

Review

Feasible Solutions for Low-Carbon Thermal Electricity Generation and Utilization in Oil-Rich Developing Countries: A Literature Review

Danny Ochoa-Correa ¹, Paul Arévalo ^{1,2,*}, Edison Villa-Ávila ^{1,2}, Juan L. Espinoza ¹ and Francisco Jurado ²

- ¹ Department of Electrical Engineering, Electronics and Telecommunications (DEET), Faculty of Engineering, University of Cuenca, Balzay Campus, Cuenca 010107, Azuay, Ecuador; danny.ochoac@ucuenca.edu.ec (D.O.-C.); eava0001@red.ujaen.es (E.V.-Á.); juan.espinoza@ucuenca.edu.ec (J.L.E.)
- ² Department of Electrical Engineering, University of Jaen, EPS, 23700 Linares, Jaen, Spain; fjurado@ujaen.es
- * Correspondence: warevalo@ujaen.es

Abstract: Transitioning to low-carbon energy systems is crucial for sustainable development, particularly in oil-rich developing countries (ORDCs) that face intertwined economic and environmental challenges. This review uses the PRISMA methodology to systematically assess the current state and prospects of low-carbon thermal electricity generation and utilization technologies in ORDCs. The study emphasizes clean thermal technologies such as biogas, biofuels, biomass, hydrogen, and geothermal energy, focusing on solutions that are technically feasible, economically viable, and efficient in combustion processes. These nations face significant challenges, including heavy reliance on fossil fuels, transmission losses, and financial constraints, making energy diversification urgent. The global shift towards renewable energy and the need to mitigate climate change presents an opportunity to adopt low-carbon solutions that align with Sustainable Development Goals related to energy access, economic growth, and climate action. This review aims to (1) evaluate the current state of low-carbon thermal electricity technologies, (2) analyze the technical and economic challenges related to combustion processes and energy efficiency, and (3) provide recommendations for research and policy initiatives to advance the transition toward sustainable thermal energy systems in ORDCs. The review highlights practical approaches for diversifying energy sources in these nations, focusing on overcoming existing barriers and supporting the implementation of clean thermal technologies.

Keywords: low-carbon; oil-rich developing countries; clean thermal generation; electricity; energy diversification; sustainable development; PRISMA methodology



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1. Introduction

In the context of global efforts to reduce carbon emissions and mitigate climate change, oil-rich developing countries (ORDCs) face unique challenges that demand tailored solutions. These challenges stem from the heavy reliance of ORDCs on fossil fuels, creating a distinct set of intertwined economic and environmental issues that differ from those faced by other nations [1,2]. Oil and gas extraction, consumption, and export are critical to their economic structures, making them particularly vulnerable to global market volatility and contributing significantly to greenhouse gas emissions. This dual dependency underscores the importance of exploring tailored strategies for transitioning these countries to more sustainable energy systems [3]. Adopting low-carbon technologies presents a viable solution for these nations to decarbonize while maintaining economic stability. However, focusing on clean thermal technologies—such as biogas, biofuels, biomass, hydrogen, and geothermal energy—may be more practical for ORDCs than large-scale solar or wind adoption, which requires significant investments in infrastructure and grid upgrades to manage intermittency and ensure reliability [4]. This does not mean that solar and wind are not suitable options.

On the contrary, they are mature technologies with competitive costs and significant potential for adoption, especially in developing nations [5]. These technologies offer a path to sustainable energy independence and enhanced energy security. However, their integration poses challenges beyond the scope of this study, which focuses specifically on low-carbon thermal technologies as a more immediate and practical solution for ORDCs. The investigation of solar and wind energy solutions merits its own dedicated analysis. Additionally, while some ORDCs may opt for carbon credits as a temporary solution to offset emissions, these mechanisms do not address the underlying structural dependence on fossil fuels and expose nations to the volatility of global carbon markets, creating economic uncertainty. The urgent need to diversify energy portfolios in these nations makes thermal energy an immediate and technically feasible solution that can help balance the dual priorities of economic development and climate action. In recent years, clean thermal technologies have offered significant advances. For instance, molten carbonate fuel cells (MCFCs) can achieve a CO₂ capture rate of 92%, while methane reforming combined with solar thermo-electrochemical processes has demonstrated a hydrogen solar efficiency of 26.25%, surpassing traditional photovoltaic electrolysis [6]. Thermal electrification through renewable energy can also significantly reduce CO₂ emissions, supporting a cleaner transition in energy-intensive industries like the chemical sector [7].

Recent studies have contributed significantly to the advancement of low-carbon technologies. For example, ref. [6] demonstrated in the UAE that a hybrid system integrating solar energy, thermal storage, batteries, and hydrogen could reduce fuel consumption by 48% and lower annual costs by 25%. In China, the “integrated energy corridor” model proposed by [7] promotes energy transmission through green electricity, hydrogen, and oxygen, facilitating the shift to low-emission energy systems. Additionally, ref. [8] compared various hydrogen production technologies, highlighting methane pyrolysis and electrolysis for their lower CO₂ emissions and competitive costs. In the UK, ref. [9] explored four scenarios for low-carbon heating, concluding that while total electrification reduces risks, it is not the most economical option. These studies illustrate the diversity of approaches being pursued globally to reduce carbon footprints and improve energy efficiency.

Other significant research includes the work of [10], which proposed a hybrid hydrogen production system combining methane oxidation and water electrolysis, demonstrating the importance of state support for such systems. Additionally, ref. [11] developed energy conversion and carbon capture models that improve wind energy absorption while reducing emissions and operational costs. Similarly, ref. [12] optimized integrated energy systems, incorporating hydrogen production and storage to achieve emission reductions. Regarding CO₂ capture, ref. [13] demonstrated that molten carbonate fuel cells are more efficient than conventional amine-based systems, providing a promising alternative for large-scale applications. Moreover, ref. [14] proposed a low-carbon economic dispatch model for virtual power plants (VPPs), integrating hydrogen storage and carbon trading mechanisms to balance environmental and economic objectives.

Several emerging trends in energy storage and hybrid systems also show promise. For instance, ref. [15] introduced an electrified methane reforming (E-SMR) process that improves thermal efficiency and reduces carbon emissions. Meanwhile, the stochastic optimization model for integrated energy production systems (IEPS) described in [16] enhances system flexibility and offers low-carbon solutions. Studies like [17,18] compared the economic viability of hydrogen production from methane and hydrogen sulfide, while ref. [19] examined vacuum gas oil pyrolysis using non-thermal plasma to reduce carbon emissions. Additionally, ref. [20] explored long-duration thermo-mechanical energy storage (TMES) for grid decarbonization, highlighting innovative concepts such as metal redox reactions and CaO hydration/dehydration processes.

In the renewable energy sector, ref. [21] proposed a hybrid hydrogen production system combining photovoltaic solar energy with methane reforming, improving efficiency and reducing fossil fuel use. Similarly, ref. [22] optimized photovoltaic systems with hybrid storage in zero-energy buildings, demonstrating the potential of advanced storage technolo-

gies in reducing carbon footprints. Research on concentrated solar power (CSP) combined with thermal storage, like that described by [23], has shown significant emission reductions in industrial applications, while ref. [24] emphasized the environmental challenges associated with lithium-ion batteries. Moreover, ref. [25] explored artificial intelligence (AI) techniques for optimizing smart grids, enhancing demand management, and integrating renewable sources more effectively.

In wind energy, ref. [26] proposed integrating wind turbines into urban grids, while ref. [27] evaluated emerging energy storage technologies like redox flow batteries for residential use. Large-scale storage solutions were further explored by [28], who investigated pumped storage systems, and [29], who analyzed district heating networks transitioning to low-carbon systems. Other studies, such as [30], highlighted the use of biogas for distributed electricity generation, and ref. [31] evaluated geothermal energy for sustainable heating and cooling. The integration of renewable energy systems into smart buildings, as demonstrated by [32], enhances efficiency and reduces carbon footprints, while ref. [33] explored wave energy as a constant renewable source for coastal regions.

Several studies have also explored the role of public policies in accelerating the adoption of renewable technologies. For example, ref. [34] examined how incentives and subsidies can support the transition to clean technologies in the industrial sector, while ref. [35] focused on optimizing hybrid renewable energy systems combining solar, wind, and battery storage to improve grid stability. Marine energy, specifically tidal turbines, was the focus of [36], highlighting its potential as a renewable energy source for coastal communities. Biomass and carbon capture technologies were investigated by [37], showing their ability to reduce greenhouse gas emissions significantly. Additionally, ref. [38] explored the use of municipal solid waste (MSW) for energy generation, while ref. [39] analyzed the role of solar energy in industrial refrigeration systems.

Finally, studies like [40] examined combining wind energy with desalination technologies, presenting a sustainable solution for water management in arid regions. Research on renewable energy's impact on national energy security, such as [41], demonstrated how it can reduce dependency on unsustainable sources. Solar energy solutions for recreational facilities were explored by [42], while ref. [43] examined combining solar photovoltaic systems with battery storage to provide electricity in isolated communities. Electric vehicles and their role in reducing emissions in the transportation sector were studied by [44], while ref. [45] analyzed the application of renewable energy technologies in agriculture to enhance sustainability. Additional research by [46,47] focused on reducing energy consumption in construction and promoting biomass energy in rural areas. The use of renewable technologies in the mining sector was investigated by [48], and geothermal energy for residential heating was evaluated by [49]. The economic and environmental benefits of solar energy in public lighting were highlighted by [50], while ref. [51] demonstrated the effectiveness of wind energy in coastal communities. Finally, ref. [52] explored the benefits of combining solar energy with storage technologies to improve grid resilience.

Despite the advancements in low-carbon thermal electricity generation, several gaps remain in the literature. Comprehensive studies comparing clean thermal technologies in the context of ORDCs, particularly hydrogen and bioenergy, are scarce. Furthermore, limited research addresses these technologies' practical and economic feasibility for large-scale applications in oil-rich regions. The interaction between current regulatory frameworks and the adoption of these technologies is insufficiently explored, especially regarding incentives, subsidies, and the adaptation of these policies to regional needs. Additionally, few studies explore the optimal integration of clean thermal technologies into existing energy infrastructures, particularly in hybrid systems.

This review aims to address these gaps by (1) evaluating the current state of low-carbon thermal electricity generation technologies, with a specific focus on hydrogen, biomass, and geothermal solutions; (2) analyzing technical and economic challenges in combustion processes and energy efficiency; and (3) providing recommendations for research and policy initiatives to advance the transition toward sustainable thermal energy systems in

ORDCs. Using the PRISMA methodology, the review assesses technological innovations, regulatory frameworks, and successful case studies to present a comprehensive overview of the field.

