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# Sustainable Energy Transition for the Mining Industry: A Bibliometric Analysis of Trends and Emerging Research Pathways

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**Abstract:** The mining industry (MI), one of the largest energy consumers globally, is under increasing pressure to transition towards more sustainable energy systems. This paper explores the current trends in sustainable energy transition (SET) in mining operations, focusing on integrating renewable energy, decarbonization efforts, economic and technological enablers, and sustainability frameworks. Through a systematic literature review utilizing bibliometric tools such as Scopus and VOSviewer 1.6.20, this study identifies key themes, trends, and challenges shaping the future of energy transition in mining. Despite advancements in renewable technologies such as solar, wind, and hydrogen, the MI faces significant barriers, including high upfront costs, logistical challenges in remote operations, and inconsistent regional decarbonization policies. The review highlights the importance of global regulatory alignment, technological innovation, and financial mechanisms to overcome these challenges and accelerate the industry's shift towards clean energy. Future research directions address gaps in renewable energy deployment, energy efficiency, and sustainability practices in the mining sector. This study aims to contribute to the academic discourse and provide actionable insights for industry stakeholders striving to achieve a SET.

**Keywords:** sustainable development; renewable energy; decarbonization; energy efficiency; mining operations; sustainability frameworks; bibliometric review

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## 1. Introduction

The mining industry (MI) is pivotal in supporting global economies by providing essential raw materials for various sectors, including energy, manufacturing, and infrastructure [1,2]. However, it is also one of the most energy-intensive industries, significantly contributing to global carbon emissions [3,4]. According to [5], the mining sector accounts for approximately 1.7 of the world's total energy demand, primarily driven by fossil-fuel consumption. This high energy demand, coupled with the industry's reliance on non-renewable energy sources, has drawn increased attention to the need for a sustainable energy transition (SET) within mining operations [6–8]. As global climate change mitigation efforts intensify, transitioning to cleaner energy alternatives has become not only an environmental necessity but also a strategic imperative for the long-term sustainability of the industry [9–11].

SET in the mining sector encompasses the shift from conventional fossil fuels such as coal and diesel to renewable energy sources, including solar, wind, and hydrogen [12–15]. This transition is crucial in aligning the MI with global decarbonization goals, such as those outlined in the Paris Agreement, which aims to limit global temperature rise to below 2 °C [16]. Researchers have highlighted that integrating renewable energy systems within mining operations can significantly reduce greenhouse gas emissions and improve energy security and long-term cost savings. For instance, studies by the World Bank Group suggest that adopting renewables in mining could reduce operational energy costs by up to 50% in specific remote mining locations, particularly when paired with energy storage solutions [17,18]. Nevertheless, there is no comprehensive synthesis that exists on the application of suitable energy technologies in the mining sector.

Despite these advantages, the transition to sustainable energy in mining is fraught with challenges. High initial capital investment, logistical barriers, and the lack of a unified regulatory framework hinder the widespread adoption of renewable energy technologies in mining. Deploying renewable infrastructure in remote and off-grid mining locations, where access to the energy grid is limited, poses significant technical challenges. Additionally, the inconsistent implementation of decarbonization policies across different regions further complicates the industry's ability to meet global emissions reduction targets; there is a need for more transparent global standards and more substantial governmental support to facilitate this energy transition, particularly in developing economies where mining remains a significant economic driver.

Our study aims to bridge the gap by systematically analyzing existing studies to identify current challenges and propose solutions for SET in mining operations by analyzing existing research via bibliometric analysis, highlighting the key themes and technological advancements that shape the future of mining energy systems. A thematic synthesis approach was used categorizing findings into four key themes: renewable energy integration, decarbonization and environmental policy, economic and technological enablers, and sustainability frameworks. By synthesizing the latest developments and trends in these areas, this paper not only provides a detailed overview of the current landscape but also identifies critical research gaps and offers future research directions. These insights aim to advance academic understanding and practical solutions to accelerate the SET within the MI.

The layout of this paper follows. Having motivated the need for this review in Section 1, Section 2 describes the research methodology. Section 3 divulges the results of the bibliometric and trend analyses of the extant literature, and Section 4 discusses these results and offers insights. Section 5 gives future research pathways, and Section 6 concludes. This study reviews the current state of SET in the MI, points out gaps, and offers future research pathways.

## 2. Research Methodology

This research study undertakes a comprehensive literature review focusing on the SET in the MI. Advanced bibliometric tools such as Scopus and VOSviewer (version 1.6.20) have been employed to systematically search, identify, and analyze relevant academic contributions. Scopus was the preferred database because of its wide range of authentic publications compared to Google Scholar, Science Direct, and Web of Science [19]. This study utilizes Scopus due to its broad coverage of high-impact journals, particularly in engineering, sustainability, and operational research. It provides structured metadata, citation analysis, and advanced filtering options essential for bibliometric studies. While Web of Science and Google Scholar offer extensive databases, Scopus ensures consistency in data extraction and citation tracking and a pervasive coverage of journals specializing

in mining (e.g., [20]). VOSviewer, a science mapping tool for producing, visualizing, and exploring bibliometric networks and content analysis, was utilized for the scientometric analysis [21]. An effective literature review requires a clear methodology to ensure rigorous and structured analysis. The literature review acknowledges potential biases, including selection bias due to thematic relevance, search strategy limitations that may exclude non-English or gray literature, and publication bias favoring significant findings. Efforts were made to ensure consistent data synthesis; however, differences in study designs and the tendency to underreport unsuccessful results may have introduced interpretation and reporting biases. Consequently, in line with PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Anlaysis) guidelines [22], this study adopts the methodical, three-phase review approach illustrated in Figure 1. The PRISMA 2020 Main Checklist is appended as a Supplementary Material and the details of the review stages follow.

