the subperiod of 2016–2021 |
|---------|--------------------------------------------------|
| Theme               | Document count | H index | Sum citations |
| SYSTEMS             | 393            | 36      | 5514          |
| CO2-EMISSIONS       | 252            | 34      | 4096          |
| CLIMATE-CHANGE      | 157            | 26      | 2189          |
| INNOVATION          | 71             | 16      | 1158          |
| LIFE-CYCLE-ASSESSMENT | 61          | 19      | 1136          |
| SUSTAINABLE-ENERGY  | 44             | 18      | 1148          |
| ENVIRONMENT         | 13             | 4       | 90            |
| INVESTMENT          | 11             | 5       | 90            |
| SUSTAINABLE-DEVELOPMENT-GOALS | 9 | 4 | 389 |
cluster networks, the evolution trajectory of key and core themes can be described by broken line in the left graph in Fig. 4. The red solid line and the orange dotted line form two areas, namely Area I and Area II in the right graph.

Evolution and emerging analysis

Basic evolution in area I RENEWABLE-ENERGY and SUSTAINABLE-DEVELOPMENT, two themes in the first
subperiod (also the two major objects of RE&SD research) evolved as the main theme or included in other themes (like POLICY), finally flowed to CO2 EMISSION and CLIMATECHANGE in the latest subperiod, which were core themes with high h-index (34, 26) and document number (252, 157). RENEWABLE-ENERGY appeared in the fourth quadrant (Q4) as a basic and transversal theme in the first two subperiods, then (included) in the first quadrant (Q1) in the last three subperiods and had an h-index rising from 2 to 65 (first to fourth subperiod). SUSTAINABLE-DEVELOPMENT basically appeared in the first quadrant (Q1) in the entire time interval with h-index rising from 3 to 18 (first to third subperiod). This thematic area also included other research themes related to POLICY, MODEL, POWER, and SYSTEM, with an h-index of 15, 22, 24, and 36.

Topics in this area were from the impact of renewable energy consumption on CO2 emissions and economic growth in different countries towards sustainable development (Ikram et al., 2020; Yang et al., 2015; Alola et al., 2019), followed by sustainable energy policy discussions, modeling and optimization for renewable energy development, and renewable energy systems for power generation (hydropower, wind power, nuclear power, solar power, etc.) (Patlitzianas et al., 2008; Bazmi and Zahedi, 2011; Alstone et al., 2015; Nehrir et al., 2011). Current research focuses on energy security, climate change (including the impact of CO2 emissions), and sustainable development, as well as sustainable energy system (Foley and Olabi, 2017; Zhang et al., 2019; Bazmi and Zahedi, 2011).

Key evolution in area II The elements in this thematic area also varied and had not evolved into a core content by the latest subperiod. Firstly, included in SUSTAINABLE-DEVELOPMENT in the first subperiod, ENVIRONMENT appeared as an emerging theme (Q3) in the third subperiod and again in the fifth subperiod (as shown in Table 3) with h-index stable at 4. INNOVATION was included in STRATEGIES (Q1) in the third subperiod, and formally appeared in the fourth subperiod, then shifted from being highly developed but isolated (Q2) to a motor theme (Q1), indicating its importance to the RE&SD research. The theme LIFE-CYCLEASSESSMENT was also highly developed but isolated (Q2) when formally appearing in the fifth subperiod with a high h-index of 19. Other themes in this area included DEVELOPMENT, STRATEGIES, and BIOFUELS, with an h-index of 3, 6, and 22.

The previous subperiods in this area focused on renewable energy strategies for sustainable development, developments in sustainable energy and environmental protection, and the development of new energy vehicles for a sustainable future (Lund, 2007; Chu and Majumdar, 2012; Midilli et al., 2006; Yuan et al., 2015). Currently, the research hotspots also involved technological innovation, environmental innovation, and sustainable energy innovation, life cycle assessment of renewable energy, and sustainable biofuel contributions (such as microalgae, a sustainable renewable energy feedstock) (Tabrizian, 2019; Khan et al., 2020; Prasad et al., 2020; Nazari et al., 2021; Medipally et al., 2015).

