“Concept mapping of human capital management in the renewable energy transition: A bibliometric analysis and divergence gap assessment”

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CONCEPT MAPPING OF HUMAN CAPITAL MANAGEMENT IN THE RENEWABLE ENERGY TRANSITION: A BIBLIOMETRIC ANALYSIS AND DIVERGENCE GAP ASSESSMENT

Abstract

The transition toward climate neutrality is reshaping economic systems and increasing the importance of human capital in green modernization. However, a significant gap persists between technological advances and the strategic management of the workforce. This study aims to systematize and conceptually map the contemporary scholarly landscape of human capital management research within the renewable energy transition. Using the PRISMA 2020 protocol, the study analyzed 2,258 Scopus-indexed documents published between 1994 and 2026 through bibliometric and science mapping methods. The methodology combined descriptive statistics, keyword frequency analysis, multiple correspondence analysis (MCA), and network co-occurrence cluster analysis using the Bibliometrix R-package and VOSviewer. The results show a rapid increase in publication activity, with an annual growth rate of 18.01%, with China, the United States, and India leading global output and the international collaboration rate reaches 28.6%. Science mapping showed that the term "human capital" entered this field more actively only after 2020 (297 occurrences), still lagging behind technological topics. MCA indicated a clear conceptual separation between knowledge domains: the relative distance between the educational and workforce clusters suggests that these themes are still weakly integrated in the literature. Network analysis identified five thematic clusters: the technological and educational foundation, macroeconomic environment and resources, strategic management and innovative transformation, the socio-labor dimension and labor market, and eco-technological regulation. These results point to the need for a more integrated approach to adaptive human capital development that connects technological change, professional mobility, and institutional learning and strengthens the role of human capital in supporting green transformation.

Keywords human resources, energy, management, competencies, green skills, transition, decarbonization, environmental economics, science mapping, PRISMA

JEL Classification J24, Q42, Q55, O15

INTRODUCTION

Current environmental challenges, especially climate change, are reshaping the energy sector, which accounts for over 75% of global greenhouse gas emissions (Climate Watch, 2026). Awareness of this emission trajectory established the Paris Agreement as the international benchmark for decarbonization, with the IPCC confirming that deep emission reductions in energy systems are essential for climate neutrality (IPCC, 2023). However, this transformation is multidimensional: it depends not only on political will, technological innovation, or financial support, but also heavily on qualified human capital to implement industrial change and introduce green innovations (Hanna et al., 2024).

In the energy transition, the contribution of human capital depends on how effectively it is managed at the organizational level. Human

Capital Management (HCM) is increasingly conceptualized as a complex system that aligns human resources, organizational practices, and strategic goals, rather than just an auxiliary HR function (Boon et al., 2018). In the context of decarbonization, this requires synchronizing competencies with technological advancements, developing adaptive capacities, and continuously reconfiguring knowledge (Popp et al., 2024).

However, despite the recognized importance of HCM, a critical scientific problem persists: the scholarly discourse surrounding human capital in the energy transition remains conceptually fragmented and structurally detached from mainstream energy policy. Existing literature predominantly examines human capital through isolated macroeconomic parameters or reactive skill-shortage assessments, leaving a chronological and thematic lag between technological deployment and workforce adaptation. Identifying these structural divergence gaps and mapping how this research landscape has evolved is therefore essential to establish a unified framework connecting energy policy with adaptive human capacity building.

1. LITERATURE REVIEW

The concept of HCM emerged in response to the increasing complexity, uncertainty, and strategic role of human capital within the knowledge economy, where traditional administration and cost control proved insufficient for sustaining competitiveness (Welpe & Rachbauer, 2006; Mayo, 2016). In contrast to the industrial logic that viewed personnel primarily as an operational expense, the new form of economic relations necessitated a focus on intangible assets, innovation, learning, and rapid adaptability (Kowalska, 2013). Within this context, HCM was established as a managerial philosophy centering primarily on people as the core strategic asset, requiring continuous investment to build resilient organizational capabilities (Welpe & Rachbauer, 2006; Mayo, 2016).

At the same time, the literature also developed a more theoretically grounded perspective in the form of strategic HCM. This approach shifted the focus from general HR practices to the specific attributes of human capital resources, including strategic value, uniqueness, and unit-level emergence (Wright et al., 2014; Boon et al., 2018, Ray et al., 2023). Empirical validation of this logic is provided by Alolayyan et al. (2021), demonstrating that strategic resource management directly stimulates human capital development, with employee commitment serving as a key mediator in this process. Similarly, the critical role of strategic human resource planning is underscored by Al-Qudah et al. (2020), proving its positive impact on overall organizational performance through the systematic alignment of workforce potential with corporate objectives.

Over time, this perspective expanded and placed HCM within the broader framework of knowledge management and intellectual capital. Effective HCM has been described as requiring the integration of human resource management strategy with knowledge management processes (Bontis & Fitz-enz, 2002; Afiouni, 2013). In this view, HCM includes not only recruitment and development processes but also the mechanisms through which individual knowledge is translated into collective organizational capabilities. This broader interpretation is illustrated by Petrova and Taghikilanidamavandi (2025), whose study of Ukrainian companies in the energy and logistics sectors shows that human capital development can support cultural transformation, with training efficiency acting as the link between innovative leadership and organizational adaptability under crisis conditions.

Recent studies increasingly examine HCM beyond the corporate level and connect it to sustainable development and energy transition processes. Within this literature, the main concern shifts to how economies and organizations build the workforce skills and structures needed for decarbonization and long-term sustainability (Hanna et al., 2024; Weishaupt & Quiceno-Soto, 2026). Green growth depends not only on technology and investment but also on the capacity of educational systems to supply competencies for renewable en-

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ergy, environmental compliance, and low-carbon innovation (Consoli et al., 2016; Popp et al., 2024). As a result, green jobs are associated with a higher intensity of cognitive skills and stricter requirements for formal education and experience than many traditional sectors (Consoli et al., 2016).

Digitalization further alters the logic of HCM by transforming the required skill sets while simultaneously reshaping managerial logic toward the continuous renewal of capabilities (Arcelay et al., 2021; Santoalha et al., 2021). The term "twin transition" increasingly appears in the literature, positioning digitalization and sustainability as complementary processes essential for a successful energy transformation (Rollnik-Sadowska, 2024). As a result, new competency requirements are emerging, as without a corresponding level of knowledge and digital skills within the workforce, even substantial investments in renewable energy sources fail to yield the expected environmental outcomes (Faisal, 2023; Rabadán-Pérez & Muñoz-Céspedes, 2026).