2. Study Selection Methodology

This systematic review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [52], with the study selection process visually summarized in Figure 1. The process begins with the identification phase, where a comprehensive search strategy is employed across prestigious databases, ensuring the retrieval of all potentially relevant studies. In the screening phase, the abstracts of the retrieved records are carefully reviewed against predefined inclusion and exclusion criteria, eliminating studies that do not meet the relevance criteria. Following this, the Eligibility and Inclusion phase involves a meticulous examination of the full-text articles to confirm their quality and pertinence, ensuring that only studies of high relevance and rigor are included in the final analysis. Finally, the synthesis phase integrates and analyzes the selected studies, providing the foundation for the findings and conclusions presented in this review. Figure A1 in Appendix A shows the standardized PRISMA 2020 flowchart for the systematic literature review reported in this article.



Figure 1. PRISMA methodology for the study selection process.

2.1. Identification Phase: Databases, Search Terms Definition

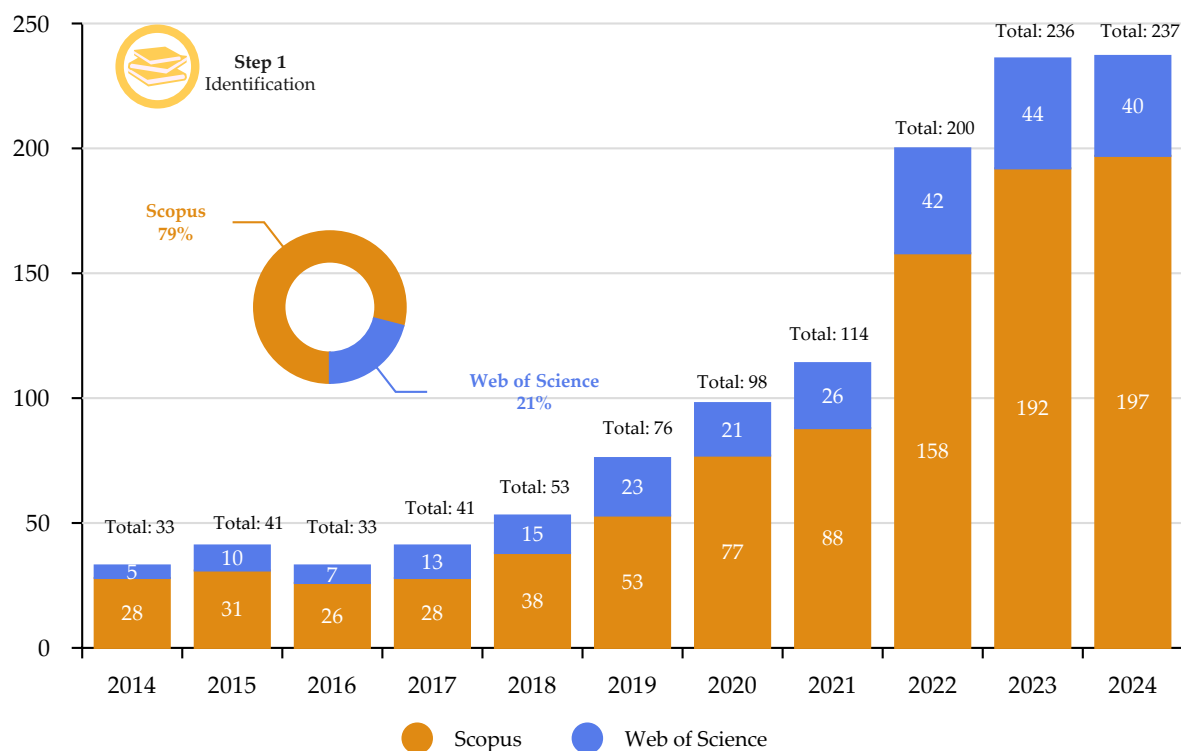
The identification phase of this systematic review involved sourcing bibliographic resources from Scopus and Web of Science, selected for their extensive coverage of high-quality research articles to ensure a comprehensive, transparent, and objective review. Both databases include prestigious publishers such as IEEE, Elsevier, Springer, Taylor and Francis, Wiley, and MDPI, providing a diverse collection of literature aligned with the review’s objectives. The authors carefully defined the search terms to capture relevant studies on low-carbon thermal electricity generation. The search strategy included filtering by publication years (2014–2024) and limiting the document type to peer-reviewed journal articles. Boolean operators (AND, OR) were employed to refine and focus the search results, enhancing the identified studies’ precision and relevance.

Table 1 provides an overview of the literature search terms and the summary of database search results from Scopus and Web of Science, as well as the number of documents retrieved, duplicates removed, and the final sample for the screening phase, which totaled 1162 unique items.

Table 1. Literature Search Terms and Summary of Database Search Results.

Database	Query String	N° of Returned Documents	Removal of Duplicates	Final Sample for Screening Phase
Scopus	TITLE-ABS-KEY (“low carbon” AND “electricity” AND (“biogas” OR “biofuels” OR “biomass” OR “hydrogen” OR “geothermal”)) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, “ar”))	935	19	916
Web of Science	ALL = (“low carbon” AND “electricity” AND “thermal ” AND “renewable”) Refined By: Publication Years: 2024 or 2023 or 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or 2014; Document Types: Article	309	63	246
Total items		1244	82	1162

Figure 2 illustrates the annual progression of the identified articles, showing a notable increase in publications on low-carbon thermal electricity technologies, particularly from 2018 onwards. This growth in relevant research underscores the rising interest in low-carbon energy solutions, particularly in the context of oil-rich developing countries.

**Figure 2.** Annual progression of the articles identified during the identification phase.

2.2. Screening Phase: Inclusion and Exclusion Criteria Definition, Article's Abstract Review

In this screening phase, articles from the last ten years were selected to ensure that the review incorporates the most current and innovative research on low-carbon thermal electricity generation and utilization, reflecting recent advancements and relevant economic trends. To maintain the integrity and depth of the review, the focus was on peer-reviewed journal articles, which provide high-quality, primary data essential for a thorough analysis. The selection of English-language articles was made to support the broad dissemination and

accessibility of knowledge, as English is widely recognized as the predominant language in global scientific communication. This approach ensures that the findings can be universally understood and applied, contributing to the ongoing dialogue within the international research community. Particular emphasis was placed on studies concentrating on low-carbon thermal electricity generation and utilization, specifically those technologically advanced and economically feasible for oil-rich developing countries. The focus included the integration of clean thermal technologies like biogas, biofuel, biomass, hydrogen, and geothermal energy. Articles that did not focus on these specific aspects or failed to address their technological maturity or economic viability were not included. The defined inclusion and exclusion criteria defined by the authors are summarized in Table 2.

Table 2. Inclusion and Exclusion Criteria for the Screening Phase.

Criterion	Inclusion	Exclusion
PublicationType	Articles from peer-reviewed journals	Conference proceedings, editorial notes, review papers, book chapters, theses, white papers, and other non-peer-reviewed materials
Language	Publications in English	Publications in languages other than English
Publication Date	Research articles published within the timeframe of 2014 to 2024	Research articles published before 2014
Accessibility	Articles accessible in full text through institutional subscriptions or as open access	Articles that lack full-text accessibility
Research Focus	Studies concentrating on low-carbon thermal electricity generation and utilization that are technologically advanced and economically feasible for oil-rich developing countries, particularly those discussing the integration of clean thermal technologies like biogas, biofuels, biomass, hydrogen, and geothermal energy.	Studies that do not focus on low-carbon thermal electricity generation or fail to address technological and economic aspects relevant to oil-rich developing countries. Additionally, articles that solely explore non-thermal renewable energy technologies without discussing their integration into thermal systems are excluded.

Two independent reviewers thoroughly assessed the abstracts of all 1162 items from the previous phase, using a binary scoring system based on the predefined inclusion and exclusion criteria. Any disagreements with the reviewer were addressed and resolved through consensus to maintain the objectivity of the selection process. As summarized in Figure 3, the screening process resulted in 808 items (69.5% of the total) that fully satisfied the inclusion criteria, while the remaining articles were excluded for either not meeting or only partially meeting the criteria.

Among the 808 items that passed this stage, the distribution by journal reveals that a significant portion of the selected studies were published in highly reputable journals. For instance, *Applied Energy* leads with 58 items, followed by the *International Journal of Hydrogen Energy* with 51 items, and *Energy* and the *Journal of Cleaner Production* with 45 items each. These journals are recognized for their rigorous peer-review processes and focus on energy research, particularly in the areas relevant to low-carbon thermal electricity generation and utilization. Other notable journals in the distribution include *Energies*, with 38 items, and *Energy Conversion and Management*, with 34 items, further underscoring the prominence of these publications in the field. The spread across various leading journals indicates a broad and diverse research base, highlighting the relevance and interest in this topic within the scientific community. The resulting 808 items will proceed to the third phase of the review process, where they will undergo a more detailed evaluation.