Emerging trends The evolutions in areas I and II mainly revealed the aspects of renewable energy, environment, and sustainable development. Apart from these, some themes in the latest subperiod should also be noticed. INVESTMENT and SUSTAINABLE-DEVELOPMENTGOALS formally appeared in this subperiod, and they were also the emerging themes in the third quadrant (Q3) with an h-index of 5 and 4. There were 9 documents related to SUSTAINABLE-DEVELOPMENT-GOALS, with the number of citations (389) being relatively high. The emerging trends mainly focused on energy investment needs for fulfilling the Paris Agreement and achieving the sustainable development goals, as well as sustainable energy planning, energy technology/impact/policy assessment, and metrics for the sustainable development goals. Therefore, the future development of RE&SD may inevitably consider renewable energy investment and sustainable development goals. This outcome is consistent with the findings of McCollum et al. (2018), Ji et al. (2020), Stoeglehner (2020), Nerini et al. (2018), and Grubler et al. (2018).

Map and alluvial analysis

The alluvial diagram and interactive hierarchical network have been used in this study to highlight and summarize the significant structural changes of subject (Web of Science categories) in the field of RE&SD research. To capture the dynamics across the links and nodes in networks, MapEquation was used as the objective function (Rosvall and Bergstrom, 2007, 2010; Rosvall et al., 2009).

Alluvial diagram

Figure 6 shows how the subject data revealed the significant structural changes that have occurred in the research field of RE&SD, specifically in five subperiods of 1988–1994, 1995–2001, 2002–2008, 2009–2015, and 2016–2021. Each subperiod occupies a column in the figure and is horizontally connected to preceding and succeeding significant clusters by stream fields. Each block of the same color in a column represents a cluster, and the height of the block reflects the change flow of the research area. These clusters are sorted from bottom to top by their size, with mutually non-significant clusters placed together and separated by a third of the standard spacing. The change of the cluster structure from one subperiod to the next subperiod is represented by the
mergers and divergences that occur in the ribbons linking the blocks at different subperiods during 1988–2021 (Rosvall and Bergstrom, 2010; Wang et al., 2019).

In the 1988–1994 column in Fig. 6, the cluster ENERGY&FUELS at the bottom was the largest, and it had the highest block, which represented the highest PageRank value (Lambiotte and Rosvall, 2012). Cluster GREEN&SUSTAINABLE&TECHNOLOGY was the second largest, ranking on top of the ENERGY&FUELS, with smaller blocks. The cluster ENERGY&FUELS had six categories/subsets (such as ENVIRONMENTAL SCIENCES, ENGINEERING, ECONOMICS), and this blue stream flowed from 1988–1994 to 1995–2001, 2002–2008, 2009–2015, and finally flowed into several clusters in 2016–2021 (like the cluster PHYSICS, CONDENSED MATTER), indicating that this research topic ran through five stages and had been a hot research topic. According to the evolution of RE&SD publications, ENERGY&FUELS cluster during 1988–1994 gradually split to ENGINEERING, ENERGY & FUELS, and ENVIRONMENTAL SCIENCES & ECOLOGY during 1995–2001.

New clusters emerged in the middle three subperiods, like BIOLOGY, ELECTROCHEMISTRY (1995–2001), URBAN STUDIES, MARINE & FRESHWATER BIOLOGY (2002–2008), and COMPUTER SCIENCE, INFORMATION SYSTEMS (2009–2015), which had weak linkage to the past. The most new flows appeared during 2002–2008. All clusters in 2009–2015 subperiod changed from splits to being clustered together and becoming the three key clusters in 2016–2021 subperiod. The largest cluster in the latest subperiod was PHYSICS, CONDENSED MATTER, including subsets of CHEMISTRY, PHYSICAL, MATERIALS SCIENCE, MULTIDISCIPLINARY, and PHYSICS, followed by the cluster COMPUTER SCIENCE and REGIONAL & URBAN PLANNING. In addition, ENGINEERING, CIVIL, OPERATIONS RESEARCH & MANAGEMENT SCIENCE, BUSINESS & ECONOMICS, and ENVIRONMENTAL SCIENCES were subsets in these two clusters.

Evolving from only two clusters in 1988–1994 subperiod, clusters of subjects continued to grow in the next three subperiods then became mature and consolidated in the latest subperiod. In general, more involved clusters and categories in RE&SD field indicated that more interdisciplinary integration was undergoing, as seen in the findings of Baleta et al. (2019) and Sathaye et al. (2011). ENERGY & FUELS, ENVIRONMENTAL SCIENCES, MATERIALS SCIENCE, and PHYSICS were mainstream disciplines in this field, while COMPUTER SCIENCE, ENGINEERING in natural science field, and REGIONAL & URBAN PLANNING, BUSINESS & ECONOMICS in social science field started to attach more attention recently, which is in agreement with the findings of Sovacool (2014). This study approves that energy studies need social science.