The deployment of Industry 4.0 technologies (AI, Big Data, IoT, Digital Twins) within the renewable energy sector necessitates a transition from stable job descriptions to predictive workforce planning and adaptive learning pathways (Arcelay et al., 2021). Digital skills thus become a vital resource for regional diversification, determining the capacity of territories to successfully transition toward green manufacturing (Santoalha et al., 2021).

At the same time, research on HCM in the renewable energy transition remains fragmented and lacks a clear conceptual structure. Specifically, in an investigation of the relationship between human capital and the deployment of renewable energy, Adepoju et al. (2022) note that this research trajectory is in its nascent stage of development and is characterized by a limited volume of publications. The majority of existing works are currently concentrated within adjacent clusters, failing to establish a unified conceptual field. The main lines of this research include: the transformation of competencies during the transition to sustainable energy (Weishaupt & Quiceno-Soto, 2026); the impact of decarbonization on job structures (Hanna et al., 2024; Das & Patil, 2025); workforce dynamics during systemic transformations (Rollnik-Sadowska, 2024); and the measurement and conceptualization of ecologically oriented employment (Kozar & Sulich, 2023; Stanef-Puică et al., 2022; Apostel & Barslund, 2024).

Despite the growing body of literature, the field remains fragmented and still lacks a unified conceptual map; in particular, theoretical HCM models often overlook the technological and regulatory specificities of the renewable energy sector. Most studies focus on isolated cases, which makes it difficult to develop a holistic view of the field's evolution.

In view of this, the study aims to systematize and conceptually map the contemporary scholarly landscape of human capital management research in the context of the transition to renewable energy. To address this objective, the study uses bibliometric analysis and examines divergence gaps between the identified research clusters.

2. METHOD

2.1. Research design

This study uses a systematic bibliometric review to examine the structure and development of research on HCM in the renewable energy transition. The methodology follows the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement to provide a transparent and reproducible procedure for selecting scholarly literature. The research process is organized according to the PRISMA 2020 flow diagram (Figure 1), which includes four phases: identification, screening, eligibility, and inclusion.

2.2. Data collection and selection criteria

For the identification phase, bibliometric data were retrieved from the Scopus database because it indexes peer-reviewed literature, provides standardized metadata, and offers broad coverage of multidisciplinary research. The search strategy was designed to cover the main dimensions of HCM in the renewable energy transition; accordingly, the keywords were grouped into three blocks:

- human capital and labor market competencies ("human capital", "workforce", "skills", "competencies", and "labor market");
- environmental and structural changes ("renewable energy", "energy transition", and "green economy");
- governance and strategic management frameworks ("management", "strategy", "governance", and "development").

The retrieval logic was formulated using Boolean operators and field tags; specifically, the TITLE-ABS-KEY tag restricts the search to the title, abstract, and keywords of the documents. The final search string applied in Scopus was as follows:

TITLE-ABS-KEY(("human capital" OR "workforce" OR "skills" OR "competencies" OR "labor market") AND ("renewable energy" OR "energy transition" OR "green economy") AND ("management" OR "strategy" OR "governance" OR "development"))

During the screening phase, the retrieved results were filtered based on the following criteria:

- source type: peer-reviewed articles, reviews, conference papers, book chapters, and books;
- language: English;
- subject area**:** Social Sciences; Environmental Science; Business, Management and Accounting; Energy; Economics, Econometrics and Finance; Decision Sciences; and Multidisciplinary.

The search was conducted and the records were exported on 11 May 2026. This date was used as the temporal cut-off point for the bibliometric dataset; therefore, all publication counts, citation indicators, and thematic patterns reported in this study reflect the indexing status of Scopus as of that date.

Additionally, the retrieved results were filtered and cleaned using OpenRefine software. This procedure included the removal of duplicate records, the harmonization of keyword variants, the normalization of singular and plural forms, and the consolidation of semantically equivalent expressions. Following the screening, the eligibility of the selected reports was manually assessed, leading to the exclusion of a certain number of works from further consideration. The primary reasons for exclusion were a lack of focus on HCM strategies; furthermore, publications lacking mandatory scholarly attributes, such as an abstract or keywords, were also omitted. This process resulted in

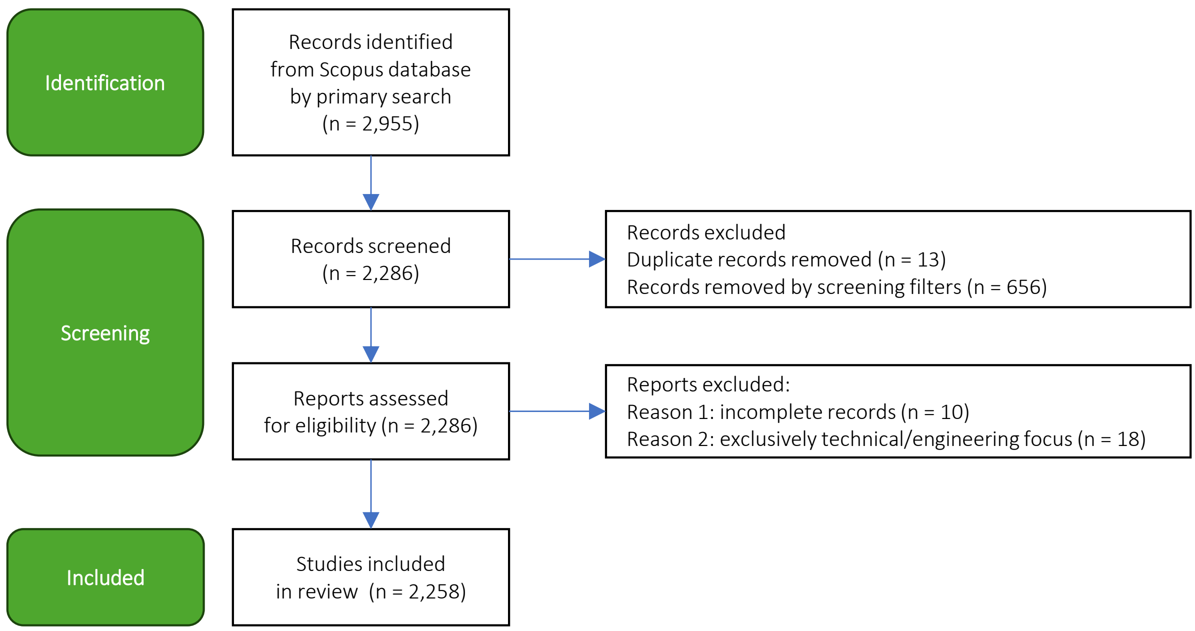

Figure 1. PRISMA flow diagram of the literature search and selection process

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the final dataset used in the analysis and improved the relevance of the selected publications to the research objective.