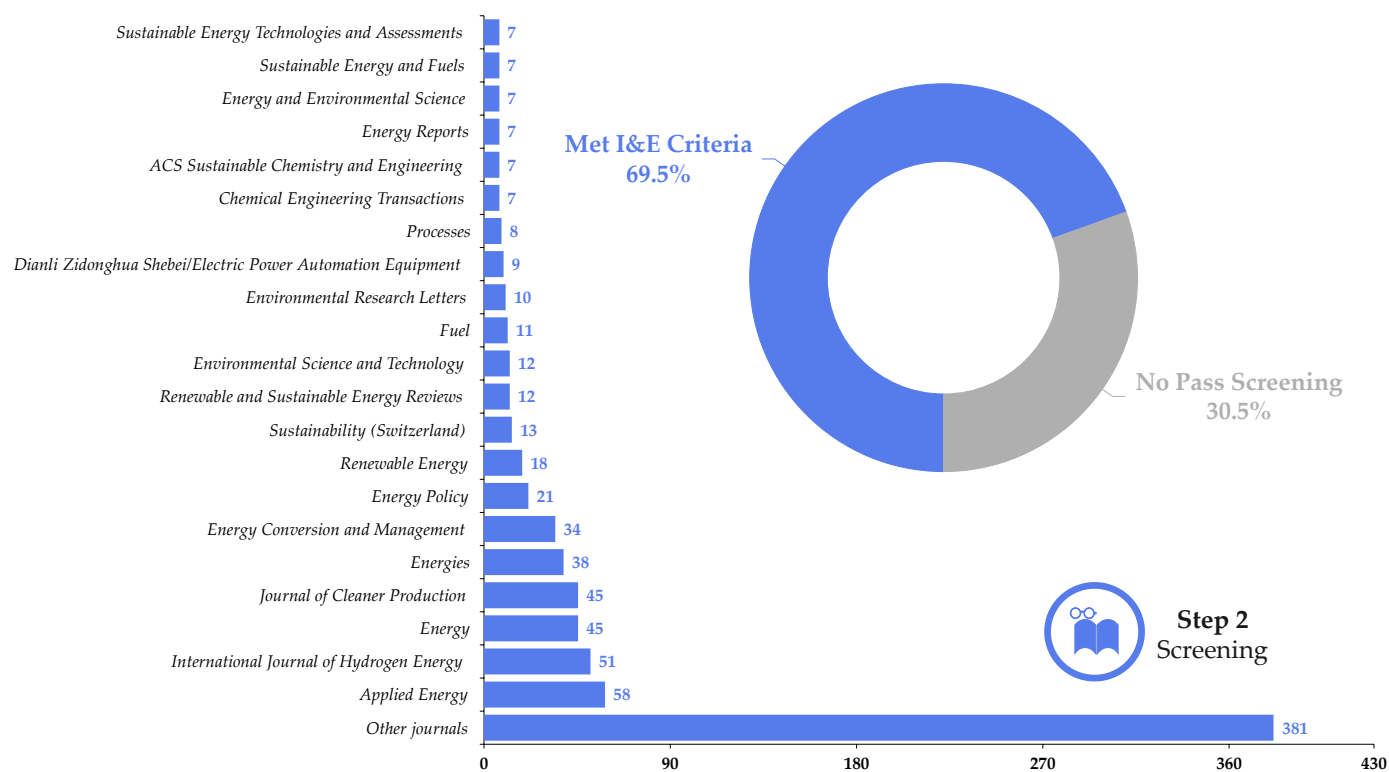


Figure 3. Summary of the Screening Phase Results.

2.3. Eligibility and Inclusion Phase: Comprehensive Full-Text Review for Assessing Studies

The Eligibility and Inclusion Phase is essential for narrowing the selection to only the most pertinent and high-quality studies for this review. Each article was meticulously evaluated during this phase through a comprehensive full-text review, applying a detailed three-level Likert scale. The evaluation focused on several critical criteria, including the study’s relevance to integrating clean thermal technologies for low-carbon electricity generation in oil-rich developing countries, the rigor and soundness of its methodology, and the originality of its contributions to the field. To verify that the selected studies specifically focused on ORDC-relevant solutions, the full text of each item was thoroughly reviewed to ensure an explicit reference to the challenges, economic constraints, or potential energy solutions in ORDCs. The score assigned to each item in this aspect was determined by the degree of specificity with which the study addressed a potential solution or conducted a focused analysis on ORDC. Studies that offered detailed insights or case studies on specific ORDCs received higher scores. Additional factors, such as the quality and reliability of the data, the practical applicability of the findings, and the technological maturity and economic viability of the proposed solutions, were also carefully assessed.

Each criterion was rated on a scale from 1 to 3, where a score of 1 indicated minimal alignment with the criterion, and a score of 3 reflected a high degree of relevance or quality. Only studies that scored well across these criteria were deemed suitable for inclusion in the review, ensuring a focused and robust analysis of the integration of clean thermal technologies in low-carbon electricity generation. This rigorous selection process helped ensure that the review encompasses studies that meet high academic standards and offer practical, impactful solutions for oil-rich developing countries. The detailed criteria and evaluation metrics are summarized in Table 3.

Table 3. Criteria and metrics used for the full-text evaluation.

N°	Criterion	Description and Evaluation Metrics
1	Relevance to Study Goals	How well the study addresses the integration of clean thermal technologies for low-carbon electricity generation in oil-rich developing countries. (1: Peripheral, 2: Related, 3: Highly Relevant)
2	Methodological Soundness	The appropriateness and robustness of the research methodology used. (1: Needs Improvement, 2: Acceptable, 3: Strong)
3	Originality and Contribution	The originality and significance of the study's contributions to the field. (1: Minor, 2: Substantial, 3: Major)
4	Data Quality and Reliability	The quality and reliability of the data presented in the study. (1: Satisfactory, 2: Good, 3: Excellent)
5	Practical Applicability	The potential for practical application of the study's findings in real-world scenarios. (1: Limited, 2: Useful, 3: Highly Applicable)
6	Technological Maturity and Economic Attractiveness for Oil-rich developing countries	The extent to which the study offers solutions that are technologically mature and economically viable for oil-rich developing countries. (1: Developing, 2: Promising, 3: Established)

During this phase, a total of 85 articles were selected from the 808 items evaluated for the systematic review. The selection process was guided by a stringent benchmark, requiring a minimum score of 14 out of 18 points (or equivalent, 77 out of 100) across the evaluation criteria. This rigorous standard ensured that the studies included in the review strongly aligned with the research goals, robust methodological approaches, significant contributions to the field, high data quality, practical relevance, and the maturity and economic viability of the technologies discussed, particularly for oil-rich developing countries. Figure 4 presents the verification matrix used to assess the eligibility of the articles.

2.4. Synthesis Phase: Bibliometric Analysis of Included Literature

This section combines the 85 articles selected during the Eligibility and Inclusion Phase to offer a detailed overview of the current research landscape on integrating clean thermal technologies for low-carbon electricity generation in oil-rich developing nations. The articles included in this analysis were carefully chosen to represent a focused and high-quality sample of the broader literature, ensuring that the review captures the most pertinent and impactful studies. These works cover various topics and are drawn from various journals, highlighting the interdisciplinary nature of this research area.

Figure 5 shows the distribution of articles across journals and highlights the prominence of certain publications in this area of research. The *Journal of Cleaner Production* leads with nine articles, followed by *Applied Energy* with seven and *Energy Conversion and Management* with six. Other notable journals include *Energies*, which has five articles; *Renewable Energy*; and *International Journal of Hydrogen Energy* and *Energy*, each contributing four articles. This distribution indicates that the underscore research is widely published across journals focusing on sustainability, energy management, and renewable technologies, underscoring the importance of these topics in the current scientific discourse.

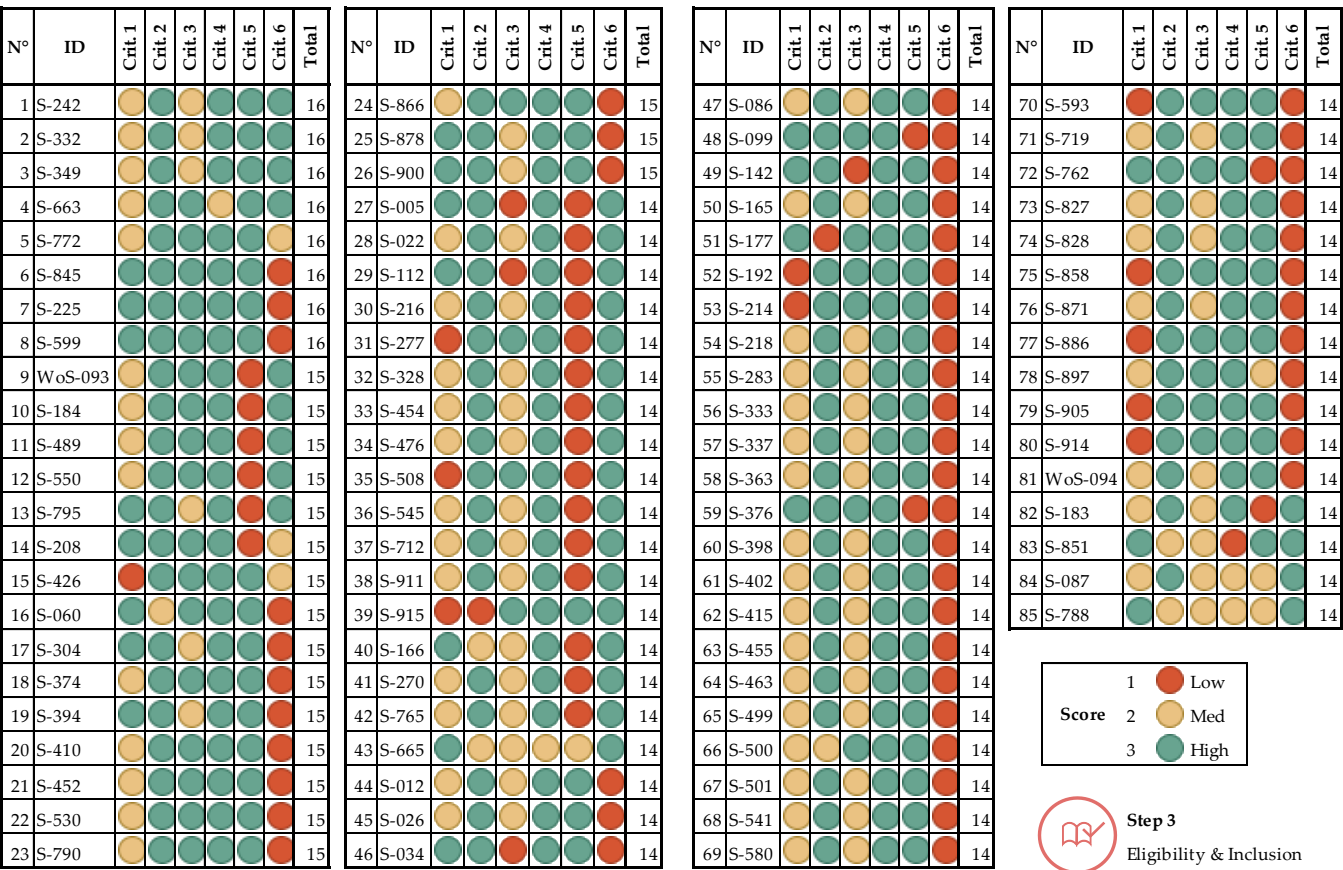


Figure 4. Verification Matrix used during the Eligibility and Inclusion Phase.

Regarding the annual progression of publications, there has been a noticeable increase in research output in recent years, with a significant rise in the number of articles published from 2021 onward, as shown in Figure 5. The year 2023 saw the highest number of publications, with 19 articles, followed closely by 2024 with 15 articles. This upward trend suggests a growing interest and urgency in advancing research on low-carbon thermal technologies, particularly in the context of oil-rich developing countries. The steady increase from 2014 to 2020 and the sharp rise in subsequent years highlight the evolving focus of the scientific community on addressing climate change through innovative energy solutions.