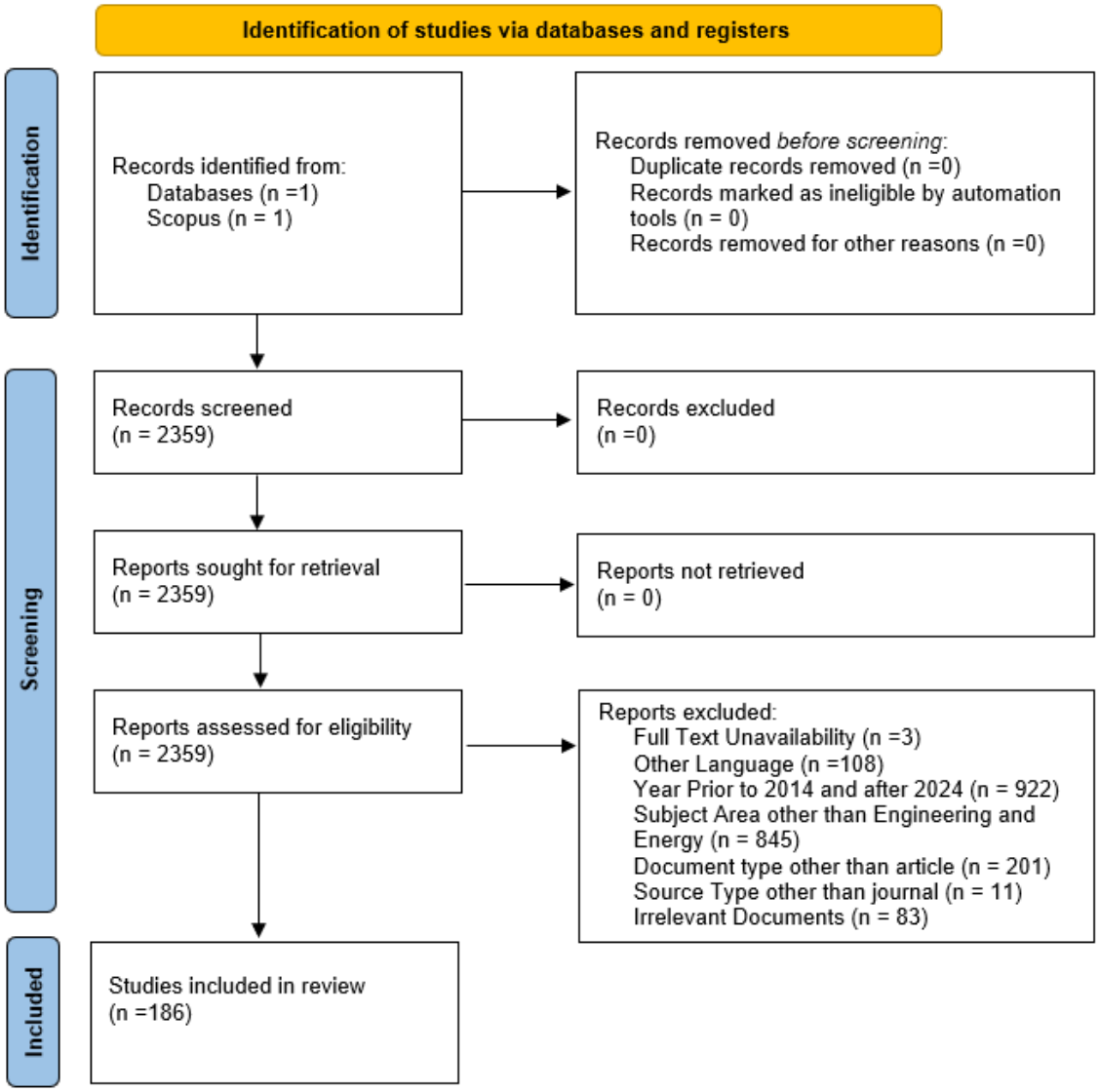



**Figure 1.** PRISMA flow diagram for this review.

### *2.1. Stage 1: Identification of Studies*

In the first stage, relevant studies were identified from Scopus using predefined search criteria and keywords related to SETs and mining. The selected keywords were included after several adjustments on Scopus ("sustainable energy" OR "renewable energy" OR "solar energy" OR "fossil fuel alternatives" OR "wind energy" OR "hydrogen" OR

"electrification") AND ("MI" OR "mining engineering" OR "mining sector" OR "mineral extraction" OR "resource extraction" OR "mineral production" OR "mining operations"). A total of 2359 records were retrieved from this search on 11 January 2025. At this stage, no records were removed due to duplication, automation exclusions, or other technical reasons, ensuring all retrieved studies underwent the screening process.

### *2.2. Stage 2: Screening of Studies*

The screening stage involved a thorough review to assess eligibility based on predefined exclusion criteria. The initial 2359 records were screened, and reports were sought for retrieval without exclusions at this point. After further assessment, studies were excluded for reasons such as full-text unavailability (3), language other than English (108), publication dates outside the 2014–2024 range (922), subject areas unrelated to engineering and energy (845), document types other than journal articles (201), non-journal sources (11), and studies deemed irrelevant based on content (83). After applying these filters, 186 studies remained eligible for further manual analysis. The authors independently screened those eligible papers to ensure consistency through cross-validation and to resolve any discrepancies.

### *2.3. Stage 3: Inclusion of Studies*

In the final stage, the remaining 186 studies were included for qualitative analysis and scientometric evaluation. The selected studies underwent detailed examination to identify knowledge gaps, technological trends, and future research directions in SET for mining operations. VOSviewer was used to visualize research networks and identify key themes. The study's structured approach, as summarized in Figure 1, ensured a robust synthesis of the existing literature. The 11 most influential studies, detailed in the next section, provided critical insights into the research landscape, guiding the discussion on technological advancements and areas requiring further exploration.

## 3. Results

This section details the findings of the bibliometric analysis of the publications related to SET in the MI.

### *3.1. Publication Sources*

Table 1 highlights the top 16 journals contributing to research on sustainable energy transitions in mining, based on an analysis of 186 papers using VOSviewer. The minimum document threshold was set to 3, yielding 16 sources. *Energies* leads with 19 documents and 200 citations, achieving a citation score of 6.2 in 2023, demonstrating its pivotal role in the field. *Journal of Cleaner Production* follows with 10 documents and a significantly higher citation count of 290, reflecting its influence with a citation score of 13.7.

Prominent energy-focused journals such as *Energy Conversion and Management* and *Renewable and Sustainable Energy Reviews* also appear, boasting high citation scores of 14.6 and 22.6, respectively. Notably, *Mining Report* has low citation activity, indicating limited influence in this domain. Although *Transportation Research Record* and *Recent Advances in Electrical and Electronic Engineering* contribute, their lower citation scores suggest niche relevance. This analysis underscores the dominance of interdisciplinary journals in shaping future research on energy transitions in mining, with a strong emphasis on sustainability and innovation.

**Table 1.** Key publication sources for energy and sustainability research.

| No | Journal | Documents | Citations | Total Link Strength | Citation Score (2023) |
|---|---|---|---|---|---|
| 1 | *Energies* | 19 | 200 | 0 | 6.2 |
| 2 | *Journal of Cleaner Production* | 10 | 290 | 0 | 13.7 |
| 3 | *International Journal of Hydrogen Energy* | 8 | 130 | 0 | 10.6 |
| 4 | *Sustainability* | 8 | 51 | 0 | 4.9 |
| 5 | *Energy Conversion and Management* | 4 | 57 | 0 | 14.6 |
| 6 | *Energy Research and Social Science* | 4 | 86 | 0 | 10.9 |
| 7 | *Mining Report* | 4 | 2 | 0 | _ |
| 8 | *Renewable and Sustainable Energy Reviews* | 4 | 158 | 0 | 22.6 |
| 9 | *Energy* | 3 | 82 | 0 | 12.7 |
| 10 | *Energy for Sustainable Development* | 3 | 5 | 0 | 7 |
| 11 | *Energy Policy* | 3 | 88 | 0 | 10.4 |
| 12 | *IEEE Access* | 3 | 8 | 0 | 9.8 |
| 13 | *Journal of Mines, Metals and Fuels* | 3 | 0 | 0 | 0.1 |
| 14 | *Minerals Engineering* | 3 | 15 | 0 | 12.1 |
| 15 | *Recent Advances in Electrical and Electronic Engineering* | 3 | 3 | 0 | 1.7 |
| 16 | *Transportation Research Record* | 3 | 4 | 0 | 3.2 |

### *3.2. Country, Co-Author, and Keyword Analyses*

Figure 2 and Table 2 present the global contributions of 28 countries to sustainable energy transition research in mining based on a VOSviewer (version 1.6.20) analysis of 50 countries. In Figure 2, the country co-authorship network colors represent regional research collaborations, with green indicating European partnerships, blue showing North American influence, and red highlighting Asian research networks. Yellow reflects Australia-Japan linkages, while purple (Indonesia) suggests isolated research efforts with minimal global connections. The visualization shows strong intra-regional cooperation, with Europe and North America closely linked, while Asia connects globally but maintains internal research clusters.

For analysis in Table 2, the minimum document threshold was set to three, and 28 countries met this criterion. The data reveal that China (29 documents, 779 citations) and the United States (33 documents, 600 citations) lead in research output and influence. These nations' high citation counts and substantial total link strengths (six and nine, respectively) indicate their central roles in shaping global research collaborations.

Australia (15 documents, 355 citations) and India (21 documents, 436 citations) also demonstrate significant contributions, reflecting their active engagement in the field. South Korea stands out with nine documents and 380 citations, supported by a high total link strength of 11, indicating strong international partnerships. In contrast, countries such as Indonesia (four documents, six citations) and Greece (three documents, 73 citations) show limited research influence and connectivity. Figure 2 visually captures these research clusters and highlights the potential for strengthening global collaboration to advance sustainable energy transitions in mining.