As a result, the initial search yielded 2,955 records from Scopus. After the removal of duplicates and the application of filters related to document type, language, and subject area, 2,286 records remained for eligibility assessment. Due to the scale of the retrieved bibliometric corpus (n = 2,286), the manual eligibility assessment was systematically executed by three independent reviewers based on the titles, abstracts, and author keywords of the records; full-text articles were examined only when metadata was ambiguous regarding thematic focus, and any discrepancies or ambiguous cases were resolved through discussion and consensus with the research lead. Following this stage, 28 publications were excluded due to incomplete records and exclusively technical/engineering focus. Consequently, the final dataset resulted in the inclusion of 2,258 documents, which formed the analytical basis for the subsequent bibliometric analysis.

2.3. Data analysis and visualization

The selected dataset was then used for bibliometric analysis with the Bibliometrix R-package and VOSviewer. The analysis proceeded in two stages: first, descriptive analysis and, second, science mapping.

During the descriptive analysis stage, the general profile of the dataset, publication dynamics, and citation indicators were evaluated quantitatively. The analysis also examined trends in publication activity across time and countries to trace the field's development, identify the most relevant publication sources, and map the international co-authorship network. Specifically, geographical distribution and scholarly impact were evaluated via the countries' scientific production and most cited countries modules using a full counting approach at the document level based on raw total citations.

To examine the intellectual structure of the field during the science mapping stage, author and index keyword co-occurrence analysis was applied. This stage encompassed:

- semantic mapping: analysing keyword frequency to identify the terminological core of the field and evaluating its dynamics;
- conceptual mapping: applying Multiple Correspondence Analysis (MCA) to construct a conceptual structure map, thereby revealing the spatial proximity or distance between key concepts;
- network cluster analysis: visualizing intellectual linkages to identify thematic clusters and verify the existence of conceptual research gaps in human capital management.

3. RESULTS

The bibliometric data show several important trends in the development of research at the intersection of HCM and energy transition. The findings are presented in two main parts: descriptive analysis of the research output and the thematic mapping of the identified knowledge clusters.

3.1. Descriptive analysis: publication trends and research landscape

The summary metrics of the compiled Scopus dataset are presented in Table 1 and describe the scope, growth and impact, author profile, and content parameters. The average annual growth rate is 18.01%, which indicates rapid development in this field, especially in recent years. The total citation count of 45,362, with an average of 19.97 citations per document, indicates strong scholarly attention to this topic.

An analysis of authorship revealed a significant predominance of collaborative teamwork over individual research. The 2,258 analyzed documents were produced by 6,625 authors, with an average of 3.4 co-authors per paper. The international co-authorship rate is also notable (28.6%), demonstrating that roughly every third publication is the result of cross-border collaboration.

The dataset spans 999 unique sources (including journals, books, and conference proceedings), indicating a wide diffusion of human capital knowledge across diverse subject areas such as energy,

Table 1. Summary of the bibliometric dataset (1994–2026)

Source: Compiled by the authors based on Scopus data using the Bibliometrix R-package.

Category	Parameter	Value	Category	Parameter	Value
Dataset scope	Sources (journals, books, etc)	999	Author profile	Total authors	6,625
	Total documents	2,258		Single-authored docs	352
	Total number of citations	45,362		Co-authors per document	3.4
Growth & Impact	Annual growth rate (%)	18.01%		International co-authorships (%)	28.6%
	Average citations per document	19.97	Content	Author's keywords	5,422
	Document average age (years)	4.08		Keywords plus	8,244

management, and environmental science. The large number of keywords (5,422 author keywords and 8,244 Keywords Plus) enables to examine the conceptual structure of the field in greater detail.

The publication timeline suggests three main stages in the development of this research area:

1. The incubation stage (1994–2010), where publication output was irregular and its volume remained strictly below 15 papers/year (average <5), as this research direction was in its infancy and existed as a highly specialized niche.

2. The growth stage (2011–2019) is characterized by a gradual escalation of interest in the "green" transformation. The annual volume of papers increased from 23 in 2011 to 73 in 2019. and a steady baseline expansion with a CAGR of 15.52%. A critical turning point occurred in 2016, when the total citation count surpassed the 1,900 threshold for the first time – a shift that correlates with the ratification of the Paris Agreement and the onset of intensive global discourse on "green" skills.

3. The explosion and consolidation stage (2020–2026) exhibits a vertical surge in both publication volume and citations. The peak of activity was recorded in 2025, reaching an all-time high of 590 publications. The annual publication volume escalated from 85 (2020) to 590 (2025), demonstrating an explosive CAGR of 47.28%.

Source: Compiled by the authors based on Scopus database.