Based on the study of keywords from the consulted works, as visualized in the word cloud map presented in Figure 5, the selected 85 articles will form the basis for the subsequent analysis and discussion, providing insights into the technological advancements, challenges, and opportunities in integrating clean thermal technologies for low-carbon electricity generation in oil-rich developing countries. These articles can be classified into the following thematic clusters: (1) Oil-Rich Developing Countries, (2) Low-Carbon Technologies for Thermal Generation, (3) Successful Case Studies and Implementation Perspectives for Oil-Rich Regions, (4) Current Regulatory Framework, and (5) Technological Innovations and Trends. The complete bibliographic information for these 85 articles can be accessed via the following GitHub URL: <https://t.ly/iG3hA> (accessed on 20 September 2024).



3.1. Oil-Rich Developing Countries

While these countries vary widely in economic capacity, infrastructure, and political contexts, their dependence on petroleum resources for domestic energy use and export revenue creates a unique set of common challenges. This reliance on oil exposes ORDCs to similar economic vulnerabilities, such as market volatility and price fluctuations, which can destabilize their economies. Additionally, the environmental impacts of fossil fuel extraction and consumption pose significant challenges for all ORDCs as they seek to transition toward low-carbon energy systems. The wide disparity in Gross National Income (GNI) does not undermine the value of examining ORDCs as a group but instead emphasizes the need for tailored solutions that account for each country's specific circumstances. While higher-income ORDCs may have the financial capacity to invest in cutting-edge technologies, lower-income nations may benefit from more cost-effective alternatives. The shared reliance on fossil fuels and the urgency of decarbonization make it both relevant and necessary to analyze ORDCs collectively while recognizing the need for context-sensitive approaches to low-carbon transitions.

It is also true that ORDCs can leverage carbon credits to offset their emissions, but this approach may only address the symptoms of carbon emissions rather than offer a long-term solution. While useful in the short term, the reliance on carbon credits might not resolve the fundamental issues of fossil fuel dependence, nor does it necessarily contribute to creating sustainable, self-sufficient energy systems. Low-carbon thermal electricity generation, by contrast, can provide a more direct and lasting reduction of emissions at the source. As highlighted in our article, ORDCs can face significant economic vulnerabilities tied to fossil fuel market volatility, making diversifying their energy matrices an urgent consideration. Low-carbon thermal technologies may offer environmental benefits, economic resilience, and energy security, advantages that might not be entirely achievable through carbon credits alone. Furthermore, investing in these technologies could foster innovation, job creation, and technological progress, potentially positioning ORDCs as more active participants in the global energy transition rather than passive actors in carbon trading schemes. Therefore, shifting to low-carbon energy sources may be environmentally necessary and strategically advantageous for ORDCs in the long run.

The economic and environmental landscape of ORDCs is deeply intertwined with the global energy market. As major oil producers, these countries have benefited from the revenues generated by oil exports, which have been vital for their economic development. However, this dependency on oil has also made their economies vulnerable to fluctuations in global oil prices, leading to economic instability. Additionally, the environmental costs of fossil fuel extraction and consumption have become increasingly apparent, with rising greenhouse gas emissions contributing to global climate change.

Transitioning to low-carbon energy systems in ORDCs is essential for mitigating climate change and ensuring sustainable economic development. These countries face significant hurdles in this transition, including a high reliance on fossil fuels, substantial transmission losses due to aging infrastructure, and financial constraints that limit their ability to invest in new technologies. Moreover, diversifying their energy matrix is urgent to reduce their dependency on a single resource and enhance energy security.

The global shift towards renewable energy presents a timely opportunity for ORDCs to adopt low-carbon solutions. By integrating clean thermal technologies such as biogas, biofuels, biomass, hydrogen, and geothermal energy, these countries can reduce their carbon footprint while maintaining economic growth. These technologies offer technically feasible, economically viable, and efficient solutions in combustion processes, including ignition, calorimetry, and thermochemical reactions.

Furthermore, the adoption of low-carbon energy systems in ORDCs is aligned with achieving several Sustainable Development Goals (SDGs), particularly those related to energy access (SDG 7), economic growth (SDG 8), and climate action (SDG 13) [54]. The transition to clean energy can drive economic diversification, create new job opportunities, and enhance resilience to climate impacts.

However, the pathway to adopting these technologies is not without challenges. ORDCs must navigate the technical complexities of integrating new technologies into existing energy infrastructures, overcome financial barriers through innovative funding, and implement policies supporting the transition to a low-carbon economy. International cooperation and investment will facilitate this transition, offering financial resources, technical expertise, and policy support.

The statistics presented in Figure 6 illustrate the distribution of the 85 selected articles across various ORDC included in the literature review. Brazil leads with the highest representation, contributing nine articles, reflecting its active engagement in research on low-carbon thermal electricity generation and utilization. Russia follows with six articles, indicating a strong focus on integrating low-carbon technologies into its energy strategy. Four articles represent Malaysia, showcasing its commitment to balancing industrial growth with sustainability goals. Iran and Mexico each contribute two articles, highlighting their efforts in optimizing energy systems and exploring renewable energy sources. The remaining countries—Qatar; Colombia; Indonesia; Venezuela; Kazakhstan; and Ecuador—each

contribute one article; reflecting their participation in the global dialogue on sustainable energy transitions, albeit at a lower intensity than the leading nations.

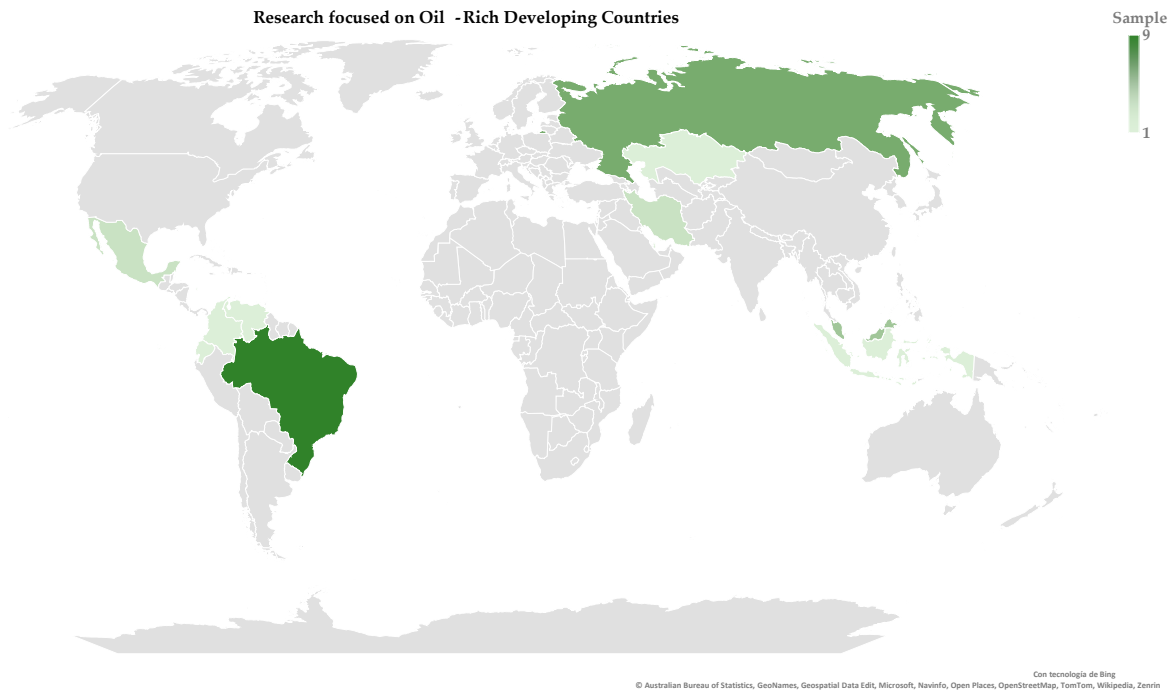


Figure 6. Distribution of the selected articles across Oil-Rich Developing Countries in the systematic literature review.

The comprehensive review of low-carbon thermal electricity generation and utilization strategies across various ORDC reflects approaches tailored to each nation's specific energy resources, challenges, and policy frameworks. In Brazil, which has the highest number of evaluated studies, the research spans multiple dimensions of renewable energy integration. From the 2024 study by Reichert et al. on forecasting renewable energy generation [55] to Brazil's focus on hydrogen economy development, as discussed in a 2022 analysis by Chantre et al. [56], the country is making significant strides in diversifying its energy portfolio and advancing its renewable energy capabilities. Brazil also continues to explore biomass utilization, particularly eucalyptus residues, under its RenovaBio policy, positioning itself as a leader in bioenergy [57]. Additionally, Brazil's involvement in the BRICS initiative, as detailed by Ma et al. [58], BRICS refers to five major emerging economies: Brazil, Russia, India, China, and South Africa. This initiative was formed to foster cooperation among these countries, particularly in economic growth, development, and global governance. These nations share common interests in creating a more balanced global financial system, improving trade relations, and enhancing their collective influence in international institutions. While Brazil possesses vast reserves of biomass and hydroelectric resources, like other ORDCs, its reliance on oil remains a shared challenge, making the transition to low-carbon energy a critical priority.

With six evaluated items, Russia plays an essential role in the global energy transition, particularly within the BRICS framework. The 2024 study by Ma et al. [58] highlights Russia's strategic focus on integrating low-carbon technologies with its industrial growth, emphasizing the potential of nuclear energy as a stable low-carbon option. Russia has made significant investments in nuclear energy, distinguishing it from many other ORDCs, yet its deep reliance on fossil fuels mirrors the broader challenge oil-rich nations face. Another significant study by Nian and Zhong [59] explores the economic feasibility of flexible energy production systems, further solidifying Russia's position as a key player in the global energy landscape. Russia's research efforts reflect its intention to balance its significant fossil fuel reserves with commitments to reduce greenhouse gas emissions. Despite these initiatives,

the entrenched nature of Russia's fossil fuel infrastructure illustrates the shared difficulty in transitioning to alternative energy systems among ORDCs.

Malaysia, featured in four items, continues to balance its industrial development with sustainability goals. The 2019 study by Khor and Lalchand [60] highlights Malaysia's efforts to integrate solar and biomass resources into its energy mix, aligning with broader regional trends toward renewable energy adoption in Southeast Asia. Additionally, Malaysia's exploration of life cycle assessments in activated carbon production, as shown in the 2016 study by Arena et al. [61], reflects the country's commitment to reducing industrial carbon footprints. Malaysia faces fewer geopolitical barriers than other ORDCs, but its dependency on fossil fuels for industrial growth parallels the common challenges of achieving a low-carbon energy transition.

Iran and Mexico, each with two evaluated items, are also making strides in low-carbon energy. In Iran, recent studies emphasize optimizing energy systems to reduce carbon emissions [62,63], while Mexico explores both carbon capture technologies and the potential of renewable energy sources to meet its growing energy demands [64,65]. These efforts highlight both countries' strategic moves towards sustainable energy transitions, capitalizing on their unique energy resources. While Mexico and Iran explore emerging technologies, they share the broader ORDC challenge of decarbonizing deeply entrenched oil-based energy systems, a critical step for achieving economic stability and climate goals.