**Figure 2.** Country co-authorship analysis.

**Table 2.** Total link strength of key countries of SET in mining research.

| No. | Country | Number of Documents | Number of Citations | Total Link Strength |
|---|---|---|---|---|
| 1 | United States | 33 | 600 | 9 |
| 2 | China | 29 | 779 | 6 |
| 3 | India | 21 | 436 | 5 |
| 4 | Australia | 15 | 355 | 11 |
| 5 | Canada | 15 | 165 | 8 |
| 6 | Germany | 10 | 143 | 7 |
| 7 | Poland | 9 | 79 | 6 |
| 8 | South Korea | 9 | 380 | 11 |
| 9 | United Kingdom | 7 | 123 | 7 |
| 10 | Chile | 6 | 140 | 5 |
| 11 | Denmark | 6 | 182 | 11 |
| 12 | Iran | 5 | 95 | 4 |
| 13 | Malaysia | 5 | 88 | 3 |
| 14 | Sweden | 5 | 134 | 6 |
| 15 | France | 4 | 96 | 5 |
| 16 | Indonesia | 4 | 6 | 3 |
| 17 | Japan | 4 | 80 | 1 |
| 18 | Norway | 4 | 245 | 6 |
| 19 | South Africa | 4 | 64 | 0 |
| 20 | Brazil | 3 | 31 | 8 |
| 21 | Greece | 3 | 73 | 0 |
| 22 | Italy | 3 | 11 | 1 |
| 23 | Peru | 3 | 13 | 0 |
| 24 | Qatar | 3 | 31 | 3 |
| 25 | Russian Federation | 3 | 63 | 0 |
| 26 | Saudi Arabia | 3 | 29 | 3 |

The analysis of global contributions to sustainable energy transition research in mining underscores the prominence of leading nations like China, the United States, Australia, and India in driving research output and fostering collaborations. The network visualization in Figure 2 and data in Table 2 highlight strong research clusters, particularly in Europe and Asia, while also revealing underrepresented regions such as Indonesia and Greece. These findings emphasize the need for broader international cooperation to bridge existing gaps and enhance knowledge exchange. Strengthening global partnerships can play a pivotal role in addressing the complex challenges associated with sustainable energy transitions in the mining sector.

### *3.3. Keyword Trend Analysis*

Figure 3 provides a comprehensive overview of the co-occurrence of key terms in sustainable energy transition research for the mining sector. Out of 2762 keywords, the minimum occurrence threshold was set to seven, resulting in 52 keywords meeting the criterion. General terms like "article" were excluded to ensure the analysis focused on relevant technical terms. The network reveals distinct thematic clusters, with terms such as "renewable energies" (33 occurrences, 33.00 total link strength) and "renewable energy resources" (28 occurrences, 28.00 total link strength) forming a central research theme. This indicates a strong emphasis on renewable energy integration, with related terms like "solar energy" (22 occurrences) and "wind power" (15 occurrences) highlighting the growing interest in sustainable energy sources.

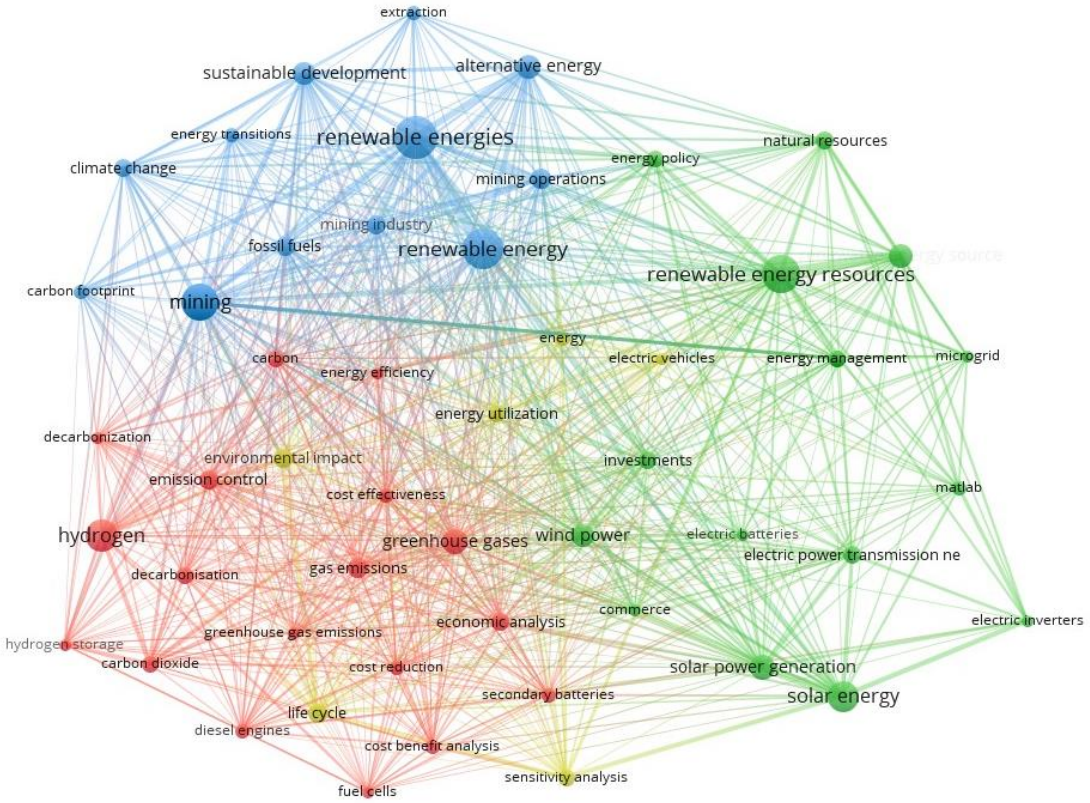



**Figure 3.** Author keywords analysis.

The colors in the author keyword co-occurrence network (Figure 3) represent distinct research themes in SET within the mining sector. Blue signifies research on renewable energy integration in mining operations, including terms such as "renewable energies", "sustainable development", "mining industry", and "climate change". This cluster highlights broad discussions on energy transition, the role of mining in sustainability, and the shift from fossil fuels to cleaner energy sources. Green represents renewable energy resources and policy, covering keywords like "renewable energy resources", "solar energy", "microgrid", "energy management", and "electric power transmission". This cluster suggests research focused on technological applications, regulatory policies, and infrastructure needed to facilitate the adoption of renewable energy in mining.

The red cluster centers on decarbonization and emissions reduction, with key terms like "hydrogen", "carbon dioxide", "decarbonization", "emission control", and "fuel cells". This area of research explores alternative fuels, carbon capture, and sustainable energy storage solutions. Yellow, on the other hand, highlights economic analysis and operational efficiency, containing terms such as "economic analysis", "cost-benefit analysis", "secondary batteries", and "energy utilization". This cluster emphasizes financial feasibility, investment considerations, and cost-reduction strategies for implementing sustainable energy solutions. The strong interconnections between these clusters indicate the interdisciplinary nature of sustainable energy transition research, where economic feasibility (yellow) links to decarbonization (red), while energy policies (green) support the broader transition of mining operations (blue).

The "mining" theme is represented by terms such as "mining" (25 occurrences, 24.00 link strength), "mining industry" (12 occurrences), and "mining operations" (13 occurrences), demonstrating a significant focus on sustainable mining practices. The presence of keywords like "sustainable development" (15 occurrences) and "environmental impact" (12 occurrences) further underscores the industry's commitment to balancing operational efficiency with environmental stewardship. The "hydrogen" cluster also stands out, with

"hydrogen" appearing 23 times and linked to terms such as "decarbonization" (7 occurrences) and "emission control" (12 occurrences), emphasizing the role of hydrogen technologies in achieving decarbonization goals.