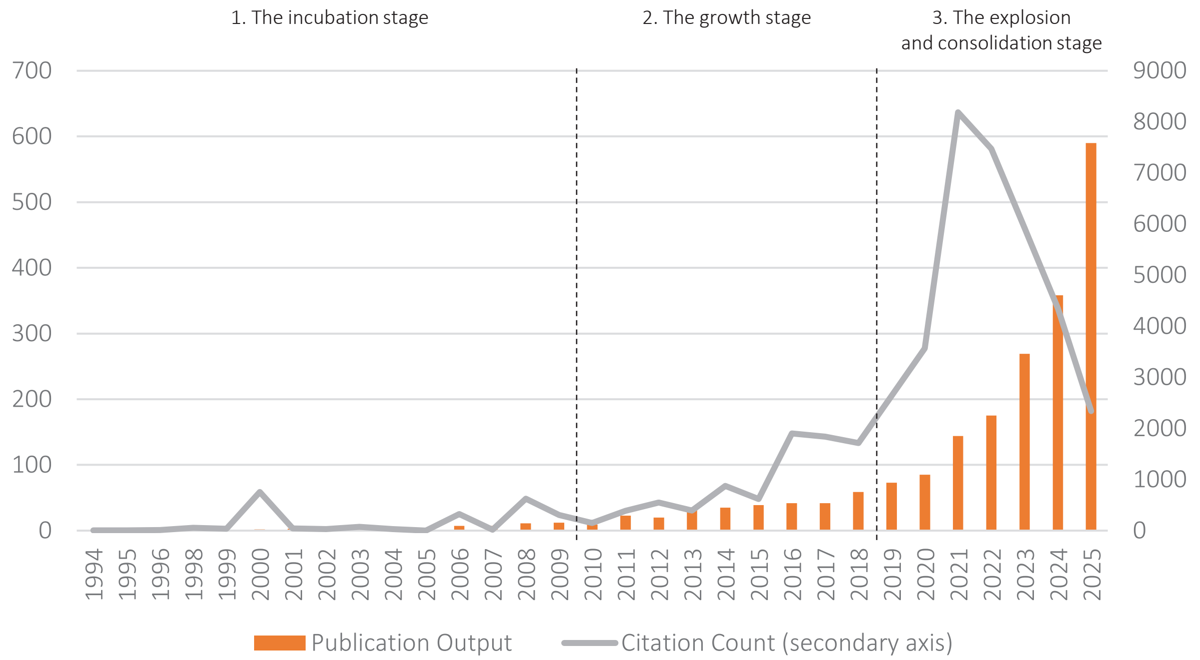

Figure 2. Annual dynamics of publication activity and citation trends in HCM within the renewable energy transition (1994–2026)

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From a geographical perspective (Figure 3), China leads in scientific output on this topic, participating in 1,390 documents within the dataset. This high publication activity is accompanied by the largest citation volume (14,811). The United States (584) and India (434) rank second and third, respectively, which points to the strategic importance of HCM transformation in the energy sector for the world's largest economies.

Some countries also show high citation rates despite a lower volume of publications. For example, Turkey, with 176 papers, ranks second in total citations (2,362), which suggests a relatively high concentration of influential studies. A similar pattern appears in Nigeria (1,017 citations across 116 papers), highlighting the relevance of African experience for research on human capital and the energy transition.

The European research landscape is represented by a robust cluster comprising the United Kingdom (399), Italy (232), Germany (187), and Poland (134). Notably, the emergence of countries such as Pakistan, Saudi Arabia, and Malaysia in the rankings underscores the globalization of this theme and its expansion beyond exclusively developed Western economies.

In addition to the geographical distribution of publication activity, analyzing the existing patterns of international research collaboration is essential. The international co-authorship rate of 28.6% is visually confirmed by the co-occurrence network of keywords and countries (Figure 4), which demonstrates a high level of integration within the global scientific landscape.

China and the United States form a powerful central hub (the green and purple clusters, respectively), acting as the primary intermediaries in cross-border collaboration. Concurrently, there is a pronounced formation of a European cluster (red) centered around the United Kingdom, alongside an Asian cluster (blue) involving India and Saudi Arabia.

The distribution of publications by source (see Figure 5) demonstrates a high degree of interdisciplinarity in research at the intersection of human capital and energy.

The most productive publication sources are *Sustainability* (131 articles), *Environmental Science and Pollution Research* (83), *Energies* (66), *Journal of Environmental Management* (46), and *Renewable Energy* (44). The concentration of papers in these venues suggests that the human dimension has become more visible within the broader sustainable development and energy transition discourse.

Source: Compiled by the authors based on Scopus database.

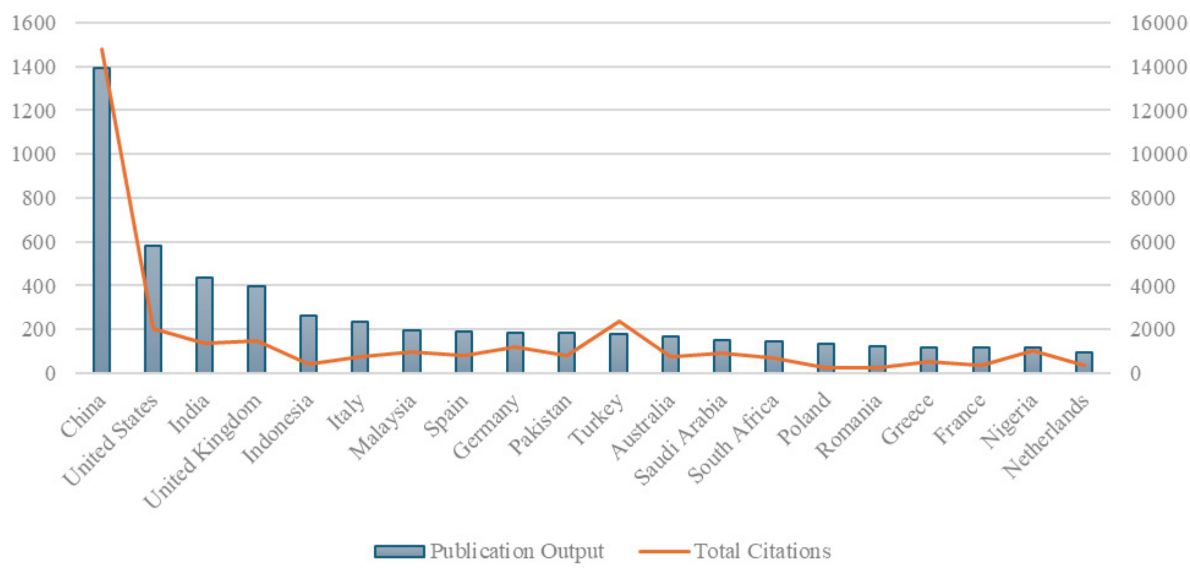

Figure 3. Geographical distribution of scientific output and citation impact in HCM within the renewable energy transition (1994–2026)

Source: Compiled by the authors based on Scopus data using the VOSviewer software..

