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Transitioning to clean energy and opportunities for developing countries

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A R T I C L E I N F O

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A B S T R A C T

The shift from fossil-based energy systems to renewable sources like solar, wind, and hydro presents both opportunities and challenges for developing countries aiming to expand energy access, promote economic growth, and meet climate goals. This study examines the technological, financial, institutional, and governance aspects of clean energy transitions, focusing on regional disparities and implications for low- and middle-income economies. A systematic review of literature was carried out using the SPAR-4-SLR methodology across Scopus, Web of Science, and Google Scholar. Only peer-reviewed studies published in English from 2009 to 2025 were included, guided by four research questions: (1) technological and resource endowments, (2) capital structuring and financial market dynamics, (3) institutional and policy frameworks, and (4) decentralized, digital energy governance. Search terms were tailored for each theme, and studies were classified by topic, region, and methodology. Results show that decentralized renewable systems—especially solar micro-grids—offer affordable alternatives to fossil fuels in rural and off-grid areas, enhancing job creation, energy security, and poverty reduction. Examples from Kenya, India, and Southeast Asia highlight the importance of policy consistency, financial innovation, and institutional preparedness in promoting clean energy deployment. Still, ongoing challenges such as high initial costs, infrastructure gaps, and limited technical skills continue to hinder progress in many regions.

1. Background of the analysis

For developing countries, transitioning to clean energy presents both structural challenges and opportunities influenced by geography, governance, and global finance [1,2]. While clean energy technologies—such as solar, wind, geothermal, and biomass—are becoming more accessible, the paths to adopting them remain uneven and contested [3,4]. This review was conducted to systematically analyze these different trajectories and the contextual factors affecting them across developing regions.

In areas like Sub-Saharan Africa and South Asia, the move toward clean energy interacts with long-standing issues like infrastructure gaps, policy uncertainty, and financial exclusion [5,6]. These regions need not only technical solutions but also frameworks that address equity, institutional capacity, and the social-political aspects of energy access [7,8]. While existing literature explores technological and financial factors, few reviews thoroughly examine how governance, financing, and decentralized energy models develop together in these contexts. This study aims to fill that gap. For example, Tanzania illustrates a broader set of challenges and opportunities faced by low- and middle-income countries in the global shift to renewables. Situated within the East African Rift Valley, Tanzania has significant potential for diverse clean energy projects [9,10]. Distributed solar technologies—mainly mini-grids and solar home systems—are emerging as practical alternatives to centralized grid infrastructure, especially in rural areas where electricity supply remains limited [11,12]. These decentralized systems enable households, schools, and health facilities to access electricity independently of the national grid, leading to measurable improvements in livelihoods and service delivery [13,14].

Clean energy deployment in developing countries is shaped by a complex interaction of technological potential, financial environments, and policy frameworks. Despite global declines in the levelized costs of

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renewable energy technologies, the financial systems needed to support their large-scale adoption remain uneven. Constraints on financing are not solely due to the availability of capital but are also influenced by the quality, maturity, and cost of that capital. Notably, higher interest rates in developing countries, mainly caused by increased political and economic risks, raise the weighted average cost of capital (WACC), limiting the feasibility of capital-intensive renewable energy projects [15–17].

Research shows that the costs of capital for technologies like solar PV, wind, and geothermal varies significantly across countries and tends to be higher in developing economies than in industrialized ones [15]. For example, in Tanzania, project financing is influenced by a shallow financial sector, limited risk mitigation options, and a lack of large-scale, patient capital [18,19]. These issues limit investor participation and slow the growth of renewable infrastructure. The problem is worsened by high transaction costs, weak credit enhancement mechanisms, and limited government guarantees—factors that discourage private-sector involvement and obstruct blended finance approaches. Public financial institutions and climate funds are trying to address these challenges by providing concessional capital, technical support, and policies that reduce risks. Multilateral organizations like the World Bank and African Development Bank have played crucial roles in mobilizing co-financing, while initiatives such as the Green Climate Fund and the Global Environment Facility have helped with project preparation and risk mitigation [20–22]. Glemarec [23] stresses that decentralized clean energy systems, like solar home systems or mini-grids, often need public support during early market stages to improve affordability, increase credit access, and overcome non-financial obstacles. While these efforts have had success in some situations, their overall coverage remains limited, and market failures continue to hinder the effective allocation and structuring of clean energy finance.