The total link strength values reflect the degree of interconnectedness between keywords. For example, "greenhouse gases" (17 occurrences, 17.00 link strength) and "carbon footprint" (eight occurrences, 7.00 link strength) demonstrate a strong association with discussions on emissions reduction and life-cycle assessments ("life cycle" with 12 occurrences). In contrast, terms like "secondary batteries" (eight occurrences) and "economic analysis" (11 occurrences) indicate emerging yet relatively underexplored research areas. Keywords such as "cost reduction" (eight occurrences) and "cost–benefit analysis" (eight occurrences) highlight a growing recognition of the need for economic feasibility studies alongside technical innovations.

This keyword analysis reveals that renewable energy, mining operations, and hydrogen-related technologies are central themes in sustainable energy transition research. High link strengths for terms like "renewable energy resources" and "mining" reflect their foundational roles in the discourse, while the prominence of "decarbonization" and "emission control" underscores the industry's focus on reducing environmental impacts. However, underexplored areas like "secondary batteries" and "sensitivity analysis" suggest opportunities for future research to enhance decision-making frameworks and improve energy storage solutions. By identifying these patterns, this analysis contributes to a deeper understanding of the research landscape and highlights potential pathways for advancing sustainable energy practices in the mining sector.

The overlay visualization in Figure 4 presents the temporal progression of research keywords related to sustainable energy transitions in mining, spanning the years 2020 to 2023. The color gradient, ranging from purple (older studies) to yellow (recent research), provides insights into evolving research trends. The prominence of "renewable energies" (yellow) and its strong connections with terms like "solar energy", "renewable energy resources", and "energy policy" indicates an increasing focus on renewable energy implementation and policy frameworks in recent studies.

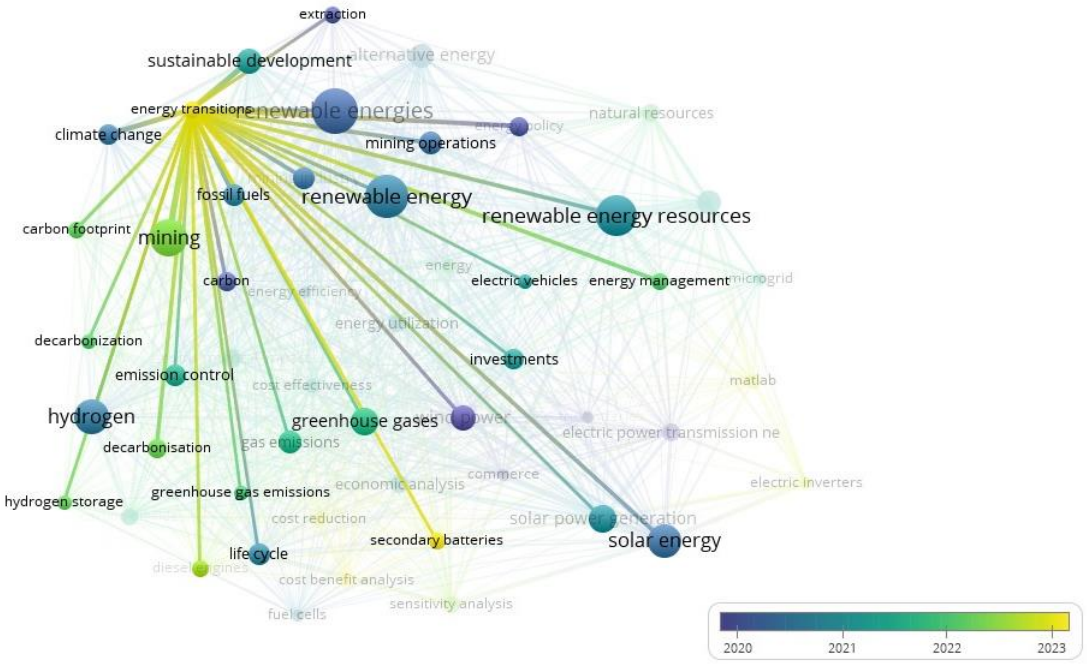



**Figure 4.** Network trends overlay visualization.

Older keywords, such as "mining", "sustainable development", and "climate change" (depicted in darker shades), reflect foundational research areas that have maintained relevance over time. Meanwhile, emerging terms like "hydrogen", "decarbonization", and "emission control" in lighter shades signify the growing interest in decarbonization technologies. The connection between "hydrogen" and "carbon dioxide" highlights efforts to address greenhouse gas emissions through innovative energy solutions.

Recent research has also expanded into topics like "electric vehicles", "microgrids", and "energy utilization", suggesting a shift toward integrating decentralized energy systems and improving energy efficiency in mining operations. The overlay visualization reveals a dynamic research landscape, where earlier discussions on sustainability and climate action have evolved into more specialized studies on renewable technologies, economic feasibility ("cost–benefit analysis" and "investments"), and life-cycle assessments ("carbon footprint" and "life cycle").

This trend analysis underscores the rapid expansion of interdisciplinary research, highlighting the importance of aligning sustainable energy solutions with both operational efficiency and environmental impact mitigation. The overlay also suggests future research directions, including optimizing secondary energy storage ("secondary batteries") and further exploring grid integration through "electric power transmission networks". These insights pave the way for advancing sustainable energy transitions in the mining industry.

The 2014–2024 period was chosen to capture a decade of research, ensuring a balanced view of past developments and emerging trends in mining transitions. This approach helps identify long-term patterns, technological shifts, and policy changes. While recent research is vital, a broader timeframe provides deeper insights into the industry's evolving sustainability efforts. Although the broader period 2014–2024 was initially considered, bibliometric analysis revealed that the most significant shifts in sustainable energy transition research in min-ing occurred between 2020 and 2023. Earlier studies were primarily policy-driven with limited technological applications, whereas recent research increasingly explores imple-mentation-focused strategies.

The comparative analysis of research trends in sustainable energy transition (SET) in mining (Table 3 below) highlights the evolution of research focus from broad sustainability themes to specialized energy solutions. Initially, research between 2020 and 2021 emphasized high-level discussions on sustainability, climate change, and renewable energy policies; this is reflected visually in Figure 4 as the blue and turqouis circles While the environmental impact of mining was a key concern, studies lacked a strong focus on specific renewable energy technologies or practical applications.

From 2021 to 2022, the research shifted towards more targeted renewable energy applications. Studies increasingly explored solar energy, energy efficiency, microgrid integration, and electric vehicle adoption in mining operations. The growing emphasis on reducing greenhouse gas emissions and carbon footprints reflected a heightened interest in quantifying the environmental benefits of sustainable energy transitions. This period also saw the emergence of energy management and grid integration studies, indicating a move towards operational sustainability.

The most recent trends from 2022 to 2023 emphasize applied technological solutions, with hydrogen energy and decarbonization becoming central themes, as shown in yellow in Figure 4, signaling 2023. Research has increasingly focused on hydrogen storage, secondary batteries, and emission control strategies, reflecting efforts toward long-term carbon neutrality. Additionally, studies linking solar power generation with economic viability through cost reduction and cost–benefit analysis indicate a growing recognition of the financial implications of sustainable energy in mining. Table 3 below encapsulates

these shifts, demonstrating how research has evolved from conceptual frameworks to implementation-focused strategies.