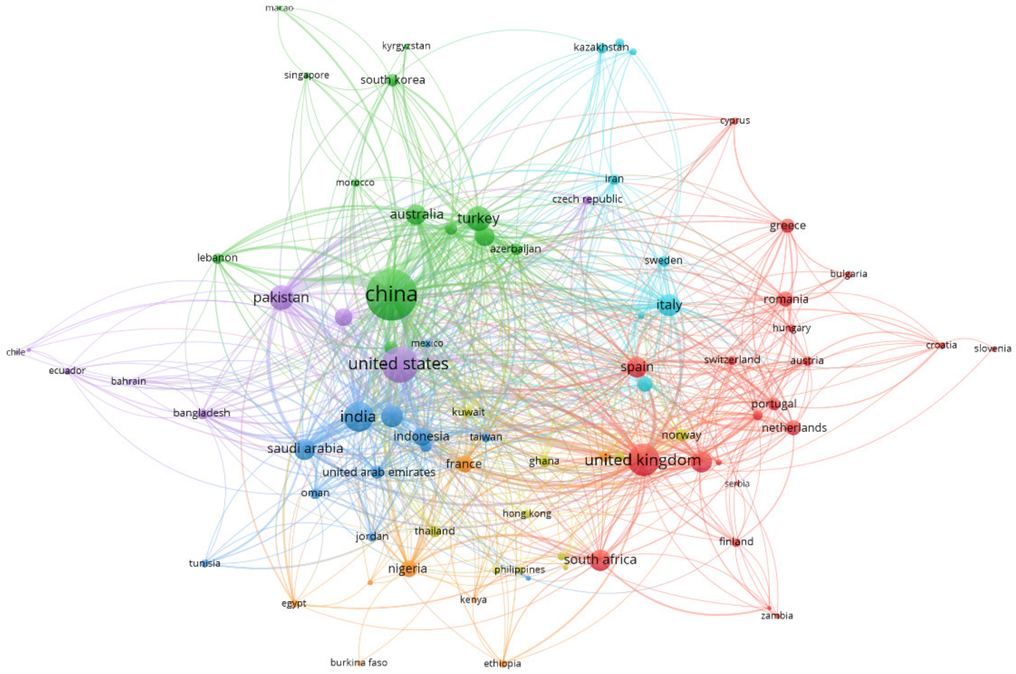

Figure 4. International co-authorship network based on country co-occurrence in HCM within the renewable energy transition

Source: Compiled by the authors based on Scopus database.

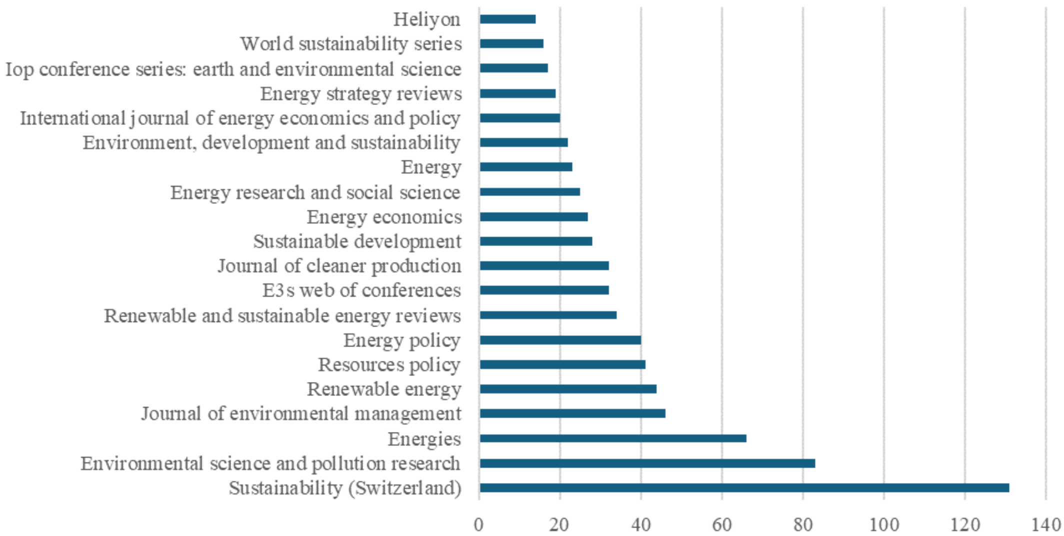

Figure 5. Most relevant sources of scientific publications in HCM within the renewable energy transition (1994–2026)

3.2. Science mapping: thematic structure and conceptual networks

Before the science mapping analysis, the keyword dataset was processed and standardized. To improve terminological consistency, synonymous concepts were merged, which enabled to identify the most relevant terms. Their visual representation is shown in Figure 6 as a word cloud.

The semantic analysis identified the most frequently used terms, including *sustainable development* (n=634), *green economy* (n=390), *renewable*

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Source: Compiled by the authors based on Scopus data using the Bibliometrix R-package.

Figure 6. Semantic mapping of the research field by keywords frequency

energies (n=360), *economic development* (n=345), *alternative energy* (n=334), and *human capital* (n=297). The prominence of these concepts shows how closely environmental, economic, and social dimensions are connected in this field.

Concurrently, the chronological analysis of keyword frequencies reveals substantial shifts in the academic discourse (Figure 7). The late 1990s and early 2000s marked the formation stage of the field's conceptual foundation, characterized by a low intensity of publications. Beginning in 2010, the first wave of research intensification occurred, primarily driven by renewable energy resources, the frequency of which rose from 44 occurrences in 2010 to 102 in 2019, accompanied by sustained interest in sustainable development and energy policy.

Source: Compiled by the authors based on Scopus data using the Bibliometrix R-package.

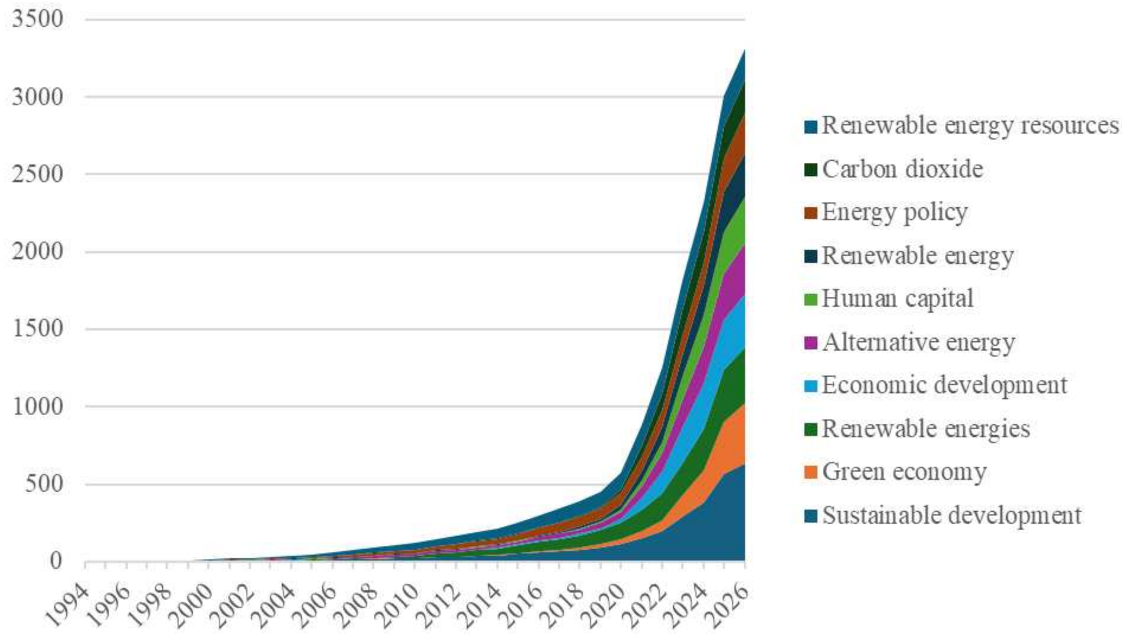

Figure 7. Mapping the evolution of the research field: keywords frequency dynamics (2000–2026)