Beyond capital dynamics, clean energy transitions in low-income countries occur in contexts where grid infrastructure, urbanization patterns, and demographic structures differ significantly from those in industrialized nations. Babayomi et al. [24] argue that pathways to low-carbon energy must reflect the developmental needs of these economies, where industrialization, job creation, and energy access remain urgent priorities. Therefore, energy planning strategies must balance climate goals with socio-economic development, emphasizing local resources, existing technical skills, and cost-effective technology options.

Technological innovation and adaptive research play key roles in shaping renewable energy systems in such settings. Mini-grids, hybrid systems, and storage technologies are increasingly vital for off-grid electrification and local energy independence, especially where expanding the main grid is not cost-effective [25–27]. Multi-microgrid (MMG) systems and smart control technologies, as shown by Xu et al. [28], represent new models for decentralized resilience, particularly in urban and peri-urban areas. Advances in energy management, especially in hybrid microgrids that combine variable renewables and reformer-based fuel cells, present opportunities for a more stable and efficient power supply [29]. Additionally, integrating demand response programs and smart metering infrastructure helps optimize system performance and balance loads ([30]; Ogunmakinde et al., 2023).

A broader institutional perspective shows that technical feasibility alone does not ensure successful energy transitions. Governance structures, regulatory consistency, and policy credibility are key to attracting long-term investments and ensuring proper implementation. Abdmouleh et al. [31] highlight how enabling regulatory frameworks, supported by fiscal incentives, predictable licensing processes, and stakeholder coordination, are crucial for renewable energy deployment. Case studies, like those by Guild [32], demonstrate how different policy designs and political economy conditions affect outcomes even among countries using similar mechanisms like feed-in tariffs. Lessons from Russia's energy strategy further reveal the limits of models heavily dependent on fossil fuel exports and emphasize the need for a shift toward innovation-driven, renewable-focused policies [33]. Given these complex dynamics, clean energy transitions in developing countries are more than just technical or financial issues. They require managing social, institutional, and political pathways that shape how energy systems develop. As Buonomano et al. [34] and Cao et al. [35] suggest, understanding these pathways involves paying attention to embedded knowledge systems, policy interactions, and local decision-making structures.

This review synthesizes insights from the technical, financial, institutional, and governance aspects of clean energy transitions in developing countries, using contexts like Tanzania to derive lessons applicable to broader policy and implementation challenges across the Global South. Previous studies have documented the persistent influence of informal practices, misaligned incentives, and elite-driven coalitions that shape energy systems in ways that often marginalize renewable deployment pathways [36,37]. However, there is still limited integration of governance frameworks with decentralized energy models and community-led development priorities. Analyses of institutional coalitions show how the political settlement and embedded power relations influence whether non-hydro renewables gain momentum, especially when donor interests align practically with domestic regimes [37]. These findings echo concerns about how energy transitions can reinforce inequalities, such as through coerced consent in mineral extraction and displacement processes [38], and how sociotechnical systems often overlook procedural and distributive justice during design and implementation [39]. As Walker Wood et al. [40] argue, dominant economic-growth-focused climate scenarios risk limiting the scope for imagining equitable, sustainability-oriented pathways that address structural inequalities and degrowth options. The material and political aspects of energy infrastructure, especially amid geopolitical disruptions, further complicate these transitions [41]. Meanwhile, systematic reviews show that developing countries face disproportionate structural barriers across regulatory, financial, and technical areas, including limited human capital, policy incoherence, and high capital costs [42]. This review aims to bridge these multidimensional constraints by applying the SPAR-4-SLR method to analyze how decentralized renewable energy models, national political coalitions, and socio-ecological justice issues intersect in shaping energy pathways. The analysis also considers the evolving priorities outlined in IPCC reports and SDG 7 indicators, which call for energy transitions that emphasize equity, agency, and sustainable development in regions often excluded from global modeling frameworks [40].

The study is guided by the following research questions.

- RQ1: How have technological capabilities and natural resource availability shaped the historical development of clean energy systems in low- and middle-income countries from 2009 to 2025?
- RQ2: What financing instruments and capital flows have supported renewable energy deployment in selected developing regions, and how do variations in financial risk environments affect investment patterns?
- RQ3: How have national and regional policy frameworks influenced clean energy governance, and what institutional mechanisms have proven effective in supporting implementation?
- RQ4: What decentralized or community-driven energy models have emerged in the past decade, and what scenarios are plausible for their evolution through 2025 based on current trajectories?