Other ORDCs such as Qatar [66], Colombia [67], Indonesia [61], Venezuela [68], Kazakhstan [69], and Ecuador [70], each represented by one study, are also contributing to the global conversation on low-carbon energy. Qatar's research centers on optimizing energy systems within its unique geopolitical context, while Colombia focuses on system optimization for renewable integration. With its considerable financial resources, Qatar has the flexibility to invest in cutting-edge technologies, but countries like Colombia may need to adopt more modest, capital-efficient solutions, such as small-scale biogas plants. Indonesia and Venezuela emphasize the sustainable production and utilization of local resources, such as biomass and hydrocarbons, to reduce carbon footprints. Kazakhstan and Ecuador are exploring the potential of emerging technologies to enhance their energy systems' efficiency and sustainability. Although these countries possess varying levels of indigenous resources and economic capacity, their shared reliance on fossil fuels makes the transition to low-carbon energy urgent and complex, highlighting the need for tailored solutions across the ORDC group.

3.2. Low-Carbon Technologies for Thermal Generation

3.2.1. Biomass Co-Firing and Its Integration with Existing Infrastructure

Biomass co-firing, where biomass is burned alongside fossil fuels, has been identified as a viable strategy to reduce carbon emissions in existing thermal power plants, offering a transitional solution without requiring a complete infrastructure overhaul. In Malaysia, the integration of biomass with coal has shown promise in reducing the carbon intensity of the country's power sector, which is heavily dependent on fossil fuels [60]. This method leverages agricultural residues as biomass feedstock, effectively lowering CO₂ emissions while utilizing the existing thermal power infrastructure, making it a cost-efficient approach for emissions reduction. European studies complement these findings by demonstrating that co-firing can increase thermal efficiency, offering a cleaner alternative to traditional coal-fired plants while substantially reducing greenhouse gas emissions [71].

Brazil's RenovaBio program provides a strong example of how national energy policies can support biomass co-firing, positioning it as a central element of Brazil's energy matrix and a key contributor to meeting emission reduction targets [57]. However, despite the potential of biomass co-firing, several challenges persist, including inconsistencies in biomass quality and the technical adaptations required to modify existing boilers for efficient biomass combustion [61]. Research in Germany emphasizes the importance of fostering policy frameworks that incentivize investments in co-firing technologies and provide the necessary training to manage the unique operational demands [72]. For

countries rich in agricultural by-products, biomass co-firing offers a pragmatic solution that balances environmental benefits with economic feasibility, making it an attractive strategy for reducing reliance on coal while transitioning to a more sustainable energy future [73].

3.2.2. Hydrogen as a Fuel for High-Efficiency Gas Turbines

Green hydrogen, produced from renewable energy sources, is becoming a key player in decarbonizing high-efficiency gas turbines, particularly in industries requiring high energy density. In Japan, research has shown that hydrogen-fueled gas turbines can significantly cut carbon emissions, with industrial applications benefiting the most due to their high energy demands [74]. These hydrogen-fueled systems produce zero direct CO₂ emissions, positioning hydrogen as a critical alternative to natural gas in the effort to decarbonize thermal power generation.

Nevertheless, several technical hurdles remain, particularly regarding materials capable of withstanding hydrogen combustion's higher temperatures and pressures. Researchers in Germany have focused on developing new alloys and turbine designs to prevent issues like NO_x emissions, which remain a concern in hydrogen combustion systems [75]. In the United States, pilot projects exploring hydrogen in combined-cycle gas turbines have demonstrated promising results, improving efficiency and emissions performance, particularly reductions in NO_x emissions [62,76]. Globally, initiatives in Europe and Asia are working to establish hydrogen production corridors, which would facilitate the scaling up of hydrogen as a mainstream fuel for power generation [77,78].

Moreover, hydrogen is increasingly seen not only as a fuel but also as an energy storage medium. In regions with high penetration of renewables like wind and solar, hydrogen can serve as a buffer to balance the intermittency of renewable energy generation by storing excess energy during peak production and releasing it when needed [79,80]. The scalability of hydrogen turbines and the expansion of green hydrogen production infrastructure are key to realizing their potential, with studies indicating that the future economic viability of hydrogen-fueled gas turbines depends heavily on reducing the cost of hydrogen production and distribution [81].

3.2.3. Geothermal Hybrid Systems for Base Load Power Generation

Geothermal hybrid systems, combining geothermal energy with other renewable sources, provide a reliable solution for base load power generation, ensuring consistent energy supply even during fluctuating demand. In Brazil, geothermal systems have been proposed as part of hybrid energy configurations that include biomass and solar energy, helping diversify the energy mix and reduce the reliance on fossil fuels [57,81]. This approach maximizes the strengths of each renewable source, with geothermal providing a steady base load and biomass or solar energy contributing during peak periods.

Iceland has set a global benchmark by integrating geothermal with hydroelectric power, demonstrating the feasibility of achieving a nearly 100% renewable energy mix in regions with ample natural resources [68,82]. Meanwhile, New Zealand's combination of geothermal and solar energy highlights how hybrid systems can achieve both cost efficiency and carbon reductions [64,83]. These configurations offer an advantage by enhancing grid stability, particularly important in countries that rely heavily on intermittent renewable sources like wind and solar. Geothermal hybrid systems ensure a constant energy flow, reducing the volatility of relying solely on variable renewables [84,85].

In Italy, new hybrid systems integrating geothermal energy with thermal energy storage have been developed, adding operational flexibility and allowing energy to be stored for use during periods of high demand or low renewable generation [65]. These innovations enhance the reliability of geothermal systems, making them more adaptable to diverse regional conditions and providing scalable solutions for expanding renewable energy capacity [55].

3.2.4. Advanced Thermal Energy Storage Solutions

Thermal energy storage (TES) plays a crucial role in increasing the efficiency and flexibility of low-carbon thermal power plants. In Spain, CSP plants equipped with TES have demonstrated more than a 20% increase in system efficiency, enabling continuous electricity supply even when solar radiation is unavailable [86]. This technological improvement boosts system efficiency and enhances grid reliability, which is essential as the share of renewables in the energy mix increases.

In China, advancements in phase change materials (PCMs) for TES have led to more compact and efficient systems, allowing for higher storage capacities and quicker response times to fluctuations in energy demand [55,87]. This is critical in regions where energy demand peaks can occur unpredictably, as TES systems can quickly release stored energy to meet those spikes. In the United States, molten salt TES has been successfully integrated with CSP plants, providing long-duration energy storage that allows for uninterrupted electricity generation during nighttime or cloudy conditions [63,88]. This kind of long-term storage is essential for reducing reliance on fossil fuels and smoothing out the intermittency of renewable energy sources [89].

TES technology continues to evolve, with innovations such as integrating TES with advanced energy management systems that optimize the use of stored energy based on real-time grid demands and generation forecasts [90,91]. As renewable energy penetration increases, TES systems will play a pivotal role in ensuring that energy systems remain stable and resilient, making them a cornerstone of future sustainable energy infrastructure [92,93].

3.3. Successful Case Studies Implementation Perspectives for Oil-Rich Regions

3.3.1. Lessons from the Middle East: Pioneering Low-Carbon Initiatives in Oil-Dependent Economies

The Middle East, a region heavily dependent on oil revenues, has seen increasing efforts to diversify its energy mix through low-carbon initiatives to reduce greenhouse gas emissions and ensure long-term energy sustainability.

A notable example is Saudi Arabia's Vision 2030, which seeks to reduce the country's reliance on fossil fuels by integrating large-scale renewable energy projects, including solar and wind power. These projects are essential to lower the energy sector's carbon footprint while leveraging the vast renewable resources available in the region [85]. Similarly, the UAE has integrated nuclear energy into its energy mix through the Barakah Nuclear Energy Plant, which is crucial in reducing dependency on oil and gas for electricity generation [94]. These initiatives are supported by robust policy frameworks that incentivize private sector investment and international collaboration, creating a conducive environment for low-carbon technologies [95].

However, these projects face challenges such as financing, technical expertise, and public acceptance, particularly in transitioning from a fossil fuel-dominated energy system. The successes in Saudi Arabia and the UAE illustrate the importance of forward-looking policies, significant financial investment, and international partnerships. These strategies provide valuable lessons for other oil-rich regions looking to diversify their energy sources while navigating the complex technical and financial landscape of low-carbon energy transitions [57,96]. The Middle East experience underscores the potential of oil-dependent economies to transition to renewable energy through strategic planning and international collaboration [67,97].

3.3.2. Transitioning National Grids: The Role of Clean Thermal Power in Africa's Oil-Producing Nations

African oil-producing nations increasingly recognize the importance of integrating cleaner energy sources into their national grids. For example, Nigeria has focused on expanding its gas-to-power projects, which utilize its abundant natural gas reserves to generate electricity with lower carbon emissions than coal and oil [67]. These projects are part of a broader strategy to enhance energy security, reduce greenhouse gas emissions,

and stabilize the national grid. In Angola, investments in combined-cycle gas turbine (CCGT) plants have improved energy efficiency while reducing carbon emissions, making the transition to cleaner power more feasible [94,98].

Despite the potential of these projects, challenges remain, such as the need for reliable energy storage systems to manage the intermittency of renewables and address fluctuations in electricity demand. Countries like Ghana are exploring biomass and waste-to-energy solutions as part of their national energy strategies, leveraging locally available resources to generate cleaner power while addressing environmental concerns such as waste management [99,100]. These initiatives are often supported by international development agencies and partnerships that help bridge the financial and technical gaps, implementing clean thermal power projects viable in the region [74,96]. Africa's oil-producing nations highlight the importance of leveraging indigenous resources, adopting adaptable technologies, and securing international support to achieve energy transition goals.

3.3.3. Public-Private Partnerships in Latin America: Leveraging Oil Revenues for Sustainable Energy

Public-private partnerships (PPPs) have emerged as a vital mechanism for leveraging oil revenues to finance sustainable energy projects in Latin America. In Brazil, the *RenovaBio* policy has successfully attracted private investment into the biofuels sector, leading to significant advancements in biomass energy production and its integration into the national grid [57]. This policy promotes renewable energy and encourages sustainable management of agricultural resources, creating economic and environmental benefits.

In Mexico, PPPs have been critical in financing geothermal and small-scale hydroelectric projects, sharing the risks and rewards between public funds and private investments [94,101]. Oil revenues are being strategically reinvested into renewable energy initiatives, reducing the dependency on fossil fuels while promoting economic growth. In Colombia, oil revenues have supported the expansion of wind and solar energy infrastructure, with private companies playing a central role in project development and operation [67,102]. These case studies demonstrate the potential of PPPs to mobilize the capital and expertise required to implement low-carbon energy projects, offering a replicable model for other oil-rich regions [103].