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A clear shift occurred after 2015, when the concepts of *green economy* and *economic development* began to appear much more frequently and then grew strongly in the 2020s. The period after 2020 is especially revealing: the terms *human capital* and *carbon dioxide* began to catch up with more established environmental categories, increasing several times over (for example, instances of *human capital* rose from 15 mentions in 2020 to 297 in 2026).

This suggests that research attention has gradually shifted from mainly techno-engineering and environmental issues toward the socioeconomic dimension of the energy transition. The identified trends also point to a research gap: work on human capital has developed more slowly than research on technological change and environmental planning.

The results are further supported by factor analysis of the conceptual structure of the research field using Multiple Correspondence Analysis (Figure 8). This analysis identifies four dominant conceptual clusters that reflect the intellectual structure of the field.

The red cluster, located predominantly in the upper right quadrant, encompasses terms related to policy and governance issues at the macro level (*green economy*, *economic growth*, *innovation*, and *environmental economics*). This cluster reflects the theoretical foundation of the transition to a low-carbon economy. The concept of *human capital* is positioned adjacent to *economic development*, which confirms the perception of human potential primarily as a resource for macroeconomic growth.

The green cluster includes terms such as *human capitals*, *personnel*, *investments*, and *economic and social effects*. The separation of these terms into a distinct group suggests that the socio-labor dimension of the energy transition constitutes a specific domain requiring dedicated management tools.

The purple cluster, which is central in terms of coverage, concentrates issues of *renewable energy resources, energy policy,* and *sustainable development*. This cluster represents the core of the field, where environmental management intersects with decision-making processes and the commercialization of energy solutions.

Source: Compiled by the authors based on Scopus data using the Bibliometrix R-package.

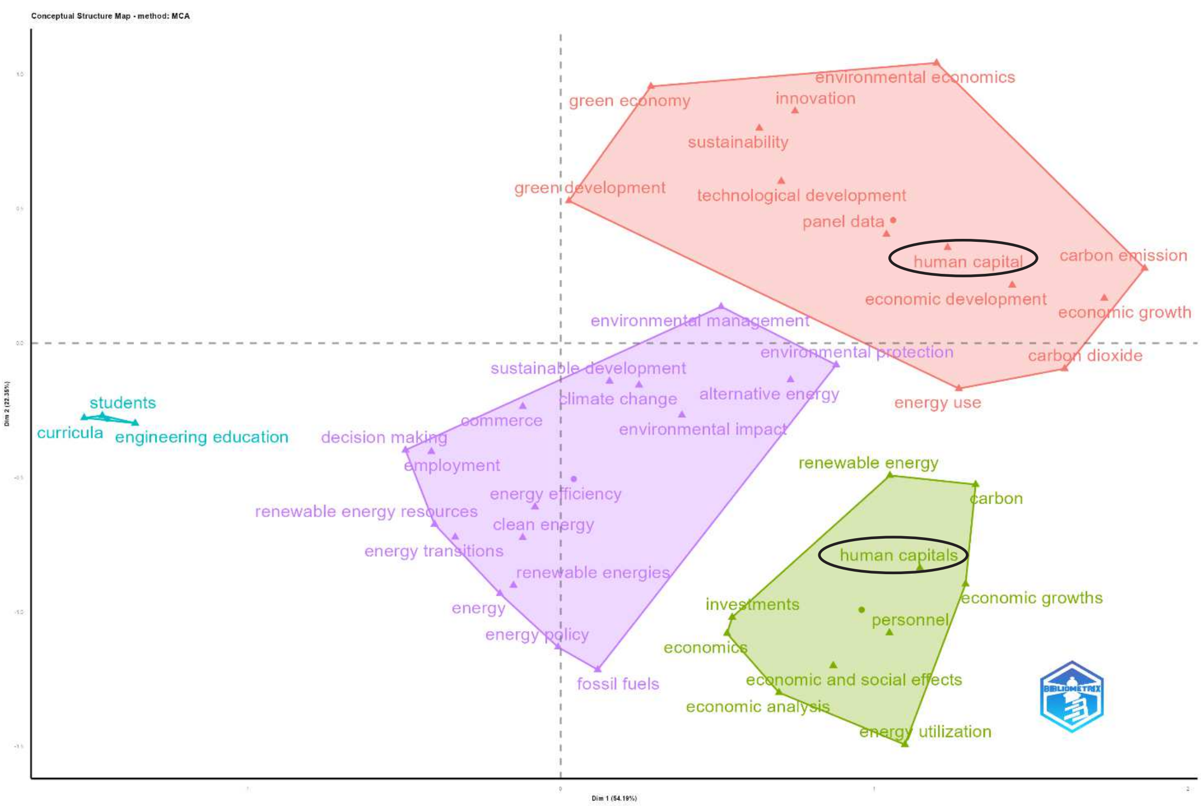

Figure 8. Conceptual structure map of the scholarly discourse: keyword factor analysis

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The isolated light blue cluster, covering the categories of *students* and *curricula*, indicates that issues of personnel training and the adaptation of educational programs currently remain on the periphery of the scholarly discourse.

Accordingly, the cluster responsible for personnel management and social effects (green) is spatially separated from the clusters representing energy policy (red) and macroeconomic growth (purple). This spatial distance suggests that energy transition and HCM are still treated as weakly connected themes in the current literature.

These patterns provide a basis for a more detailed thematic analysis of the field. Using cluster analysis of the bibliometric data, a network map of key concepts was constructed based on co-occurrence analysis (see Figure 9).

The network visualization distinguishes five major thematic research clusters that together form the broader scholarly landscape of the energy transition. A systematized description of these domains and their key determinants is provided in Table 2. These clusters are not isolated; rather, they form an interconnected research network in which the main intersection points indicate the strategic directions of the field's development.