The conceptual framework for transitioning to clean energy and the related opportunities for developing countries, shown in Fig. 1, describes the interconnected roles of institutional structures, financing mechanisms, technological innovation, and global cooperation. It highlights how these elements interact within larger socio-technical systems, guided by energy justice principles and informed by the multi-level perspective. This framework provides a basis for analyzing how developing countries can navigate and utilize the clean energy transition to achieve inclusive, resilient, and sustainable development

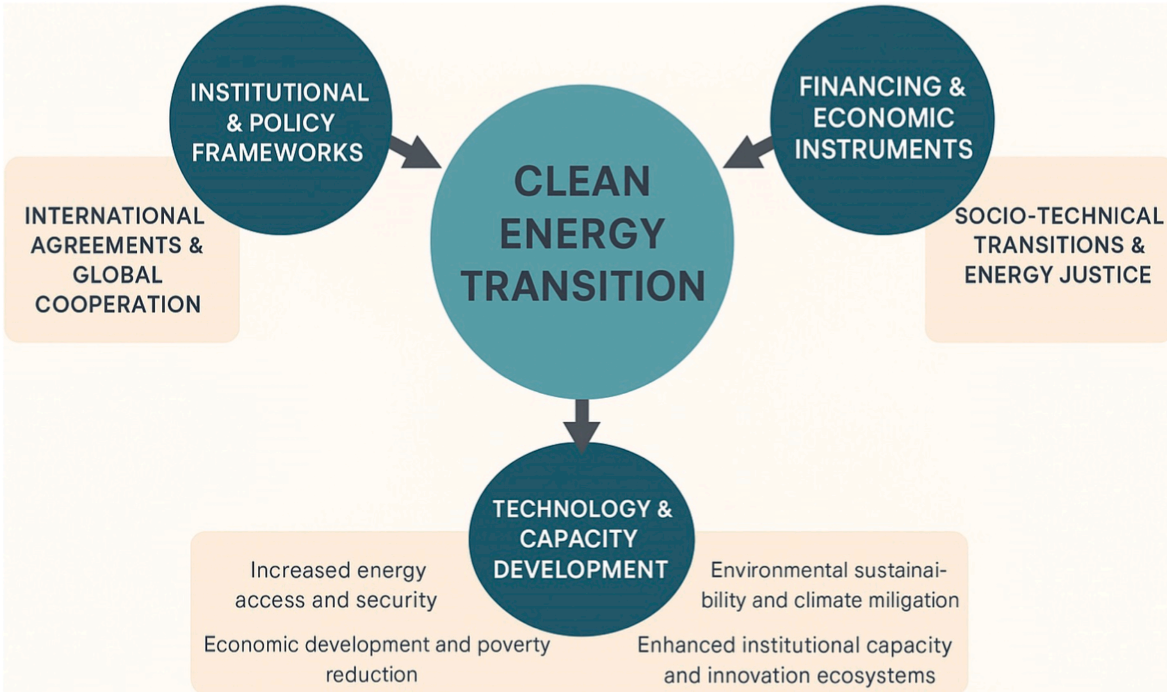

Fig. 1. Conceptual framework showing the shift to clean energy and related opportunities for developing countries. The diagram combines institutional and policy aspects, funding methods, technological options, and international collaboration. It also includes analytical views from energy justice and the multi-level perspective (MLP) to emphasize systemic, cross-scale interactions shaping energy transitions.

outcomes.

2. Methodology

This study adopts a structured literature review approach using the Scientific Procedures and Rationales for Systematic Literature Reviews (SPAR-4-SLR) framework, focusing on four research questions related to clean energy transitions. Searches were carried out across Scopus, Web of Science, and Google Scholar, limited to peer-reviewed journal articles, institutional reports, and empirical case studies in English published between 2009 and 2025, as also outlined by Ogunmakinde et al. [43].

2.1. Search strategy and syntax

Exact search strings were used to ensure transparency and replicability (see Appendix 1), including.

- **RQ1** (Technological and resource endowments):

("solar energy deployment' OR "wind energy infrastructure') AND ("Africa' OR "Asia")
("critical minerals' AND "clean energy') OR ("green hydrogen' AND "readiness")

- **RQ2** (Capital structuring and finance):

("green bonds' AND "clean energy') OR ("climate finance' AND "developing countries")
("Export Credit Agencies' OR "digital finance platforms') AND "renewable energy".