**Table 3.** Comparative analysis of research trends in SET in mining (2020–2023).

| Period | Research Focus | Notable Keywords | Implications |
| --- | --- | --- | --- |
| 2020–2021 | High-level discussions on sustainability and climate change impacts, broad re-newable energy policies | "Sustainable development", "climate change", "renewable energies", "fossil fuels", "carbon footprint", "mining" | Foundational research setting the stage for energy transition discussions but lacking specific technological applications. |
| 2021–2022 | Shift towards targeted renewable energy applications, focus on energy efficiency, microgrids, and electric vehicle integration | "Renewable energy", "solar energy", "energy management", "electric vehicles", "greenhouse gases", "emission control" | Increased focus on operational sustainability, addressing emissions reduction and integration of sustainable technologies into mining. |
| 2022–2023 | Emphasis on applied technological solutions, hydrogen energy, and decarbonization strategies | "Hydrogen", "decarbonization", "hydrogen storage", "secondary batteries", "solar power generation", "cost-benefit analysis" | Stronger industry shift towards practical solutions for carbon neutrality, energy storage, and economic viability of sustainable mining operations. |

Table 4 exhibits a comprehensive summary of recent and influential research studies focusing on sustainable operational efficiency in mining, with a particular emphasis on renewable energy adoption, environmental monitoring, and process optimization. The studies analyzed cover various technological advancements, such as the implementation of hybrid energy systems, renewable resource management, and innovative solutions for mine rehabilitation. For instance, [23] explores rare earth element (REE) recovery from mining tailings using low-energy systems, demonstrating the potential to support mine rehabilitation. Several studies, such as [24], delve into the decarbonization of gold mining by integrating renewable energy sources, showing a significant reduction in $CO_2$ emissions. These findings emphasize the growing shift toward net-zero goals through strategic energy transitions and innovative energy recovery methods.

Despite the promising results, Table 4 also outlines limitations that require further exploration, such as high capital costs, policy enforcement gaps, and performance issues in varying environmental conditions. Notably, [25] underscores the potential of hybrid hydrogen and wind systems in remote cold-climate mines but highlights the need for more case studies in diverse climatic conditions. Collectively, the studies in Table 4 provide valuable insights into the pathways for achieving sustainable mining operations through technological innovation and strategic resource planning.

The qualitative analysis employed thematic analysis to assess the 186 articles, focusing on relevance, citation impact, and journal ranking. The 11 most influential studies, highlighted in Table 4, were selected for their critical insights into technological advancements and research gaps. These studies guided discussions on emerging trends and helped identify areas needing further exploration, ensuring a comprehensive and impactful analysis of the research landscape.

**Table 4.** Summary of influential studies on sustainable mining and renewable energy integration.

| Author | Year | Title | Research Objectives | Findings | Limitations | Conclusion | Future Research |
|---|---|---|---|---|---|---|---|
| Levett et al. [23] | 2024 | Water-soluble Rare Earth Elements (REEs) Recovered from Uranium Tailings | Analyze rare earth element recovery for mine rehabilitation. | REE recovery demonstrated using low-energy systems in rehabilitation. | Scaling requires hydrology and stability studies. | REE recovery supports mine rehabilitation with green technologies. | Develop large-scale solar-assisted leaching systems. |
| Trench et al. [24] | 2024 | Gold Production and the Global Energy Transition—A Perspective | Achieve net-zero emissions in gold production with energy transition. | Gold mining with renewables reduces $CO_2$ emissions by 78%. | Supply chain decarbonization remains partial. | Net-zero goals are feasible with integrated renewables. | Certify carbon-neutral gold supply chains. |
| Velický [26] | 2023 | Renewable Energy Transition Facilitated by Bitcoin | Examine Bitcoin mining's impact on balancing renewable energy grids. | Bitcoin mining stabilizes energy grids using surplus renewable energy. | Environmental impacts of mining energy usage remain high. | Bitcoin mining can function as a dynamic load to reduce curtailment. | Research green consensus algorithms for mining. |
| Marín et al. [27] | 2023 | Design for Sustainability: An Integrated Pumped Hydro Reverse Osmosis System to Supply Water and Energy for Mining Operations | Explore the viability of hydro-reverse osmosis for mine water management. | Hydro-reverse osmosis reduced mine water costs and GHG emissions. | High initial costs for implementation. | Hydro-reverse osmosis systems are feasible for remote sites. | Reduce capital costs of hydro-reverse osmosis units. |
| Pouresmaieli et al. [28] | 2023 | Integration of Renewable Energy and Sustainable Development with Strategic Planning in the Mining Industry | Develop strategic frameworks for renewable energy in mining. | Renewables reduced costs and decarbonized mining supply chains. | Gaps in policy enforcement impact outcomes. | Strategic renewables lower supply chain costs and emissions. | Deploy energy storage to stabilize mining grids. |
| Kalantari and Ghoreishi-Madiseh [25] | 2022 | Hybrid Renewable Hydrogen Energy Solution for Remote Cold-Climate Mines | Evaluate hydrogen and wind integration for decarbonizing open-pit mines. | Cost reduction and full decarbonization achieved with hybrid systems. | Limited climate case studies. | Hybrid systems show cost-effective potential for mine decarbonization. | Optimize configurations for varying wind levels. |
| Igogo et al. [17] | 2021 | Integrating Renewable Energy into Mining Operations: Opportunities, Challenges, and Enabling Approaches. | Assess renewable energy integration challenges and opportunities in mining. | Renewable adoption reduces costs and improves community engagement. | High capital costs and regulatory challenges. | Renewables can enhance sustainability and reduce GHG emissions. | Implement regulatory frameworks for renewables. |
| Quiñones et al. [29] | 2020 | Analyzing the Potential for Solar Thermal Energy Utilization in the Chilean Copper Mining Industry | Quantify solar thermal energy's feasibility in Chilean copper mining. | Solar thermal energy provided up to 30% of heat demand in mining. | Strong dependence on solar irradiance levels. | Solar thermal systems can replace a significant amount of fossil fuels. | Study thermal energy storage for large-scale integration. |
| Imasiku and Thomas [30] | 2020 | The Mining and Technology Industries as Catalysts for Sustainable Energy Development | Quantify energy efficiency and GHG reduction in copper mining operations. | Improved refining efficiency and electrification can halve energy use. | Does not assess all stakeholder energy inputs. | Industrial collaborations can improve copper extraction efficiency. | Promote tech-driven knowledge-sharing partnerships. |

**Table 4.** *Cont.*

| Author | Year | Title | Research Objectives | Findings | Limitations | Conclusion | Future Research |
|---|---|---|---|---|---|---|---|
| Kuyuk et al. [31] | 2019 | Designing a Large-scale Lake Cooling System for an Ultra-deep Mine: A Canadian Case Study | Study mine exhaust heat recovery for renewable energy. | Waste heat recovery enhanced site sustainability with minimal costs. | Requires high heat-to-energy conversion ratios. | Heat recovery improves energy self-sufficiency in remote mines. | Optimize thermal conductivity in mine recovery systems. |
| Pamparana et al. [32] | 2017 | Integrating Photovoltaic Solar Energy and a Battery Energy Storage System to Operate a Semi-autogenous Grinding Mill | Optimize SAG mill energy using PV-BESS systems. | PV-BESS systems improved mill efficiency and reduced emissions. | No data on system reliability during cloudy periods. | PV-BESS systems lower operational emissions and costs. | Assess seasonal impacts on energy storage performance. |

## 4. Discussion

Following the scientometric analysis of the bibliometric characteristics of SET in the MI, the in-depth qualitative discussion shifted towards summarizing emerging themes related to energy transition in mining, identifying existing research gaps, and proposing a comprehensive framework by linking current research topics to potential future directions.

### *4.1. Key Themes Identified for SET in the MI*

This section describes the key themes of SET in the MI, including core principles and methodologies for evaluating existing studies and strategies for addressing the challenges and opportunities in the transition process. The discussion will explore how renewable energy integration (core principle), decarbonization and environmental responsibility (performance evaluation), economic and technological enablers (operational considerations), and sustainability frameworks and policy alignment (strategic considerations) can be optimized to bridge gaps and drive future innovations in mining.