The first cluster focuses on the foundation of the energy transformation, from specific energy sources to personnel training. Within this domain, studies address renewable energy systems, the optimization of energy consumption policies, and decarbonization. Workforce development is an essential component (keywords: *personnel training, workforce development*), since the operation of advanced systems requires appropriate competencies. Khattak (2025) argues for a substantial shift in educational paradigms and proposes an interdisciplinary model that synchronizes technical, socioeconomic, and environmental aspects of learning. This approach supports the integration of renewable technologies across all levels of education and helps build ecologically aware and resilient communities able to respond to the challenges of the energy transition.

Source: Compiled by the authors based on Scopus data using the VOSviewer software.

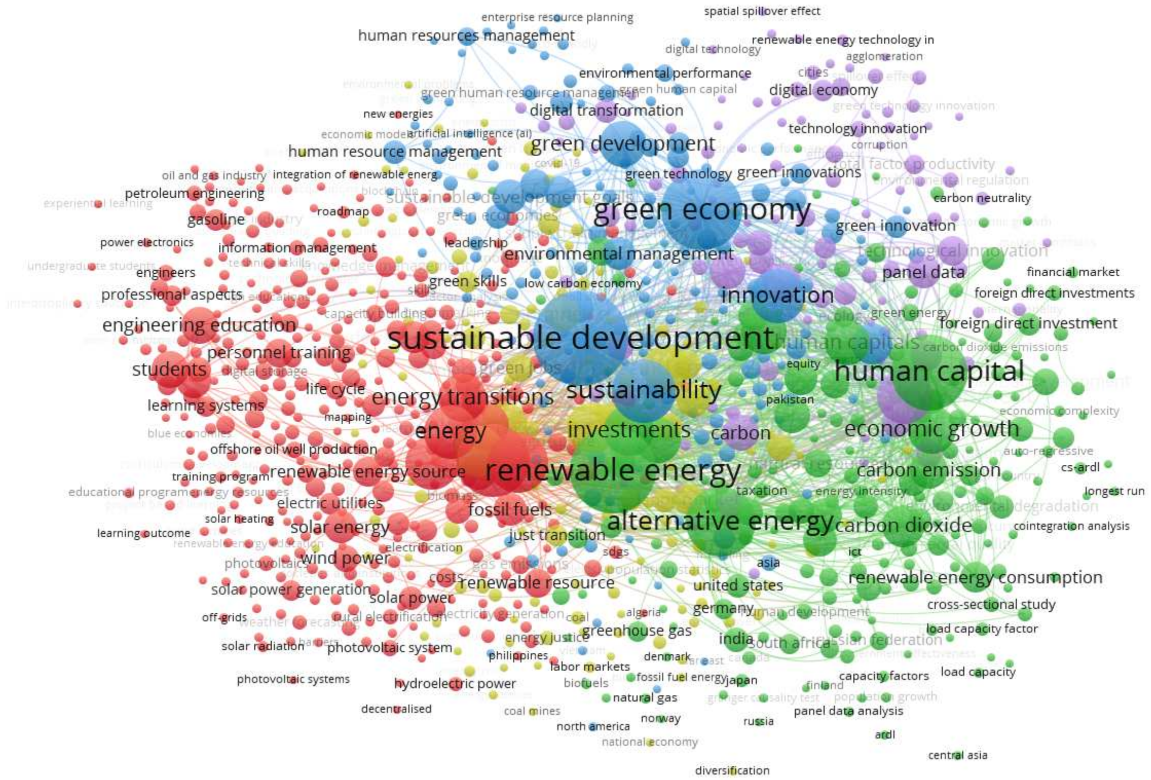

Figure 9. Network map of key concepts in the scholarly discourse: cluster analysis of keywords based on their co-occurrence

Table 2. General characteristics of the primary thematic research clusters

Cluster	Color	Designation / Name	Keywords
I	Red	Technological and educational foundation	renewable energies, energy policy, energy transitions, energy efficiency, solar energy, wind power, education, personnel training, workforce development
II	Green	Macroeconomic environment and resources	*human capital, investments, economic growth, carbon emission, environmental policy, financial development, natural resources, green finance, globalization*
III	Blue	Strategic management and innovative transformation	sustainable development, green economy, innovation, environmental economics, human resource management, digitalization, technology adoption, corporate social responsibility, industry 4.0, economic performance
IV	Yellow	Socio-labor dimension and labor market	energy transition, climate change, economic and social effects, employment, commerce, clean energy, labor market, green jobs, green skills, green entrepreneurship
V	Purple	Eco-technological regulation	economic development, environmental protection, investment, technological innovation, carbon emissions, energy consumption, energy conservation, environmental regulations

This process is further operationalized for the Technical and Vocational Education and Training (TVET) sector by Azar et al. (2025), emphasizing the critical necessity of embedding artificial intelligence and digital tools into curricula. This integration not only facilitates the preparation of personnel for "smart" production but also bridges the gap between rapid technological progress and environmental responsibility. Based on a bibliometric analysis, Torres-Rivera et al. (2025) propose a conceptual framework for designing Master's programs aimed at training "socio-technological researchers." They emphasize that education in this field should extend beyond technical disciplines and incorporate analytical and socio-political competencies.

The second cluster has a strong econometric orientation and examines human capital as a factor of economic growth, financial development, and carbon emissions. In this cluster, human capital is considered mainly through macroeconomic indicators such as investment, environmental taxes, and emissions. A study on G7 countries by Hao et al. (2021) shows that human capital development, together with renewable energy use and environmental taxation, plays an important role in reducing carbon dioxide emissions. The results indicate that this impact varies depending on the stage of economic development. Pata and Caglar (2021), using the case of China, also suggest that stronger human capital can reduce the ecological footprint over the long term even when current clean energy volumes remain limited.

Furthermore, focusing on Ethiopia, the transition to renewable energy is shown by Wang and Debel (2025) to be critical for ensuring the sustainability of industry and infrastructure. A significant long-term relationship between industrial value-added, renewable energy consumption, and economic growth was identified. However, it is noted that an increasing share of renewable energy is accompanied by rising emissions, which necessitates the simultaneous implementation of energy efficiency measures and the alignment of clean energy initiatives with workforce development.

The third cluster represents the managerial and innovation-oriented level, where digitalization, ecological innovation, and intellectual capital management intersect. The arrangement of terms points to the growing integration of digital technologies into human resource management within the context of sustainable development. Javed et al. (2026) argue that progress toward sustainable development goals and lower carbon dioxide emissions depends on a synergistic approach. Their study suggests that digital transformation has a stronger environmental effect when it is supported by an educated workforce with a high level of knowledge and skills. Lin and Ma (2022) report a similar pattern: the mitigating effect of green technologies on carbon emissions becomes statistically significant only when human capital reaches a certain threshold.