- **RQ3** (Policy and institutional frameworks):

("renewable energy governance') OR ("policy coherence' AND "energy transitions")
("inclusive access' AND "institutional design') OR ("bottom-up planning")

- **RQ4** (Digitalization and decentralized governance):

("blockchain energy trading') OR ("decentralized energy systems' AND "resilience")
("AI for microgrids') OR ("energy communities' AND "Southeast Asia").

2.2. Study selection process

The study selection followed a structured screening protocol summarized in a PRISMA flow diagram (see Fig. 2). After initial searches across databases—such as Scopus, Web of Science, and Google Scholar—the results were filtered and screened in multiple stages.

- **Scopus:** 1234 results → 211 after initial filters → 227 included
- **Web of Science:** 845 results → 188 after initial filters → 57 included
- **Google Scholar:** 310 results → 28 included after screening

After removing duplicates, inaccessible materials, editorials, and non-scholarly content, a total of 146 studies were retained for analysis. Additionally, 6 studies were included solely based on methodological criteria, bringing the overall total to 152 studies.

The Risk Of Bias In Systematic Reviews (ROBIS) tool was used to evaluate the risk of bias across all included studies, ensuring a consistent and transparent quality assessment [44]. Gray literature was excluded to maintain focus on peer-reviewed academic and institutional sources. To reduce potential selection bias, sources were selected from a wide range of geographic regions and institutional affiliations. Thematic triangulation was conducted using key analytical categories, including technological readiness (such as solar, wind, and hydrogen systems), financial mechanisms (including green bonds, export credits, and digital platforms), policy and governance frameworks (covering regulatory coherence and multilevel institutional design), decentralization and