*Renewable Energy Integration.* Renewable energy integration focuses on replacing traditional fossil fuel-based energy sources with renewable alternatives such as solar, wind, and hydrogen in mining operations [12,13]. This transition is a core principle of sustainable energy practices, aiming to reduce the environmental footprint of the mining sector while ensuring operational efficiency. Renewable energy sources offer the potential to significantly cut down greenhouse gas emissions, reduce reliance on non-renewable resources, and contribute to a more sustainable mining process [33,34]. Integrating these technologies is vital for meeting global sustainability goals and minimizing the negative environmental impact of mining. The challenges of integrating renewable energy into mining include the high initial costs, variability in energy supply, and the need for energy storage solutions. Mining sites often operate in remote locations, which presents logistical challenges in deploying large-scale solar farms or wind turbines. However, technological advances such as energy storage systems and hybrid solutions (e.g., combining solar with traditional energy sources) offer promising opportunities to overcome these hurdles and ensure a stable energy supply for mining operations. Renewable energy integration also provides long-term economic benefits, as it can reduce energy costs over time, especially as the cost of renewable energy technologies continues to decrease. Moreover, companies that invest in renewable energy improve their environmental performance and align with stricter regulations, enhancing their corporate social responsibility profile. Integrating renewable energy is a fundamental step toward a more sustainable and economically viable future for the MI.

*Decarbonization and Environmental Policy.* Decarbonization in the MI refers to reducing carbon emissions across all mining activities, from exploration to extraction and processing. This theme emphasizes the MI's responsibility to minimize environmental impact and aligns with global efforts to combat climate change. Environmental policies and regulations, such as carbon taxes and emissions caps, are increasingly pushing mining companies to adopt low-carbon technologies and practices. Decarbonization is essential not only for reducing the carbon footprint of mining but also for maintaining compliance with international sustainability standards. Implementing decarbonization strategies requires a multi-faceted approach, including the adoption of cleaner energy sources, improving energy efficiency, and utilizing carbon capture technologies [35–37] and the scope within which the decarbonization is aimed (e.g., [38]). Mining companies are exploring innovative solutions, such as the electrification of machinery and vehicles, transitioning from diesel-powered equipment to electric alternatives, and adopting smart technologies to optimize energy usage. Decarbonization efforts in the mining industry vary significantly across regions, with developing countries facing unique challenges in policy enforcement, financial constraints, and fossil-fuel dependency. In South Africa, policies like the Renewable Energy Independent Power Producer Procurement Program (REI4P) and self-generation incentives have led to increased adoption of solar and wind energy in mining, as seen in Gold Fields' South Deep Mine, which reduced carbon emissions by 110,000 tons annually. However, inadequate grid infrastructure limits further expansion. Chile has adopted a carbon tax (USD 5 per ton of $CO_2$) and a green hydrogen strategy, allowing firms like BHP's Escondida Mine to transition to 100% renewable energy by 2025 and reducing $CO_2$ emissions by three million tons annually, but prohibitive costs and limited hydrogen production remain barriers. India is focusing on the electrification of mining fleets under FAME-II and renewable energy incentives, enabling Tata Steel's Joda East Mine to integrate electric dump trucks, reducing fuel costs by 30%, though weak EV infrastructure and coal dependence persist. In contrast, Indonesia's Carbon Economic Value (CEV) policy introduced a carbon trading mechanism, but fossil-fuel subsidies continue to limit impact, with mining companies like Vale Indonesia turning to hydropower for nickel mining and cutting 200,000 tons of $CO_2$ annually, yet coal-fired power plants still dominate the sector. These cases highlight the divergence in decarbonization approaches: where Chile and South Africa lead in renewable integration, India focuses on electrification, and Indonesia struggles with policy enforcement. A harmonized international strategy, supported by climate finance, technology transfer, and hybrid energy models, could accelerate mining decarbonization across developing economies.

These efforts are evaluated based on their ability to reduce emissions, improve efficiency, and contribute to long-term environmental sustainability. Environmental policies play a critical role in driving the decarbonization agenda within the MI. Governments are increasingly introducing stringent regulations that require mining companies to disclose their carbon emissions and set targets for reduction; companies that fail to comply face penalties and reputational damage. Conversely, those that successfully implement decarbonization strategies not only contribute to a cleaner environment but also gain a competitive advantage in the marketplace by aligning with the growing demand for sustainable practices.

*Economic and Technological Enablers*. Economic and technological enablers refer to the financial and technical aspects that facilitate the energy transition in mining. The excessive cost of implementing renewable energy systems, upgrading existing infrastructure, and adopting innovative technologies can be a significant barrier for mining companies [39,40]. However, innovative financing models, such as green bonds, government incentives, and public–private partnerships, are emerging as solutions to support the energy transition.

Economic considerations must balance the initial investment costs with long-term savings from lower energy consumption and reduced emissions. Economic enablers play a crucial role in accelerating the transition to sustainable energy in mining, particularly through the declining cost of renewable energy technologies and supportive financial mechanisms. The levelized cost of energy (LCOE) for solar and wind power has significantly decreased, making these alternatives more financially viable for mining operations, especially in remote areas. Additionally, carbon pricing mechanisms, government subsidies, and tax incentives have encouraged mining companies to adopt low-carbon technologies. A notable example is BHP's Nickel West project in Australia, which has integrated a 100 MW solar farm and battery storage to power its operations, significantly reducing reliance on fossil fuels. Similarly, Gold Fields' Agnew Gold Mine became the first Australian mine to be powered by a hybrid renewable microgrid comprising wind, solar, battery storage, and gas backup, leading to a 50% reduction in carbon emissions and operational cost savings. These economic incentives reduce financial barriers, making sustainability an increasingly cost-effective option for the mining industry. On the technological side, advancements in energy storage, smart grids, and digital mining solutions are critical enablers of SET. Technologies like hydrogen fuel cells, electrification of mining equipment, and artificial intelligence (AI)-driven optimization tools can help improve energy efficiency and reduce operational costs. For example, AI can help monitor and predict energy usage, allowing companies to reduce waste and improve energy management across operations. These technologies also enable the MI to meet regulatory standards more efficiently. Economic and technological enablers reduce the cost of transitioning to sustainable energy and provide a competitive edge by improving operational efficiency. Companies that leverage the latest technologies and financial mechanisms can optimize their energy consumption, lower emissions, and reduce operating costs over time. As these technologies evolve and become more affordable, they will continue to play a crucial role in enabling a smooth and cost-effective energy transition in the mining sector. Technological advancements are also crucial enablers of this transition, with innovations in hydrogen energy, battery storage, and digitalized energy management systems reshaping mining operations. The deployment of hydrogen-powered haul trucks, such as the NuGen Zero Emission Haulage Solution by Anglo American, is a prime example, demonstrating the feasibility of replacing diesel fleets with hydrogen fuel cell electric vehicles (FCEVs). This initiative, first implemented at the Mogalakwena Platinum Mine in South Africa, is expected to cut diesel consumption by one million liters annually, significantly reducing carbon emissions. Another significant technological enabler is the Rio Tinto Gudai-Darri Mine in Western Australia, which integrates solar energy, autonomous haulage, and AI-driven energy optimization systems to enhance operational efficiency and sustainability. Furthermore, blockchain-based energy trading platforms, such as those evaluated by Glencore and BHP, are being explored to enhance transparency and efficiency in renewable energy procurement and carbon credit trading. These advancements highlight the growing role of technology-driven energy solutions in the decarbonization of mining operations.

*Sustainability Framework*. A sustainability framework provides a strategic approach to integrating sustainable practices throughout the MI's operations. This framework incorporates key aspects such as environmental stewardship, social responsibility, and economic viability, ensuring that mining activities align with global sustainability goals. The framework helps guide the industry's transition to cleaner energy by setting clear goals, defining best practices, and establishing accountability measures. Sustainability frameworks often include life-cycle assessments (LCAs) to evaluate the environmental impact of mining operations from start to finish. LCAs are a critical tool within the sustainability framework, as they provide a comprehensive view of the environmental impact of mining activities.