Digitalization is examined as a mediating channel by Ullah et al. (2026), reinforcing the impact of human capital on the clean energy transition in G20 countries. The integration of digital and green strategies is confirmed to create a unified concept of a "twin transition," where knowledge and digital skills are pivotal for the efficient utilization of renewable energy sources.

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The fourth cluster focuses on the practical implementation of the transition through the creation of green jobs, skills development, and the analysis of social effects on the labor market. It is highlighted by Briggs et al. (2022) that as the global transition to renewable energy accelerates, regional labor markets may encounter certain obstacles, including "boom-bust" development cycles, personnel shortages, demographic aging, and intense competition. The labor market is proposed to be viewed as an interconnected ecosystem to ensure flexibility between traditional and green sectors.

The necessity for targeted reskilling, rather than mere job creation, during the green transformation is underscored by Jomaa (2026), Sharma et al. (2025), and Kozera-Kowalska (2024). The integration of new approaches (Industry 5.0) requires a transition from static labor metrics to flexible skills.

The fifth cluster covers the restructuring of industrial frameworks, the implementation of industrial policies, and the effects of regulatory instruments on energy conservation and ecosystem preservation. Avom and Mbida Obe (2026) examine the impact of green finance on the energy transition across 63 developing countries between 2000 and 2022. Their results suggest that this effect is mediated by green technologies, human capital, and ecosystem preservation. They also show that transition outcomes depend heavily on the quality of governance, including anti-corruption efforts, regulatory quality, and the rule of law.

Taken together, the mapping and clustering results show that the scientific landscape of HCM within the energy transition does not evolve in isolation. Instead, it forms a structured, multi-level framework in which each cluster represents a distinct functional layer of a broader system.

4. DISCUSSION

The results suggest that human capital in the renewable energy transition functions as an active mediator of technological, institutional, and social change rather than as a passive resource. At the same time, the systematic bibliometric review highlights a clear imbalance: technological aspects of the transition are well documented, whereas mechanisms of professional adaptation, continuous upskilling, and long-term skill reproduction remain less studied (Adepoju et al., 2022; Hanna et al., 2024; Rollnik-Sadowska, 2024). This study therefore redirects attention from technology deployment alone to the institutional and educational conditions that support human capital renewal.

Although existing reviews generally link decarbonization to net-positive job creation, micro-level processes remain less studied, particularly worker mobility between sectors and the transferability of competencies (García-García et al., 2020; Hanna et al., 2024). Current evidence shows that education and professional training institutions often lag behind the pace of technological transformation and, in some cases, even reproduce outdated energy models (Lucas et al., 2018; Vakulchuk & Overland, 2024). This finding questions the common assumption that competence development automatically advances alongside technological change. Instead, the results suggest that human capital formation in the energy transition is an independent policy and institutional challenge rather than a direct byproduct of innovation dynamics.

The results also carry important theoretical implications. The literature presents human capital in at least three distinct roles: as a macro-resource, supporting renewable energy penetration and broader ecological modernization (Adepoju et al., 2022); as a specialized skill set, referring to the educational pathways and professional competencies needed to operate new energy technologies (Lucas et al., 2018; Vakulchuk & Overland, 2024; Weishaupt & Quiceno-Soto, 2026); and as a socio-economic variable, linked to employment, compensation, justice, and regional adaptation (García-García et al., 2020; Stark et al., 2023; Ding & Hirvilammi, 2024). This conceptual multiplicity explains why the field remains fragmented. Different research clusters operate with divergent units of analysis, distinct vocabularies, and conflicting criteria for evaluating transition success.

A key implication of these results is that they make this divide more visible and analytically explicit. The evidence suggests that it is not enough to treat human capital as a static stock of knowledge, skills, and qualifications. A more useful framework treats human capital as an adaptive system that responds to technological, market, and institutional disruptions. Within this perspective, the key issue is not only the current stock of skills, but also the ability of workers, organizations, and institutions to renew competencies quickly, recombine them under new production conditions, and sustain professional mobility.

From this perspective, the cluster analysis can be read not only as a thematic map, but also as evidence of uneven integration across the field. The peripheral position of the educational cluster and the separation of the socio-labor dimension from the politico-economic core indicate a broader deficit in system adaptability. The main challenge is therefore not only a shortage of qualified personnel for the green transition. It also stems from the fact that the mechanisms through which human capital is reproduced are not yet embedded in the energy transition framework as deeply as technological, regulatory, and investment mechanisms.

From a methodological standpoint, the results unveil several limitations within the current research domain. The majority of bibliometric studies rely heavily on Scopus or Web of Science, utilizing a standardized toolkit such as VOSviewer, CiteSpace, or Bibliometrix (Adepoju et al., 2022; Torres-Rivera et al., 2025). While this methodology effectively maps clusters, keywords, authorship networks, and publication dynamics, it is inherently limited when analyzing how human capital is operationalized, how skills are measured, how labor quality and inclusiveness are compared, or how the macro-level energy transition connects to micro-level professional mobility. Thus, despite a proliferation of reviews, the field exhibits a persistent scarcity of integrated explanatory models.

CONCLUSION

The goal of this study is to systematize and conceptually map the contemporary scholarly landscape of HCM within the renewable energy transition, identifying key structural and chronological divergence gaps across research domains. Following the PRISMA 2020 protocol, the study utilized Scopus data and an analytical framework combining descriptive bibliometric and science mapping stage using the Bibliometrix R-package and VOSviewer.

Scientometric descriptive analysis reveals rapid exponential growth in research activity (18.01% annual rate) alongside strong international co-authorship (28.6%)) led by China, the United States, and India, though output remains fragmented across 999 sources. The science mapping results demonstrate a notable chronological lag, as “human capital” explicitly integrated into energy discourse only after 2020, while Multiple Correspondence Analysis (MCA) and network co-occurrence highlight structural detachment between technical energy policy and practical workforce training or socio-labor mechanisms.

These empirical findings indicate that the academic discourse on green transitions remains conceptually fragmented and reactively focused on macroeconomic indicators rather than adaptive human capacity building. Consequently, overcoming these spatial and chronological gaps requires shifting from reactive responses to systemic, integrated policies that align technological innovation with proactive workforce formation, institutional learning, and professional mobility.

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