3.3.4. Overcoming Socioeconomic Barriers: Community Engagement and Low-Carbon Technology Adoption

One of the significant challenges in adopting low-carbon technologies in oil-rich regions is overcoming socioeconomic barriers, especially in communities heavily reliant on fossil fuel industries. Successful case studies emphasize that community engagement is crucial for facilitating the transition to low-carbon technologies. For example, in Nigeria, community-based programs have been implemented to raise public awareness about the benefits of clean energy and involve local stakeholders in the decision-making process [85]. This approach has helped garner public support for renewable energy projects, such as mini-grids powered by solar and wind energy, providing reliable electricity to remote areas while reducing reliance on diesel generators [94,104].

In Venezuela, partnerships with local cooperatives have facilitated the deployment of solar energy systems in rural communities, ensuring the social acceptance of these projects while creating jobs and providing economic benefits [74,100]. Similarly, geothermal projects in Ecuador have involved indigenous communities in the development process, ensuring that local stakeholders benefit from job creation and sustainable economic growth [57,97]. These examples highlight the importance of adopting inclusive approaches that address the socioeconomic realities of communities, ensuring that the transition to low-carbon technologies is equitable and socially sustainable.

The transition to low-carbon technologies in ORDCs can have significant social impacts, particularly in communities dependent on fossil fuel industries. Job losses and economic disruptions can lead to resistance unless proactive measures are taken. Solutions include job retraining programs to reskill workers for green energy sectors and developing

community-owned energy projects to create local jobs and foster acceptance of renewable technologies. To ensure equitable transitions, governments should implement just transition policies prioritizing community involvement, reskilling, and local job creation.

3.3.5. Economic Barriers and Solutions for Community Engagement in Low-Carbon Technology Adoption

In the context of ORDCs, the economic aspect is important in determining the success of low-carbon technology adoption. While various countries, such as Saudi Arabia and the UAE, have made substantial financial investments in renewable energy under their respective national strategies, many ORDCs face financial constraints that hinder their ability to transition from fossil fuels to clean energy technologies. For instance, the initial costs of integrating solar and wind energy into the national grid or retrofitting existing infrastructure to accommodate hybrid systems (such as co-firing or hydrogen-based generation) represent a significant economic barrier for countries heavily reliant on fossil fuels [57,85,94].

Although projects like Saudi Arabia's Vision 2030 and the UAEs Barakah Nuclear Plant have succeeded in the Middle East, they require substantial government subsidies and public-private partnerships to share the financial risks [94,95]. Additionally, financial assistance from international institutions has been key in ensuring these initiatives are economically viable, with external funding often offsetting the significant costs associated with scaling up renewable energy projects [96]. Economic constraints in African nations such as Nigeria and Angola also play a major role in the slow transition toward clean energy solutions. Projects like combined-cycle gas turbine (CCGT) plants offer lower emissions but require considerable upfront investments, and the economic viability of such initiatives often depends on international funding or public-private partnerships [94,98]. Angola's reliance on gas-to-power projects exemplifies how resource availability can mitigate some financial concerns, but other ORDCs may struggle to secure the capital required to pursue similar paths [67]. Therefore, while these successful case studies demonstrate the potential of low-carbon technologies, the economic context remains a significant constraint, especially for ORDCs. Governments must design financial policies that facilitate private investment and offer targeted subsidies to lower the barrier to entry for clean energy technologies [57,67].

3.4. Current Regulatory Framework

3.4.1. Comparative Analysis of Carbon Pricing Mechanisms and Their Impact on Thermal Generation

Carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems, have proven pivotal in promoting the adoption of low-carbon technologies, particularly in the thermal generation sector. However, the effectiveness of these mechanisms varies by region, with success largely contingent on the level of carbon pricing and the reinvestment of revenues into clean energy projects. The European Union's Emissions Trading System (EU ETS) is an example of a successful carbon pricing mechanism that has shifted the energy mix away from carbon-intensive generation methods by making fossil-fuel-based power less economically viable [105,106]. In contrast, regions without stringent carbon pricing measures struggle to transition to low-carbon thermal generation, as fossil fuels remain competitive due to their lower upfront costs [85,107].

In order to enhance the impact of carbon pricing in ORDCs, governments should implement policies that reinvest carbon revenues into renewable energy projects and incentivize innovation in low-carbon technologies, such as biomass co-firing and hybrid systems. Additionally, the stability and predictability of carbon pricing must be ensured, as long-term price signals are crucial for encouraging investments in emerging technologies [108,109]. Policies should also account for the synergies between carbon pricing and other regulatory measures, such as renewable energy targets, to amplify the overall impact on the energy transition [67,96].

3.4.2. Regulatory Innovation: Creating Incentives for Hybrid Thermal Systems

Regulatory frameworks need to be innovative and flexible to create incentives for deploying hybrid thermal systems that combine traditional thermal power with renewable energy sources. In countries like Japan, tax incentives and subsidies have successfully encouraged the integration of hydrogen into combined-cycle gas turbines (CCGTs), making these systems more attractive by reducing the financial burden of initial investments [110]. Similarly, Australia's regulatory environment has been adapted to support solar thermal integration with coal-fired power plants, providing a smoother transition to low-carbon energy without compromising grid stability [105,111].

In ORDCs, regulatory frameworks should be designed to promote hybrid systems by offering financial incentives, such as feed-in tariffs or renewable portfolio standards (RPS), specifically for hybrid thermal systems. Moreover, regulatory support for research and development (R&D) in hybrid technologies is essential to drive down costs and foster technological innovations. Collaboration between government agencies, private stakeholders, and research institutions is critical to creating a regulatory environment that facilitates technological advancement and promotes the widespread adoption of hybrid thermal systems [105,108].

3.4.3. Evaluating the Effectiveness of Renewable Portfolio Standards in Promoting Low-Carbon Thermal Technologies

Renewable portfolio standards (RPSs) have played a key role in promoting adopting renewable energy technologies, but their effectiveness in supporting low-carbon thermal generation varies by region. In the U.S., states with aggressive RPS mandates have successfully integrated biomass and geothermal technologies into their thermal power sectors, contributing to significant emissions reductions and greater energy diversity [112–115]. However, the success of RPS in promoting low-carbon thermal technologies depends on factors such as the availability of renewable resources and the financial incentives provided to utilities [67,116].

For ORDCs, designing RPS policies that reflect the local energy context is crucial. This may include additional incentives for technologies like biomass co-firing or geothermal hybrid systems, which can be integrated into existing thermal infrastructure. In regions where renewable resources are limited, complementary policies, such as grid modernization and energy storage incentives, should be implemented to ensure the effective integration of low-carbon technologies [85,117]. A comprehensive regulatory approach that includes RPS as well as grid and storage enhancements will maximize the potential of low-carbon thermal technologies in ORDCs [105].

3.4.4. Future-Proofing Regulations: Adapting Policies for Emerging Low-Carbon Technologies

As low-carbon technologies evolve, regulatory frameworks must remain flexible and adaptable to ensure that outdated policies do not hinder innovations. The rapid development of hydrogen and advanced energy storage solutions requires new regulations that accommodate these technologies, such as those being implemented in Europe to support the commercialization of hydrogen [105,118]. In particular, policies that facilitate the integration of hydrogen into existing natural gas infrastructures are essential for scaling up hydrogen adoption in thermal generation.

Additionally, the rise of decentralized energy systems, supported by renewables and energy storage, calls for grid regulations that allow for greater flexibility and the integration of distributed energy resources (DERs) [74,106]. Future-proofing regulations also involve addressing the social and environmental impacts of deploying new technologies. Policy-makers must ensure that new regulations contribute to sustainable development goals (SDGs) and avoid exacerbating social inequalities. Instruments such as dynamic pricing and real-time grid management tools can be introduced to improve grid reliability while supporting the transition to low-carbon energy systems [85,119]. By proactively adapting

regulations to emerging technologies, ORDCs can create an environment for low-carbon innovations, accelerating the transition to sustainable and resilient energy systems [101].

3.4.5. Economic Considerations for Future-Proofing Regulations in Emerging Low-Carbon Technologies

The economic impact of regulatory frameworks, particularly concerning carbon pricing mechanisms and subsidies for low-carbon technologies, cannot be ignored. The introduction of carbon taxes or cap-and-trade systems, while effectively reducing emissions, places an additional financial burden on industries and governments in ORDCs [105,106]. In regions with weaker economies, these costs may hinder the adoption of low-carbon technologies as industries struggle to remain competitive while complying with environmental regulations.

For instance, carbon pricing mechanisms such as the EU Emissions Trading System (EU ETS) have been instrumental in driving the adoption of clean technologies in Europe by making carbon-intensive energy production less economically viable [105,106]. However, in ORDCs, where economies largely depend on fossil fuel exports, implementing similar systems could be prohibitive without external financial support or significant reforms to mitigate the financial impact on domestic industries [107,108].

Furthermore, the reinvestment of carbon revenues into clean energy projects, as seen in Scandinavian countries, offers a model for how ORDCs could balance the economic impact of carbon pricing with the promotion of low-carbon technologies [74]. In these cases, carbon tax revenues have been used to subsidize renewable energy initiatives, reducing the overall financial burden on governments and encouraging investment in cleaner technologies [108]. For ORDCs, implementing such a reinvestment strategy could provide a dual benefit of reducing emissions while supporting the clean energy sector's growth. Regulatory innovation is also necessary to reduce economic barriers. In countries like Japan and Australia, hybrid thermal systems have been incentivized through tax breaks, feed-in tariffs, and renewable portfolio standards (RPS), helping to offset the initial costs of transitioning from conventional to hybrid systems [105,110]. For ORDCs, similar economic incentives must be introduced to encourage the integration of renewable energy with traditional thermal generation. Financial assistance, particularly in subsidies or international funding, will enable this transition [111,112].

While low-carbon technologies reduce emissions, they also have environmental trade-offs. For example, hydrogen production can strain water resources, and battery manufacturing creates waste and pollution. Regulatory frameworks must address these risks by promoting sustainable practices, such as material recycling and responsible resource management. Future regulations should incorporate environmental safeguards and promote sustainable production practices to minimize the environmental impact of low-carbon technologies.

3.5. Technological Innovations and Trends

3.5.1. Digital Twins and Predictive Analytics in Thermal Power Plants

Digital twins and predictive analytics are transforming the operation and maintenance of thermal power plants by enabling real-time monitoring and simulation of plant processes. A digital twin is a virtual physical asset model, allowing operators to simulate performance under various conditions and optimize operational efficiency. This technology has proven particularly beneficial in nuclear power plants, where predictive analytics can help anticipate failures in critical components, allowing maintenance to be scheduled before issues arise. This proactive approach significantly reduces downtime and enhances the plant's overall efficiency [59,120].