By evaluating all stages, from resource extraction to waste disposal, LCAs help mining companies identify areas where improvements can be made, such as reducing water usage, improving waste management, and minimizing energy consumption. The sustainability framework also promotes the circular economy concept by encouraging the recycling of materials and reducing waste in mining operations. A key example of sustainability integration can be observed in the complex mining approach proposed by [41], where traditional mining operations are transitioning towards multi-product production that aligns with Environmental, Social, and Governance (ESG) principles. Their study highlights how integrating water desalination, methane utilization, and secondary raw material recovery within coal mining operations not only enhances sustainability but also ensures economic viability by repurposing waste into valuable by-products. This multi-resource utilization model demonstrates how mining companies can leverage sustainable technologies to reduce environmental footprints while creating additional revenue streams. Furthermore, Bondarenko et al. [41] emphasize the necessity of incorporating alternative energy sources, such as low-potential thermal energy from mine groundwater, to support circularity in mining operations. These insights reinforce the sustainability framework's role in facilitating the industry's shift towards resource-efficient and resilient mining models.

The success of a sustainability framework depends on the alignment of company policies with local and international regulations, as well as stakeholder engagement. Mining companies must collaborate with governments, communities, and other stakeholders to ensure that sustainability goals are achieved. By incorporating sustainability into the core of their operations, mining companies protect the environment and enhance their reputation, ensure regulatory compliance, and create long-term economic value. We note that the ESG framework has been extensively examined in the context of mining sustainability, addressing environmental, social, and governance factors. However, to achieve a more holistic and inclusive approach, ESG has been extended to the QBL—Quadruple Bottom Line [42] by incorporating cultural sustainability. This expansion recognizes the critical role of cultural heritage, local traditions, and indigenous knowledge in shaping sustainable mining practices, ensuring that technological advancements align with societal values and long-term community well-being. In alignment with the QBL framework, cultural sustainability plays a vital role in the long-term success of mining operations. Culture encompasses the values, practices, and traditions of the communities where mining takes place, and respecting these cultural dimensions is essential for maintaining positive relationships with local stakeholders. Cultural sustainability involves ensuring that mining practices do not disrupt the social fabric of communities or erode their cultural heritage. This includes promoting indigenous knowledge systems, protecting sacred sites, and engaging in culturally appropriate consultation processes. By integrating cultural considerations into their sustainability frameworks, mining companies not only foster goodwill but also build resilience in operations by enhancing community trust and collaboration. Including culture within the QBL emphasizes businesses' broader responsibilities to preserve social identity and local customs, which are integral to achieving a truly sustainable and inclusive circulatory in the MI.

*Limited Adoption of Renewable Energy Technologies*. The adoption of renewable energy technologies in the MI remains limited due to several factors despite their critical role in SET. Renewable technologies such as solar, wind, and hydrogen power offer substantial benefits in reducing carbon emissions and lowering reliance on fossil fuels. However, the initial investment costs for setting up renewable energy infrastructure, especially in remote mining locations, are high. Additionally, mining sites may face logistical challenges, such as a lack of proximity to renewable energy grids or rugged terrain for installing solar farms or wind turbines. These barriers create a significant gap in the widespread implementation

of renewable energy technologies in mining. To address this gap, mining companies must explore hybrid energy solutions combining renewable energy with traditional power sources to ensure reliable energy supply in remote locations. Governments and investors also need to provide financial incentives and support to reduce the capital burden on mining companies. In addition, advances in renewable technology and energy storage solutions can help make these technologies more accessible and cost-effective. Closing this gap will allow the MI to reduce its environmental impact and make significant strides towards sustainability.

*Inconsistent Decarbonization Efforts Across Regions*. While global climate goals require a unified approach, decarbonization efforts across the MI are inconsistent, primarily due to varying regulatory frameworks and regional economic conditions. In some countries, mining companies face strict environmental policies that enforce emissions caps and require sustainability reporting, pushing them towards adopting low-carbon technologies. In other regions, however, the absence of such stringent regulations or the economic reliance on fossil fuels results in less urgency for decarbonization. This regional disparity creates a significant gap in the MI's collective ability to reduce carbon emissions on a global scale. To close this gap, there needs to be a harmonized approach to decarbonization, with international bodies advocating for stronger, unified environmental policies. Cross-border collaboration, where mining companies share the best practices and technologies, could help level the playing field and encourage more widespread adoption of decarbonization strategies. Moreover, governments in lagging regions should offer incentives or subsidies to promote cleaner mining operations, ensuring that all regions contribute equally to global decarbonization efforts.

*Technological Gaps in Energy Efficiency and Smart Solutions*. Although energy-efficient technologies like AI-driven energy optimization tools, hydrogen fuel cells, and electrified mining equipment offer tremendous potential, a gap remains in their widespread application in the MI. Many mining companies, notably smaller or less technologically advanced ones, do not have access to the infrastructure or expertise needed to implement these technologies. This gap slows the potential improvements in energy efficiency that could reduce operational costs and environmental impact. Without advanced technological solutions, mining operations continue to rely on traditional, less efficient methods, contributing to higher carbon emissions and energy waste. Closing this technological gap requires investment in research and development to create more affordable, accessible, and scalable energy-efficient technologies. Governments and international organizations should also encourage technology transfers, providing mining companies with the tools and expertise they need to modernize their operations. Collaboration between tech companies, governments, and the mining sector will be crucial in closing this gap and driving innovation to ensure that energy-efficient technologies become standard in mining operations across the globe.

*Economic Barriers to Large-Scale Implementation*. Economic barriers remain a significant challenge in implementing the MI's renewable energy and sustainability initiatives. The upfront costs associated with transitioning to renewable energy infrastructure, deploying advanced technologies, or complying with decarbonization policies can be prohibitive, especially for smaller mining companies. Additionally, the return on investment for renewable energy projects may take several years to materialize, making them less attractive to companies with limited financial flexibility. This gap hinders the widespread adoption of sustainability initiatives, as companies may prioritize short-term cost savings over long-term environmental and operational benefits. To address these economic barriers, governments and financial institutions should offer more attractive funding mechanisms, such as green bonds, subsidies, or low-interest loans, to encourage investments in sustainable

energy projects. Public–private partnerships can also be critical in reducing financial risks and sharing the burden of initial investments. Moreover, as renewable energy technologies continue to decrease in cost and global regulations become stricter on carbon emissions, the economic case for sustainability will strengthen, encouraging more companies to invest in energy transition initiatives. By addressing these economic barriers, the MI can accelerate its path towards sustainability while maintaining financial viability.

### *4.2. Bridging the Circularity Gap in SET in the MI*

Bridging the circularity gaps for SET in the MI requires targeted strategies across key areas. To enhance renewable energy integration, governments and financial institutions should provide more substantial incentives, such as tax breaks and subsidies, to offset the high initial capital costs of renewable energy projects. Public–private partnerships can share risks and benefits, making it easier for mining companies to adopt clean energy technologies like solar, wind, and hydrogen. Additionally, developing scalable renewable energy solutions tailored to remote mining locations can help overcome logistical barriers and facilitate widespread adoption in the industry.

Decarbonization efforts must be globally standardized to ensure consistency across regions. International regulatory bodies should establish unified decarbonization standards and carbon pricing mechanisms for the mining sector. For example, a relevant case study is Poland, which has implemented the EU Emissions Trading System (ETS) to regulate carbon emissions, particularly in its coal-dependent mining sector. Despite being subject to carbon pricing, Poland's mining industry has faced challenges in transitioning to cleaner energy due to economic dependency on coal and slow adoption of renewables. Some mining companies have begun investing in carbon capture and storage (CCS) and renewable energy integration, but policy inconsistencies and financial constraints have limited large-scale implementation. While carbon pricing has increased operational costs, it has also driven companies to explore low-emission technologies to maintain competitiveness. However, Poland's reliance on coal-fired power continues to hinder full decarbonization, requiring stronger policy enforcement and incentives to accelerate sustainable mining transitions [43]. Creating platforms for knowledge sharing on low-carbon technologies and emissions reduction best practices would further drive global adoption of decarbonization strategies. Investment in technology transfer and innovation is essential for closing the technological gap. Governments and industry leaders must invest in R&D to develop affordable, scalable solutions such as AI-powered systems, energy-efficient equipment, and advanced energy storage technologies. Facilitating access to these technologies through industry-wide collaboration and technology hubs will accelerate their adoption.