**Interactive hierarchical network**

By using interactive zoomable map for networks clustered with Infomap (Bohlin et al., 2014; Edler et al., 2017), Fig. 7 displays the interactive hierarchical networks of five subperiods to reveal and highlight the essential structures of RE&SD field. Modules (clusters) are drawn as circles with area proportional to the contained flow. The thickness of the module border is proportional to exiting flow. The links between nodes are aggregated at the module level, and their thickness is proportional to the flow between modules (darker color means higher flow). In the visualization of hierarchical networks, the highest-ranking nodes were shown in a module, the links between them with the highest flow, the names of a select few high-ranking nodes, and more details are continuously displayed as the layout zooms in. This approach is called rank-based level-of-detail and can be thought of as rank thresholding as a function of scale. When
zooming in on a module far enough so that it could contain a low-detail network, its contents (contained nodes or sub-modules) are revealed. Therefore, parent modules and their sub-modules in the field of RE&SD can be found in Fig. 7.

The networks composed of parent modules for the five subperiods were shown on the left side of the graph, which displayed the highest-ranking nodes. The tree path was root, and the degree was 0. Information list on the right presented the corresponding number of nodes, links, and leaf nodes. In the first four subperiods, the number of the above three showed an increasing trend over time, and the network scale became larger. In the final 2016–2021 subperiod, modules were back to three, that is, the clustering results were more concentrated recently. However, the network size still increased, with the highest leaf nodes being 79.

By zooming in on three modules (named 1, 2, and 3) in the 2016–2021 subperiod, the low-detail networks with contained nodes (sub-modules) were displayed on the right side of the Fig. 7. The hierarchical networks of secondary and three-level sub-modules of 1 PHYSICS, CONDENSED MATTER, 2 COMPUTER SCIENCE, and 3 REGIONAL & URBAN PLANNING were expanded, such as the leaf nodes of 1:1:3 MATERIALS SCIENCE, MULTIDISCIPLINARY, 2:1:3 COMPUTER SCIENCE, INFORMATION SYSTEMS, and 3:1:3 DEVELOPMENT STUDIES. The biggest module ENERGY & FUELS in the first 1988–1994 subperiod was in tree path of 1:3 (GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY) in the 2016–2021 subperiod, as 1:3:3.

**Trends and future research directions**

The evolution and emerging analysis from longitudinal analysis based on SciMAT highlighted two emerging themes in the field of RE&SD research, namely INVESTMENT and SUSTAINABLE-DEVELOPMENT-GOALS, which formally appeared in the latest 2016–2021 subperiod. They emphasized the energy investment needs for fulfilling the Paris Agreement on climate change and renewable energy perspective approaches to achieve the sustainable development goals.

(1) Energy investment needs. Current research contributes to status and future investment potential in renewable energy, the drivers of renewable energy investments, investment risk evaluation and optimization for renewa-
ble energy project, and policy and regional discussions to generate the framework to facilitate decision making in renewable energy investments towards green and sustainable investments. Future research still requires energy investment needs for both the Paris Agreement and sustainable development goals. Low-carbon investments are necessary, and more capital would have to be mobilized to close the investment gap for a 2°C or 1.5°C future (McCollum et al., 2018).

(2) Sustainable development goals (SDGs). From the current literature, integrated spatial and energy planning is an important field of action to reach SDGs (Stoeglechner, 2020), and a set of science-based metrics can promote the alignment of action decisions with SDGs (Buonocore et al., 2019). The interlinkages between energy and the SDGs are also a research focus (Santika et al., 2019). According to the latest 2020 SDG report, affordable and reliable energy is now needed more than ever, especially after the COVID-19 pandemic, which represents the biggest shock to the global energy system in decades and has caused tremendous uncertainty in efforts toward SDG 7 achievement (Cf, 2015; Hefron et al., 2021). However, the pandemic can either widen the sustainable energy access gaps or accelerate the path towards achieving SDGs, depending mostly on governments’ sustained policies to take the lead in pursuing structural reductions in emissions to accelerate the development and deployment of a full range of renewable energy solutions.