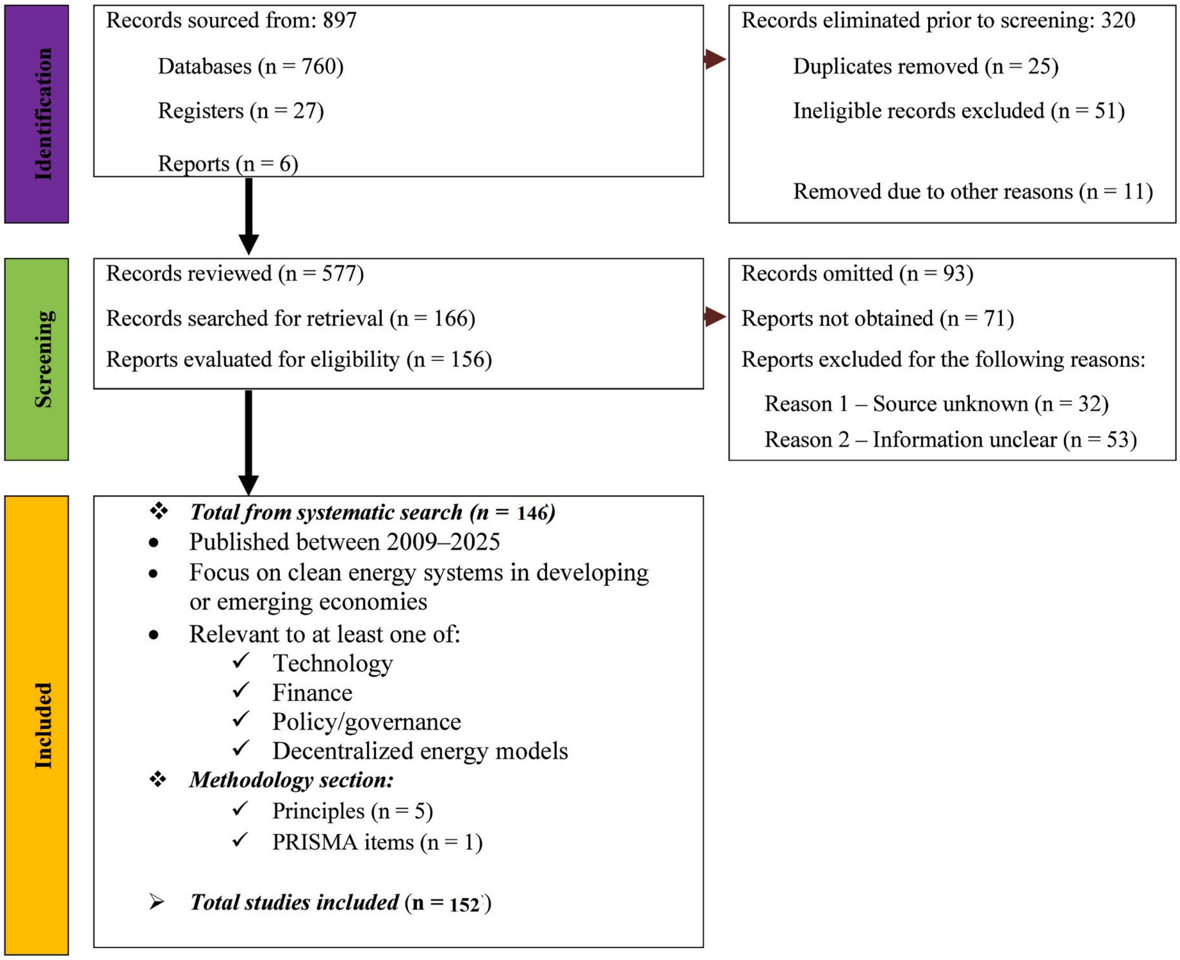

Fig. 2. The PRISMA flow diagram showing number of studies identified for eligibility in the presented study.

digital innovation (such as blockchain applications, AI-based optimization, and energy community initiatives), and social and regional equity (focusing on inclusivity, local ownership, and energy justice). These themes were used to cross-verify findings across the four research questions, ensuring conceptual consistency, regional diversity, and interdisciplinary depth in the review.

2.3. Coding and thematic analysis

All included studies were systematically coded based on thematic categories, regional focus, and disciplinary perspective. A preliminary coding framework was created through a pilot analysis of a selected sample of studies. This process helped identify key themes that aligned with the research questions and guided the organization of findings. To enhance coding reliability and minimize individual bias, two authors independently coded a subset of 100 studies. Inter-rater reliability was evaluated using Cohen's Kappa, which yielded a score of 0.70, indicating substantial agreement [46]. Any discrepancies were reviewed and resolved through discussion to ensure consistency in coding across the dataset.

Cross-referencing and thematic triangulation were applied to identify relationships among themes and across research questions. The final coding structure enabled the synthesis of findings across varying regional contexts and disciplinary perspectives. Further details on coding categories, thematic clustering, and cross-tabulation procedures are available in Supplementary Material File 1.

2.4. Quality assessment

A quality appraisal framework was included to evaluate the methodological strength and policy relevance of the selected studies. Scoring rubrics were adapted from established critical appraisal tools and customized to fit the interdisciplinary nature of the review. Each study was assessed across key areas, including clarity of research design, transparency of data sources, analytical rigour, and relevance to policy or practice in clean energy transitions. Scores were given on a standardized scale, enabling comparative evaluation and filtering of studies with limited reliability or applicability. The quality assessment process helped inform the weighting of findings and the interpretation of thematic patterns. Detailed scoring criteria and the distribution of quality ratings are available in Supplementary Material File 2.

2.5. Protocol registration

Although not originally preregistered, the methodological structure is retrospectively aligned with the International Prospective Register of Systematic Reviews (PROSPERO) and Open Science guidelines for systematic review protocols [47,48].

3. Findings and discussion

3.1. Trajectories and emerging scenarios in clean energy transitions

Understanding the evolution of clean energy systems involves tracing key institutional and technological developments while also recognizing how new models of decentralization, regional experimentation, and digital innovation are changing future pathways. This section draws on diverse disciplinary contributions to examine shifts in energy governance and highlights scenarios likely to influence transition trajectories across selected developing regions.

3.1.1. Historical milestones in clean energy policy and institutional change

(i) Pre-2010: Early implementation of CDM and structural limitations

The Clean Development Mechanism (CDM), established under the Kyoto Protocol, aimed to involve developing countries in international carbon markets through certified emission reduction (CER) credits [49]. It jump-started a multibillion-dollar global offset market and helped develop internationally recognized procedures and methodologies for reducing greenhouse gases (GHG) [50]. Early progress was mainly seen in countries like Brazil, India, and China, where stronger institutional frameworks and investment climates supported project development.