In addressing the economic barriers, diversified funding mechanisms such as green bonds, sustainability-linked loans, and carbon credit markets should be expanded to support mining companies in financing large-scale sustainability initiatives. Long-term sustainability funds and low-interest loans for energy transition projects would alleviate the financial burden on mining companies, especially smaller firms. Clear metrics for calculating long-term savings from renewable energy projects would also help companies better understand the financial benefits of transitioning to sustainable energy, encouraging broader investment in these initiatives. By addressing these gaps through a combination of financial, technological, and regulatory solutions, the MI can achieve a successful SET.

## 5. Future Research Pathways

Based on the literature and key theme analysis in the preceding sections, we identify and delineate future research directions (see Figure 5) to foster the ongoing transition towards sustainable energy and environmentally responsible practices within the MI.

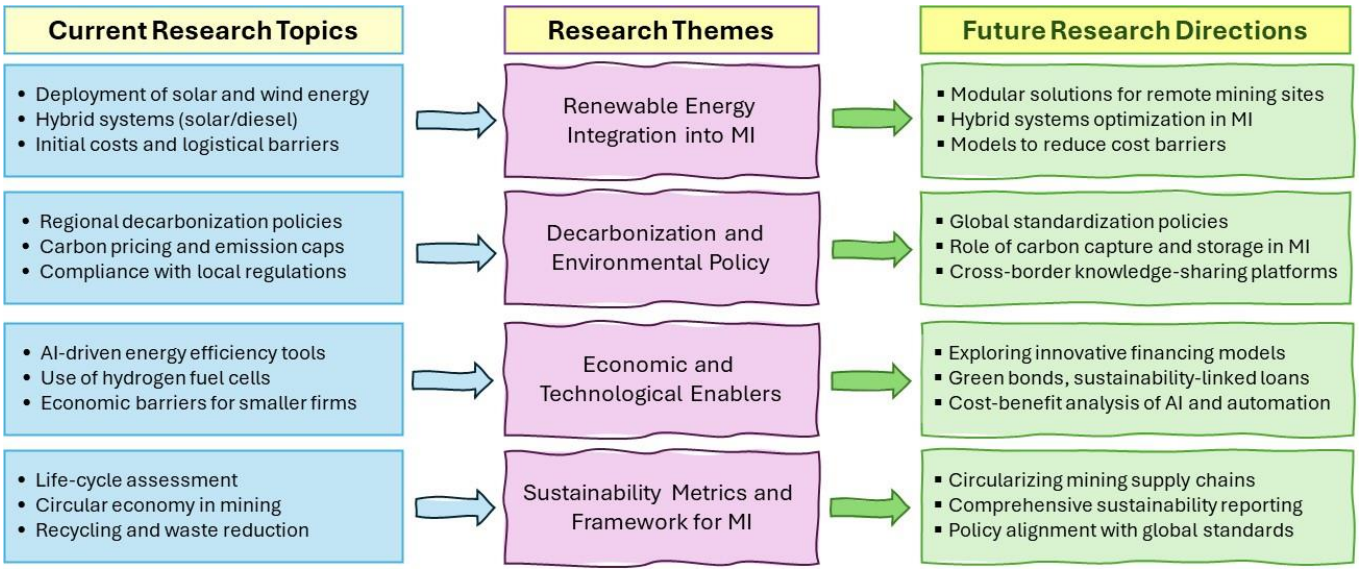



**Figure 5.** Framing future research directions for SET in MI.

### *5.1. Advancements in Renewable Energy Technologies for Remote Mining Operations*

Future research should focus on developing scalable, cost-effective renewable energy solutions specifically designed for remote and off-grid mining sites. This includes hybrid systems that combine solar, wind, and hydrogen technologies with reliable energy storage systems. Investigating the feasibility of integrating smart grids or microgrids to manage energy distribution and consumption efficiently at these remote sites could also be a key area of study. Additionally, exploring ways to reduce the deployment costs of these technologies through innovative financing models and modular designs would support widespread adoption in the mining sector.

### *5.2. Global Decarbonization Policies and Their Impact on Mining Operations*

A significant future research direction involves studying the effects of harmonized global decarbonization policies on the MI. This research could assess how different regions implement decarbonization strategies and measure global carbon pricing mechanisms or emissions standards' economic, environmental, and operational impacts. A relevant case study is Poland, which has implemented the EU Emissions Trading System (ETS) to regulate carbon emissions, particularly in its coal-dependent mining sector. Despite being subject to carbon pricing, Poland's mining industry has faced challenges in transitioning to cleaner energy due to economic dependency on coal and slow adoption of renewables. Some mining companies have begun investing in carbon capture and storage (CCS) and renewable energy integration, but policy inconsistencies and financial constraints have limited large-scale implementation. While carbon pricing has increased operational costs, it has also driven companies to explore low-emission technologies to maintain competitiveness. However, Poland's reliance on coal-fired power continues to hinder full decarbonization, requiring stronger policy enforcement and incentives to accelerate sustainable mining transitions. Research can also explore the interplay between local regulations and international agreements, identifying pathways for mining companies to comply with and benefit from uniform decarbonization frameworks. The role of carbon capture and storage technologies in meeting decarbonization goals could also be a focus of further study.

### *5.3. Technological Innovation for Energy Efficiency and AI Integration in Mining Operations*

Research should delve deeper into developing and applying energy-efficient technologies and artificial intelligence (AI) tools to optimize energy use in mining operations. Future

studies could investigate how AI-driven monitoring systems, machine learning algorithms, and autonomous equipment can enhance the efficiency of renewable energy utilization and reduce overall energy consumption. The use of AI to predict energy demand, automate decision-making processes, and improve the accuracy of sustainability reporting could also be explored. Furthermore, research on the economic viability of these technologies, particularly for small- and medium-sized mining companies, would provide valuable insights into their scalability.

### *5.4. Sustainability Frameworks and Life-Cycle Assessments for Circular Mining Practices*

Further research could explore the development of comprehensive sustainability frameworks tailored to the MI, integrating LCAs and circular economy principles. This includes evaluating the environmental impacts of mining operations from exploration to waste management, focusing on minimizing resource extraction, and promoting recycling and reuse within the supply chain. It would also be quite valuable to investigate how mining companies can align with global sustainability standards, such as the United Nations Sustainable Development Goals (SDGs), and how they can measure and report on their progress toward these goals. Additionally, research on incorporating circular economy practices into mining operations could lead to more sustainable and efficient resource use.

## 6. Concluding Remarks

SET in the MI represents a pivotal shift that is critical for reducing the sector's environmental impact and essential for securing its long-term viability in an increasingly carbon-conscious global economy. This comprehensive review has highlighted the vital role of renewable energy integration, decarbonization efforts, economic and technological enablers, and sustainability frameworks in driving this transition. While considerable progress has been made, particularly in adopting technologies such as solar, wind, and hydrogen energy, several key challenges remain, including the high initial costs of renewable energy infrastructure, logistical difficulties in remote mining locations, and inconsistent decarbonization policies across different regions.

Addressing these barriers will require a coordinated approach involving governments, industry stakeholders, and the research community. Stronger regulatory frameworks, innovative financing models such as green bonds, and advances in energy-efficient technologies will be crucial in accelerating the adoption of clean energy solutions in mining operations. Furthermore, harmonizing global decarbonization policies and technological innovations like AI-driven energy management and energy storage systems will enable mining companies to achieve greater operational efficiency while reducing their carbon footprint.

In conclusion, SET in mining is not just an environmental necessity but a strategic opportunity for the industry to align with global sustainability goals, improve cost efficiencies, and enhance its competitive edge in the future. By continuing to innovate, collaborate, and invest in sustainable energy practices, the MI can lead global efforts to combat climate change and create a more resilient, sustainable future for generations to come.

## 7. Limitations

This review excluded non-English studies, potentially introducing geographic bias.

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