Furthermore, significant structural changes from the alluvial diagram and interactive hierarchical network indicated that more interdisciplinary integration was undergoing in RE&SD. In order to fill knowledge gaps in critical areas, there is an urgent need for scientists from different disciplines to share knowledge and collaborate and achieve the sustainable development goals with interdisciplinary research.

Conclusion and policy recommendation

A science mapping and visualization analysis on a dataset of 4289 research articles from 1988 to 2021 was conducted to reveal scientific structure and evolution in the field of RE&SD. A data analysis system (DAS) with two main modules was developed for scientific visualization based on longitudinal and mapping change analysis. The co-word network and alluvial diagram of subject were generated by using SciMAT and the MapEquation. The results provided visual insights into the knowledge structure and evolutions in RE&SD research.

Conclusion remarks

The longitudinal analysis of RE&SD from the co-word networks revealed the dynamic aspects of scientific research in the five subperiods. Overlap fractions with high stability indices indicated that RE&SD research gradually formed a community in which terminology became consolidated. Strategic diagrams and thematic areas were extracted and combined with performance analysis, from which two main RE&SD thematic areas and emerging areas were identified, including the following: (1) The basic evolution centered on renewable energy and sustainable development has evolved into the recent period of CO₂ emissions and climate change in the latest 2016–2021 subperiod, combined with other research themes related to policy, model, power, and system; (2) the key evolution centered on the varied elements in this thematic area has the current research hotspots including technological, environmental, sustainable energy innovation, and sustainable biofuel contributions; (3) the emerging trends of future development of RE&SD may inevitably consider renewable energy investment and sustainable development goals.

The alluvial diagram and interactive hierarchical network revealed significant structural changes from subject data. Evolving from only two clusters in 1988–1994 subperiod, clusters of subjects continued to grow, then became mature and consolidated in the latest subperiod, indicating that more interdisciplinary integration was undergoing. ENERGY & FUELS, ENVIRONMENTAL SCIENCES, MATERIALS SCIENCE, and PHYSICS were mainstream disciplines in this field, while COMPUTER SCIENCE, ENGINEERING in natural science field, and REGIONAL & URBAN PLANNING, BUSINESS & ECONOMICS in social science field started to attract more attention recently.

Policy recommendation

The findings in this paper can provide researchers and policymakers with insights into future research directions and policy recommendations for the sustainable development of renewable energy. A comprehensive review and scientific structure of RE&SD through science mapping analysis help scholars inspire relevant ideas and encourage them from different disciplines to share knowledge and collaborate. Policymakers could consider energy investment needs and renewable energy perspective approaches to achieve sustainable development goals.

Increased financing and investment are needed to address the underfunding of local energy innovation. In addition, appropriate market design is also needed to foster competition and innovation, as well as attract investment at scale. Governments’ sustained policies to accelerate the development and deployment of a full range of renewable energy
solutions are critical. At the same time, active policy efforts to support flexibility investments to maintain the energy and flexibility transition going are required especially after the COVID-19 pandemic.

**Limitation and future recommendation**

There are some limitations to this study. Only keyword and subject were selected for scientific structure and evolution analysis, while other entities, such as authors, affiliations, and cited references can also be included for a comprehensive discussion. The analysis technique has some limitations in terms of the type of methodology and focuses only on published articles in the journal. Furthermore, evolution analysis only revealed significant structural changes in the subject data; thus, in addition to addressing the above limitations and model improvements, a perspective on the evolution of renewable energy technologies is also a viable avenue for further research.

**Acknowledgements** The authors would like to thank the anonymous referees for their insightful comments and suggestions to improve this paper.

**Author contribution** ML constructed the method framework, analyzed and interpreted the literature data regarding renewable energy and sustainable development, and was a major contributor in writing the manuscript. YL conceptualized, reviewed, and edited the manuscript. XX verified the visualization process and results. All authors read and approved the final manuscript.

**Funding** This research was supported by the Humanity and Social Science Youth Foundation of the Ministry of Education of China (Grant No. 17YJC630096), Youth Program of the National Social Science Foundation (Grant No. 19CJL047), and the China Scholarship Council (Grant No. 201706240166).