Meanwhile, the adoption of CDM in Sub-Saharan Africa remained limited, mainly due to high entry costs, complicated approval procedures, and fragmented institutional environments that hindered participation [51,52]. Weak regulatory oversight and limited technical capacity not only reduced the number of projects but also slowed the transfer of knowledge into national energy planning frameworks (Mok et al., 2011; [53]).

In sectors like construction and the built environment, there was potential for CDM projects, but they were underused due to barriers in planning, procurement, and operation, along with a general lack of awareness and guidance on implementation [54]. Furthermore, questions around justice within the CDM framework have gained attention, especially concerning distributive fairness. Many projects failed to provide equitable benefits across regions, exposing imbalances in how mitigation opportunities and development benefits were shared [55]. The early phase of the CDM helped establish climate mitigation efforts in developing countries, but its shortcomings highlighted the need for stronger governance, more inclusive participation, and better integration of sustainability and justice issues into carbon market mechanisms.

(ii) 2015–2020: Paris Agreement and the rise of NDC frameworks

The Paris Agreement established a global governance framework based on Nationally Determined Contributions (NDCs), allowing countries to express climate commitments aligned with their domestic priorities while contributing to worldwide mitigation goals [56]. Nations such as Morocco, Kenya, and Vietnam started including renewable energy targets within their national development policies, signaling a shift toward integrating climate and energy strategies [57,58]. Regional initiatives like the African Renewable Energy Initiative (AREI) played a role in coordinating national efforts and promoting sharing of technical expertise.

The introduction of the NDC approach brought new reporting requirements through the Enhanced Transparency Framework (ETF), designed to improve the monitoring of mitigation and adaptation actions [59,60]. These frameworks aim to motivate countries to enhance their climate efforts via regular reviews, although the success of this approach is still being evaluated [61]. Challenges such as data quality issues, varying timelines, and differing methodologies have complicated efforts to compare and compile national contributions, especially in sectors like Agriculture, Forest, and Other Land Uses (AFOLU), where many developing nations face capacity limitations [61].

Countries envisioned various roles for governments in executing NDCs, often as regulators, market facilitators, or enablers of low-carbon transition environments. These roles vary across regions and income levels but collectively emphasize the crucial role of public institutions in climate governance under the Paris Agreement [62]. Although the global stocktake process offers a route for coordinating and refining national commitments, uncertainties in emissions accounting standards and lack of transparency in implementation create doubt about whether current pledges will meet the long-term temperature targets [56,63]. While the initial wave of NDCs may not yet fully realize the Paris goals, their complete implementation would promote more equitable distribution of greenhouse gas emissions on a per capita basis over time, influencing future burden-sharing and fairness in global climate efforts [64]. This period also saw increased acknowledgment of the importance of transparency mechanisms, not only for accountability but also for fostering trust among nations and strengthening the legitimacy of climate governance structures [59,62]. Despite the development of new institutional commitments, issues related to funding gaps, donor influence, and ongoing dependence on fossil fuels remain deeply rooted, especially in lower-income countries where external funding patterns and domestic priorities continue to guide energy policies [65,66].

(iii) Post-2020: Pandemic disruptions and reconfiguration of energy priorities

The COVID-19 pandemic exposed structural weaknesses in energy systems and revealed bottlenecks in global supply chains, especially for clean energy technologies. Lockdowns disrupted manufacturing and logistics, causing delays in renewable energy deployment and unprecedented volatility in fossil fuel markets [67]. In response, governments rethought their energy priorities, updating policies to improve grid resilience, diversify energy sources, and localize generation capacity. These changes often aligned with economic recovery efforts aimed at stabilizing jobs and infrastructure. The pandemic also sparked increased interest in community-scale energy systems as a way to boost economic recovery and strengthen social ties, especially in areas underserved by centralized infrastructure [68,69]. Modular and decentralized energy models gained popularity as flexible solutions in humanitarian and crisis-prone settings, where energy access intersects with broader social protection goals.

Some countries used this disruption to explore ways to accelerate the transition to a low-carbon economy. Renewable energy became more visible as a cost-effective and reliable alternative, and global interest in green recovery strategies grew alongside declining fossil fuel consumption [70–72]. This was reflected in expanded green financing mechanisms, increased international cooperation, and the inclusion of energy transition goals in broader stimulus packages [67]. However, the pace of recovery varied greatly by region, depending on political commitment, resource availability, and institutional capacity [73]. Medium- and long-term changes emerged across sectors like electric mobility, energy generation, and transportation [74]. Recovery efforts affected both traditional and renewable energy sectors, changing consumption patterns and raising awareness about energy security and digital vulnerabilities. The increased reliance on remote operations and automated systems highlighted cybersecurity risks in increasingly digitalized infrastructures [75]. This shift underscored the need for integrated strategies that address both physical and digital resilience in energy systems.