Integrating digital twins with advanced predictive analytics tools also enables early anomaly detection in critical components, extending the lifespan of equipment and minimizing the risk of catastrophic failures [74,121]. Additionally, by optimizing fuel consumption through real-time simulations, these technologies contribute to lowering greenhouse gas

emissions by reducing waste and improving overall efficiency [70]. Despite their promise, adopting digital twins faces challenges, particularly in ORDCs, where high initial costs and a lack of digital infrastructure present significant barriers. To support adoption, governments should consider offering incentives for investments in digital infrastructure and training programs for technical personnel, enabling broader use of these innovations in thermal power plants [98].

3.5.2. The Rise of AI-Driven Energy Management Systems for Thermal Generation

Artificial intelligence (AI)-driven energy management systems are becoming increasingly important for optimizing thermal generation. These systems use machine learning algorithms to analyze large datasets from power plants, enabling real-time adjustments in fuel mix, load balancing, and demand forecasting. This precise control over energy production processes significantly improves fuel efficiency and cost savings [76,81].

AI-driven systems also play a critical role in integrating renewable energy sources with traditional thermal generation. By dynamically adjusting power outputs based on renewable energy availability, these systems ensure a stable and reliable power supply while minimizing reliance on fossil fuels. This is particularly important as thermal plants increasingly operate alongside intermittent renewable energy sources like solar and wind [91,122]. AI technologies can also respond rapidly to fluctuations in operational conditions, making them highly flexible and adaptive to the complex needs of modern power systems [70,123]. As AI technology advances, its role in enhancing the efficiency, sustainability, and resilience of thermal generation will likely expand, further supporting global efforts to decarbonize energy systems [124]. For ORDCs, adopting AI in thermal generation offers a path to more efficient and sustainable energy production, and governments should promote its deployment through policy measures such as grants for AI research and tax incentives for energy utilities investing in AI technologies.

3.5.3. Advanced Materials for Enhanced Thermal Efficiency

The development of advanced materials has been instrumental in improving the thermal efficiency of power generation systems. High-temperature ceramics, advanced coatings, and superalloys have been particularly impactful in enhancing the durability and performance of turbines and boilers, which are exposed to extreme temperatures and pressures in thermal power plants. These materials increase the efficiency of thermal processes and extend the lifespan of critical components, reducing maintenance costs and improving overall plant reliability [43,110].

Superalloys, in particular, allow gas turbines to operate at higher temperatures and pressures, thereby improving combustion efficiency and reducing fuel consumption [99]. Additionally, advanced thermal insulation materials are being used to minimize heat loss in various parts of thermal power plants, further enhancing the overall efficiency of these systems [109]. Continued innovation in material science will play a critical role in the future of thermal power generation, enabling plants to operate at higher efficiencies with lower emissions. Governments and industries in ORDCs should prioritize adopting advanced materials to extend the lifespan of existing thermal assets and reduce the environmental impact of power generation.

3.5.4. Trends in Modular Thermal Generation Units for Decentralized Energy Systems

The trend toward modular thermal generation units is gaining traction, especially in decentralized energy systems where flexibility and scalability are critical. Unlike traditional large-scale power plants, modular units are smaller, more adaptable, and can be deployed faster, making them an ideal solution for remote or off-grid regions that lack extensive grid infrastructure [76,81]. These modular units provide reliable power with lower upfront capital investment and can be scaled up or down based on demand.

In addition to their flexibility, modular thermal units can be integrated with renewable energy sources, creating hybrid systems that combine thermal power's reliability with re-

newables' sustainability [110,120]. This is particularly valuable in regions with intermittent energy needs or where grid expansion is not economically feasible. By combining thermal generation with renewable sources, these hybrid systems can ensure continuous power supply while minimizing emissions and reducing dependency on fossil fuels [109,121]. As the energy landscape continues to evolve, modular thermal generation units are expected to play a significant role in transitioning to more resilient and sustainable energy systems. Their adaptability makes them an attractive option for ORDCs and other regions seeking to enhance energy access and security without sacrificing environmental sustainability [74].

3.5.5. Financial Viability of Modular Thermal Generation Units in Decentralized Energy Systems

Implementing low-carbon technologies, such as digital twins, AI-driven energy management systems, and advanced materials, presents both economic opportunities and challenges for ORDCs. While these technologies offer substantial long-term benefits regarding efficiency gains, reduced emissions, and lower operational costs, their adoption often requires significant upfront capital investments [76,99].

For example, digital twins and predictive analytics require the installation of advanced monitoring systems and ongoing costs related to data analysis and system integration [59,120]. For many ORDCs, where digital infrastructure is still developing, these costs can be prohibitive, and the economic viability of implementing such technologies depends on the availability of international funding or private sector investment [98,121]. Governments must consider offering tax incentives or subsidies to lower these barriers and make adopting digital solutions more economically feasible [74]. Similarly, AI-driven energy management systems present significant cost-saving opportunities by optimizing fuel usage, balancing loads, and facilitating the integration of renewable energy sources [76,91]. However, the initial investment required to install and maintain these systems and the need for technical expertise remains a major economic hurdle for many ORDCs [123]. In these cases, economic incentives such as grants for AI research and development (R&D) could support these innovations' technological advancement and financial feasibility [124].

The development and deployment of advanced materials, such as high-temperature ceramics and superalloys, also face significant economic constraints due to their high production costs and the complexity of integrating these materials into existing power infrastructure [43]. Despite their potential to enhance thermal efficiency and reduce fuel consumption, the financial burden of implementing such materials may deter their widespread use in ORDCs without substantial economic support from government programs or international funding sources [110]. The challenge for modular thermal generation units lies in the high initial capital costs associated with building smaller, decentralized energy systems. While modular units offer flexibility and can be integrated with renewable energy sources, their economic viability depends on the availability of subsidies and financing mechanisms to support their deployment in remote or off-grid regions [110,120]. Regulatory reforms that incentivize the deployment of modular systems through subsidies and support for public-private partnerships could play a crucial role in overcoming these financial barriers [109,124].

Modular thermal units offer environmental benefits by reducing emissions and minimizing land disruption. Socially, they empower communities by improving energy access in remote areas, fostering local resilience and independence from centralized energy systems. Incentives should be provided for community-based modular systems, particularly in underserved regions, while ensuring their deployment aligns with environmental protection goals.

The following Table 4 presents a detailed summary of the main challenges, opportunities, and policy recommendations based on the discussions in the previous sections. It synthesizes the insights gained from analyzing low-carbon technologies for thermal generation, including integrating digital twins, AI-driven energy management systems, advanced materials, and modular thermal generation units, as addressed in earlier sections.

Table 4 highlights the specific barriers to adopting these technologies in ORDCs, such as high upfront costs, infrastructure limitations, and regulatory hurdles. It also presents the opportunities these technologies offer, such as improving energy efficiency, reducing emissions, and integrating renewable energy sources. The policy recommendations then focus on viable strategies to overcome these barriers, including financial incentives, regulatory reforms, and the promotion of research and development (R&D). These recommendations aim to accelerate the implementation of low-carbon technologies and foster a sustainable energy transition in ORDCs.

Table 4. Summary of Challenges, Opportunities, and Policy Recommendations in Low-Carbon Thermal Generation Technologies.

Low-Carbon Technology	Challenges	Opportunities	Policy Recommendations	References
Biomass Co-firing	High upfront costs, emissions control, infrastructure retrofitting	Utilizes agricultural waste, reduces fossil fuel dependence	Subsidies for retrofitting existing infrastructure; incentives for agricultural waste management	[57,60,61,71–73]
Hydrogen for Gas Turbines	Requires infrastructure expansion, expensive hydrogen storage	Zero direct CO ₂ emissions, decarbonizes high energy industries	Investments in hydrogen infrastructure and storage technologies, support for R&D	[62,74–81]
Geothermal Hybrid Systems	High capital cost, site-specific resource dependency	Stable base load power, suitable for resource-rich regions	Geothermal exploration grants, financial incentives for infrastructure development	[55,57,64,65,68,81–85]
Thermal Energy Storage (TES)	High implementation costs, integration challenges with renewables	Enhances flexibility, supports renewable energy integration	Policies promoting energy storage systems, tax breaks for TES projects	[55,63,86–93]
Modular Thermal Generation Units	High initial capital investment, rural deployment challenges	Suitable for decentralized and off-grid areas, flexible	Support for decentralized systems, public-private partnerships, rural energy development programs	[74,76,81,91,109,110, 120,121]
Digital Twins and Predictive Analytics	High cost of digital infrastructure, requires technical expertise	Improves operational efficiency, reduces emissions	Grants for digital infrastructure in power plants, incentives for AI, and predictive analytics	[59,70,74,120,121]
AI-Driven Energy Management	Expensive implementation, need for technical expertise	Optimizes energy generation and integration with renewables	Research grants for AI-driven energy management systems, subsidies for implementation	[70,76,81,91,122,123]
Advanced Materials for Thermal Efficiency	High production costs, complex integration with existing systems	Enhances efficiency, reduces emissions, and extends equipment lifespan	Financial support for adopting advanced materials, R&D tax credits	[43,74,99,109,110]

3.5.6. Barriers to Investment in Low-Carbon Thermal Technologies in ORDCs

Based on the reported literature review findings, despite the potential of low-carbon thermal technologies to support a sustainable energy transition in ORDCs, significant challenges impede large-scale investment in these technologies. These barriers vary considerably across different socio-economic and political contexts. In higher-income ORDCs, such as Russia, Qatar, and Kazakhstan, the wealth generated from oil and gas has created economies deeply dependent on fossil fuel exports, shifting towards low-carbon alternatives politically and economically challenging. For instance, the fossil fuel industry in

Russia is central to economic stability and energy security. While there is growing interest in hydrogen and carbon capture technologies, investments in renewables remain slow, largely due to the political influence of the oil and gas sectors.

Similarly, Qatar and Kazakhstan rely heavily on fossil fuel revenues, which account for a substantial portion of government income. Although Qatar has initiated renewable energy projects, such as solar and carbon capture, the country remains reluctant to divest from its highly profitable natural gas industry, inhibiting large-scale investments in cleaner technologies. In these nations, the entrenched political power of fossil fuel industries, coupled with concerns that transitioning to low-carbon technologies could negatively impact economic growth, has resulted in a lower priority being placed on cleaner energy investments.