**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

**References**

Alola AA, Bekun FV, Sarkodie SA (2019) Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. Sci Total Environ 685:702–709. https://doi.org/10.1016/j.scitotenv.2019.05.139

Alstone P, Gershenson D, Kammen DM (2015) Decentralized energy systems for clean electricity access. Nat Clim Chang 5(4):305–314. https://doi.org/10.1038/nclimate2512

Baleta J, Mikulčíč H, Klemes J, Urbaniec K, Duš N (2019) Integration of energy, water and environmental systems for a sustainable development. J Clean Prod 215:1424–1436. https://doi.org/10.1016/j.jclepro.2019.01.035

Bazmi AA, Zahedi G (2011) Sustainable energy systems: role of optimization modeling techniques in power generation and supply-a review. Renew Sustain Energy Rev 15(8):3480–3500. https://doi.org/10.1016/j.rser.2011.05.003

Bekun FV, Alola AA, Gyamfi BA, Ampomah AB (2021) The environmental aspects of conventional and clean energy policy in sub-Saharan Africa: is N-shaped hypothesis valid? Environ Sci Pollut Res 28:66695–66708. https://doi.org/10.1007/s11356-021-14758-w

Bekun FV, Alola AA, Sarkodie SA (2019) Toward a sustainable environment: nexus between CO2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. Sci Total Environ 657:1023–1029. https://doi.org/10.1016/j.scitotenv.2018.12.104

Bekun FV, Yaļčiner K, Etokakpan MU, Alola AA (2020) Renewed evidence of environmental sustainability from globalization and energy consumption over economic growth in China. Environ Sci Pollut Res 27:29644–29658. https://doi.org/10.1007/s11356-020-08866-2

Bohlin L, Edler D, Lancichinetti A, Rosvall M (2014) Community detection and visualization of networks with the map equation framework, in: Measuring scholarly impact. Springer Cham pp. 3–34. https://doi.org/10.1007/978-3-319-10377-8_1

Börner K, Chen C, Boyack KW (2003) Visualizing knowledge domains. Ann Rev Inf Sci Technol 37(1):179–255. https://doi.org/10.1002/aris.1440370106

Buchmayr A, Verhofstadt E, Van Ootegem L, Delmás DS, Thomassen G, Dewulf J (2021) The path to sustainable energy supply systems: proposal of an integrative sustainability assessment framework. Renew Sustain Energy Rev 138:110666. https://doi.org/10.1016/j.rser.2020.110666

Buonocore JJ, Choma E, Villavicencio AH, Spengler JD, Koehler DA, Evans JS, Leliëneveld J, Klopf, Sanchez-Pina R (2019) Metrics for the sustainable development goals: renewable energy and transportation. Palgrave Communications 5:1–14. https://doi.org/10.1057/s41599-019-0336-4

Callon M, Courtial JP, Turner WA, Bauin S (1983) To problematic networks: an introduction to co-word analysis. Soc Sci Technol 63(8):1609–1630. https://doi.org/10.1080/01071002/2019.1647883

Cf O (2015) Transforming our world: the 2030 agenda for sustainable development. United Nations: New York, NY, USA

Chu S, Majumdar A (2012) Opportunities and challenges for a sustainable energy future. Nature 488(7411):294–303. https://doi.org/10.1038/nature11475

Cobo MJ, Chiclana F, Collop A, de Ona J, Herrera-Viedma E (2013) A bibliometric analysis of the intelligent transportation systems research based on science mapping, IEEE Trans Intell Transp Syst 15(2):901–908. https://doi.org/10.1109/TITS.2013.2284756

Cobo MJ, López-Herrera AG, Herrera-Viedma E, Herrera F (2011) An approach for detecting, quantifying, and visualizing the evolution of a research field: a practical application to the Fuzzy Sets Theory field. J Informetr 5(1):146–166. https://doi.org/10.1016/j.joi.2010.10.002

Cobo MJ, López-Herrera AG, Herrera-Viedma E, Herrera F (2012) Scimat: a new science mapping analysis software tool. J Am Soc Inf Sci Technol 63(8):1609–1630. https://doi.org/10.1002/asi.22688

Danish MSS, Elsayed MEL, Ahmadi M, Senjyu T, Karimi H, Zahedi H (2020) A strategic-integrated approach for sustainable energy systems optimization modeling techniques in power generation and supply-a review. Renew Sustain Energy Rev 15(8):3480–3500. https://doi.org/10.1016/j.rser.2011.05.003

Buonocore JJ, Choma E, Villavicencio AH, Spengler JD, Koehler DA, Evans JS, Leliëneveld J, Klopf, Sanchez-Pina R (2019) Metrics for the sustainable development goals: renewable energy and transportation. Palgrave Communications 5:1–14. https://doi.org/10.1057/s41599-019-0336-4