3.1.2. Prospective scenarios shaping future energy transitions

(i) Digitalization and the rise of trustless energy trading

Digital infrastructure is transforming how decentralized systems operate and interact with national grids. AI-enabled microgrids enable more dynamic, responsive control over distributed energy resources, improving load forecasting, fault detection, and self-healing capabilities in local networks [215]. These technologies boost the operational resilience of off-grid and hybrid systems, especially in areas with unstable grid connectivity.

Blockchain-based platforms have created new opportunities for peer-to-peer energy trading by providing secure, transparent transaction records that do not depend on centralized authorities. These systems use smart contracts to automate settlements and direct energy flows between users [77,78]. In settings where public trust in utilities is limited or regulatory frameworks are still developing, distributed ledger technologies support new forms of energy governance. These mechanisms enable communities to set their own trading rules and verify transactions independently of traditional intermediaries. Pilot projects across East and Southeast Asia show how tokenized energy contracts are gaining popularity among households, cooperatives, and small businesses [79]. Participants engage in local energy exchanges, often backed by rooftop solar and small-scale storage, reducing dependence on external suppliers and boosting affordability. These setups create flexible markets where pricing and access are negotiated in real time, influenced by user preferences and actual energy availability.

Beyond trading, digital systems are being used for grid balancing, emissions tracking, and user engagement. Platforms that combine AI and blockchain are beginning to integrate data analytics for carbon accounting and adaptive tariff setting, supporting more participatory and transparent decision-making. As digital architectures evolve, their ability to foster local autonomy, reduce administrative hurdles, and align with decarbonization efforts is increasingly recognized across different regions.

(ii) Critical minerals, resource politics, and global asymmetries

The extraction, trade, and governance of critical minerals play a key role in shaping global energy transitions, especially as new geopolitical alignments form. The expansion of the BRICS+6 bloc and the creation of new economic alliances are changing the governance of critical mineral supply chains. These changes challenge the core assumptions of the rules-based international trading system, where Western institutions once dominated but now face a multipolar trade landscape [80]. Strategic minerals like cobalt, lithium, and nickel are no longer just commodities; they are tools of statecraft in a broader contest for industrial advantage and national security.

Efforts to boost domestic value addition in resource-rich countries reflect a wider political and economic shift [81]. Instead of merely exporting raw materials, countries such as the Democratic Republic of the Congo are developing midstream and downstream capabilities like battery precursor production [82]. This shift remains limited by inadequate infrastructure, lingering postcolonial dynamics, and global competition for investment, but it indicates a move toward more active roles in the low-carbon economy [82]. Similar patterns are seen across other mineral-rich regions where local actors aim to transition from extractive dependence to manufacturing and processing.

The logistics of mineral transport worldwide are also changing. Maritime routes for critical mineral trade are increasingly seen through a geopolitical lens, where competition over strategic chokepoints and shipping corridors adds volatility to supply security. Tensions influence the scope and safety of maritime infrastructure, as states vie for control over emerging shipping lanes and key logistics hubs [83]. These trends are worsened by climate change and deglobalization, which pose new challenges to mineral flow stability and global trade resilience. Decarbonization efforts in the mining and refining sectors further complicate these issues. Companies producing lithium, nickel, and cobalt are adopting strategies like onsite renewable energy, energy-efficient equipment, and electric vehicles within their operations [84,85]. Despite these efforts, supply chain emissions remain largely unaddressed, and most firms lack comprehensive Scope 3 inventories or fully integrated low-carbon technologies throughout their production cycles [86]. External pressures from regulations, investor scrutiny, and technological advancements will influence the future of these efforts [87].