The situation is more complex in middle-income ORDCs like Brazil, Mexico, Malaysia, and Colombia. While these countries have taken significant steps toward integrating renewable energy into their energy mix, they still face substantial economic and political barriers. Brazil, for example, has made notable progress in bioenergy and geothermal projects through public-private partnerships. However, its sizable oil industry remains a dominant economic force, and political instability has delayed deeper commitments to low-carbon thermal technologies. Although it has explored geothermal and biofuels as part of its diversification strategy, Mexico has seen inconsistent energy policies due to political shifts, particularly under administrations prioritizing fossil fuels for national energy security. Malaysia's investments in solar and biomass are growing, yet the country continues to rely heavily on coal and natural gas, with government policies that favor traditional thermal power generation. Likewise, Colombia has shown interest in renewable sources like wind and solar, particularly in its northern regions. However, ongoing political and security challenges, coupled with the economic significance of the oil industry, limit the scale of investments in low-carbon technologies. Thus, despite the desire to invest in cleaner energy, the solid economic dependency on fossil fuels and political volatility present formidable challenges in scaling up low-carbon thermal solutions in these countries.

For lower-income ORDCs, such as Iran, Venezuela, Indonesia, and Ecuador, the barriers are even more pronounced. Iran and Venezuela, despite their vast oil reserves, face severe economic sanctions and political isolation, which restrict their access to international capital and technology necessary for renewable energy investments. Venezuela's oil infrastructure has collapsed amid political and economic crises, making investments in cleaner energy nearly impossible. Iran faces similar challenges, with its energy sector heavily focused on fossil fuels and domestic political constraints limiting the government's capacity to prioritize low-carbon technologies. Indonesia and Ecuador, while exploring renewable energy options like geothermal and hydropower, struggle with financial limitations that hinder large-scale adoption of low-carbon technologies. In Indonesia, fossil fuel subsidies and economic reliance on coal exports slow the transition to cleaner thermal systems, while Ecuador, despite making progress with hydropower, faces infrastructural and financial challenges that limit the expansion of low-carbon thermal technologies.

Finally, in evaluating the future of low-carbon thermal technologies for ORDCs, understanding the Compound Annual Growth Rate (CAGR) of these emerging energy solutions is essential for guiding investment decisions [125,126]. The biogas market, valued at USD 89 billion in 2023, is projected to grow at a CAGR of 4.2% from 2024 to 2032, signaling steady growth driven by the increased focus on utilizing agricultural and municipal waste to produce renewable energy [127]. Biofuels show significant potential globally, with notable regional differences: the Middle East and Africa are expected to see the highest growth in biofuels, with a CAGR of 9.6% between 2021 and 2030, while Europe and Latin America are forecast to grow at a more modest rate of 4% in the same period [128], reflecting varying government policies and economic incentives across these regions. Biomass co-firing technologies, critical for countries aiming to integrate renewable energy into existing thermal infrastructures, are projected to expand at a CAGR of 6.3% from 2024 to 2030 [129], highlighting the rising importance of decarbonizing power generation in nations such as India

and China. The hydrogen market, another key technology for decarbonizing industrial sectors, is poised to grow from USD 242.7 billion in 2023 to USD 410.6 billion by 2030, with a CAGR of 7.8% [130], driven by government investments in hydrogen-based economies and the increasing adoption of low-emission fuel sources. Geothermal energy, valued at USD 6.6 billion in 2021, is expected to reach USD 9.4 billion by 2027 with a CAGR of 5.9% [131], reflecting its rising appeal as a reliable baseload energy source, particularly for countries seeking to reduce dependence on intermittent solar and wind power. These growth trends underscore the importance of scaling investments in low-carbon thermal technologies to meet decarbonization goals and ensure energy security and economic stability in ORDCs. By leveraging the existing infrastructure and focusing on these technologies' consistent energy supply and cost-efficiency, ORDCs can attract long-term investments that promote sustainability and growth. Table 5 summarizes the CAGR of the identified low-carbon thermal generation technologies.

Table 5. CAGR of low-carbon thermal generation technologies.

Technology	Market Size (2023)	Projected Market Size	CAGR	Year Range
Biogas	USD 89 billion	N/A	4.2%	2024–2032
Biofuels	USD 110 billion (2021)	N/A	9.6% (Middle East and Africa), 4% (Europe and Latin America)	2021–2030
Biomass Co-firing	USD 133.97 billion	N/A	6.3%	2024–2030
Hydrogen	USD 242.7 billion	USD 410.6 billion	7.8%	2023–2030
Geothermal Energy	USD 6.6 billion	USD 9.4 billion	5.9%	2022–2027

4. Conclusions

This study provides a comprehensive systematic literature review of the feasible solutions for low-carbon thermal electricity generation and utilization in oil-rich developing countries. Using databases such as Scopus and Web of Science, 85 articles were carefully selected and analyzed, covering a wide range of technologies, including biomass co-firing, hydrogen fuel for gas turbines, geothermal hybrid systems, and advanced thermal energy storage.

The review highlights that oil-rich developing countries, such as Brazil, Russia, and Malaysia, are at the forefront of research and implementation of low-carbon technologies to reduce their reliance on fossil fuels and enhance their energy security. Brazil emerges as the most frequently studied country, integrating biomass into its energy matrix under the RenovaBio program and exploring hydrogen economy development. Russia follows with significant research focused on nuclear energy and flexible energy production systems, reflecting its strategy to balance fossil fuel reserves with low-carbon commitments. Malaysia is recognized for its efforts to balance industrial growth with sustainability by integrating solar and biomass resources. Other countries like Iran, Mexico, Qatar, Colombia, Indonesia, Venezuela, Kazakhstan, and Ecuador contribute to the global discourse on low-carbon energy, albeit somewhat. The review underscores the importance of regulatory frameworks and public-private partnerships in driving the adoption of these technologies, as evidenced by successful initiatives in the Middle East, Africa, and Latin America.

However, the study acknowledges limitations, such as focusing on a specific subset of countries and technologies, which may not fully capture the global diversity of low-carbon strategies. Additionally, the reliance on published literature may exclude emerging trends not yet documented in academic research. Nonetheless, the review highlights that while there is significant potential for low-carbon thermal technologies, economic dependency on fossil fuels, political challenges, and financial constraints often impede large-scale investments. Addressing these barriers will require tailored strategies and international cooperation to foster an enabling environment for the energy transition in these countries. Despite these limitations, the review aims to provide valuable insights into the current state and future directions of low-carbon thermal energy solutions in oil-rich developing countries, offering a foundation for further research and policy development in this critical area.

Finally, this research shows that the solutions identified in this study could also apply to countries highly dependent on other fossil fuels, such as natural gas and coal. These nations face similar challenges in transitioning to low-carbon energy systems, as their economies are tied to fossil fuel exploitation. The low-carbon technologies examined—such as biomass co-firing; hydrogen fuel for gas turbines; and geothermal hybrid systems—are viable for diversifying energy mixes and reducing fossil fuel dependence. These technologies offer pathways to decarbonize energy sectors without completely overhauling existing infrastructure, making them suitable for countries like Poland, Singapore, and Australia. Thus, this study's findings are relevant not only for ORDCs but also for countries with similar energy structures, providing a flexible framework for adopting low-carbon thermal technologies. Future research expanding the scope to these nations would be valuable in understanding how such solutions could be adapted to their specific contexts.

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Appendix A. PRISMA 2020 Flowchart of the Literature Review Process

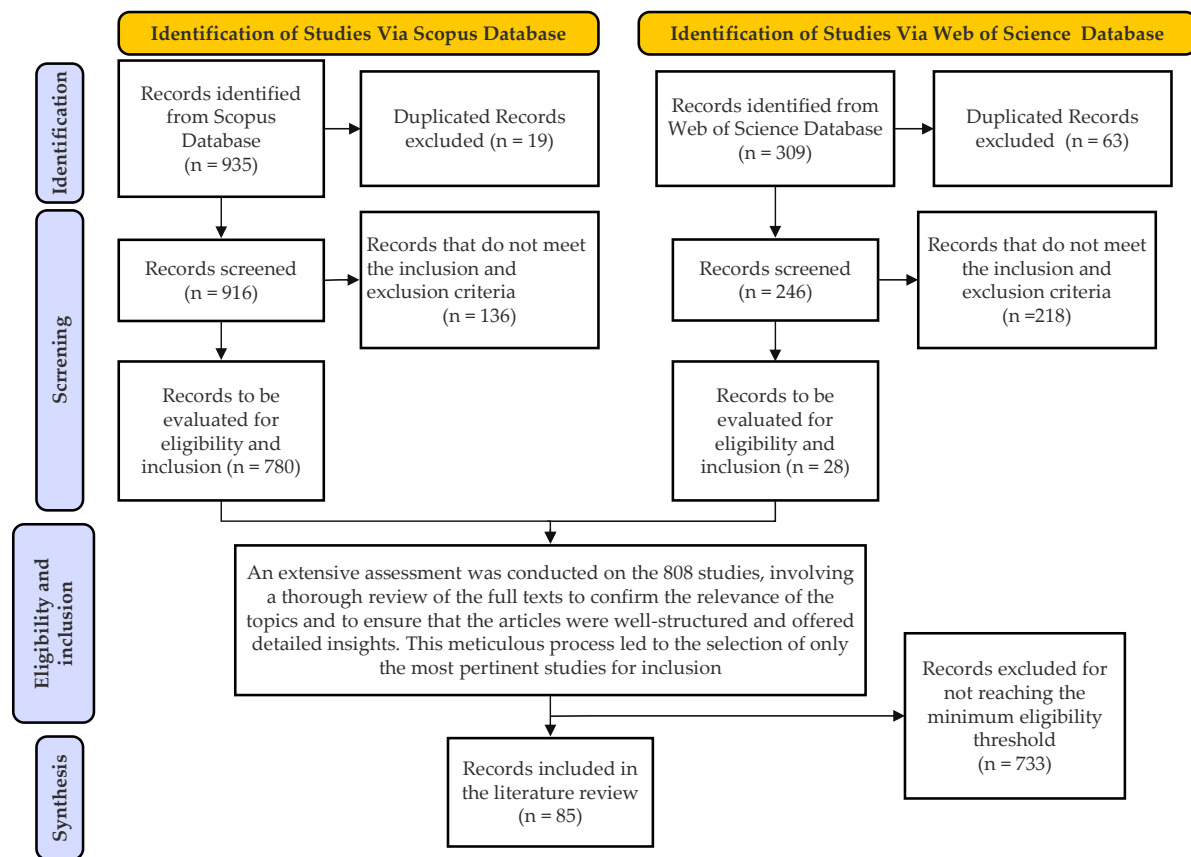


Figure A1. PRISMA 2020 Standardized Flowchart [52].

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