Meanwhile, attention is increasing on how to manage end-of-life materials from energy transition technologies. China's battery recycling industry illustrates both the potential and limits of circular approaches. While China has built an extensive recycling network, dominance by low-capital enterprises, fragmented supply chains, and weak enforcement limit the sector's effectiveness. Policy evolution has gone through phases of testing, institutionalization, and restructuring, but key barriers like overcapacity, unclear stakeholder roles, and uneven regional development persist. Emerging economies can learn valuable lessons from these experiences for their own pursuit of sustainable resource recovery [88]. In places like Tanzania, political strategies around resource control interact with foreign investment, often causing friction in developing renewable energy infrastructure [89]. External actors in technology and capital investment create asymmetries that influence how resource sovereignty is expressed in national energy planning. These dynamics reflect ongoing struggles over ownership, benefit sharing, and developmental priorities in the energy transition [90]. Overall, these points to future where critical minerals serve both as enablers of new technologies and as instruments of geopolitical influence. Shifting power relations, trade realignments, and national resource governance strategies will likely remain key factors shaping energy transitions across regions and institutions.

(iii) Climate migration and off-grid system resilience

Shifting climate conditions are driving forced displacement in regions like the Sahel, Horn of Africa, and coastal South Asia. This creates new demands on energy supply models for refugee settlements, disaster-prone areas, and transitional communities. Energy systems in these situations increasingly focus on modularity, portability, and resilience rather than cost efficiency. Solutions such as solar-battery microkits, hybrid PV-diesel systems, and mobile energy pods are being tested for their ability to provide essential services during emergencies [215]. The integration of energy planning into humanitarian responses is expanding from basic lighting to include communication, cooling, and mobility support.

(iv) Institutional hybridity and community co-governance

Governance arrangements supporting energy transitions are becoming increasingly diverse, shaped by the interaction of national frameworks and community-level action. In countries such as Nigeria, Ecuador, and Pacific Island nations, hybrid institutional forms are emerging that balance formal regulation with participatory mechanisms and localized oversight [69]. These arrangements often include collaborative platforms that allow for shared responsibilities across government, civil society, and community actors, enabling more responsive and adaptive energy governance. Such hybrid configurations are not uniform; their success often depends on context-specific factors such as political culture, institutional capacity, and social trust. Caggiano et al. [91] highlight the importance of behavioural and relational dimensions in decentralized systems, emphasizing the role of trust-building, equity considerations, and user satisfaction in sustaining energy initiatives. When embedded into governance design, these social factors help align energy systems with local values and preferences while supporting transparent decision-making.

Participatory processes are increasingly viewed as essential to ensuring that energy transitions reflect democratic norms and diverse interests. Radtke and Renn [92] propose a mediative governance model that combines top-down coordination with bottom-up engagement. Their comparative framework, drawn from five democratic policy styles, suggests that no single mode of governance can fully address the complexity of energy transitions. Instead, a mix of inclusive and reflexive strategies is necessary to ensure legitimacy, actor collaboration, and long-term adaptability.

In contexts marked by institutional fragmentation or political constraints, such as Palestine, horizontal coordination among multiple actors has played a key role in advancing renewable energy deployment. Khaldi et al. [93] identify a transition management approach that operates at strategic, tactical, and operational levels, enabling the mobilization of diverse institutions and supporting localized experimentation. Their findings show that governance networks—rather than top-down policies alone—are vital in expanding renewable energy access under conditions of uncertainty and resource scarcity.

On a broader scale, energy infrastructure development intersects with questions of land use, social identity, and environmental justice. Sareen [94] explores these intersections using political ecology and urban studies, among other fields, to examine how decisions about infrastructure siting and access reflect—and sometimes reproduce—existing socio-spatial inequalities. This framing emphasizes the need for energy governance models that are both procedurally fair and attentive to distributive outcomes across multiple levels. In the MENA region, countries such as Morocco, Egypt, and Oman demonstrate diverse pathways shaped by national economic structures and institutional arrangements. Michailidis et al. [58] analyze how political stability, regulatory quality, and targeted investment in renewable infrastructure contribute to progress in each country. Morocco's model of energy leadership, based on coordinated investments and policy coherence, shows the potential of integrated governance to advance low-carbon transitions. Meanwhile, Egypt and Oman face constraints linked to environmental pressures and fossil fuel reliance, where hybrid strategies connecting central planning with decentralized innovation may help overcome structural barriers. These examples illustrate the evolving landscape of energy governance, where institutional hybridity enables more responsive, inclusive, and adaptive pathways. Community co-governance, when supported by conducive policy environments, can facilitate energy access, strengthen system resilience, and reflect a diversity of social values and priorities.

3.2. Technological and resource endowments for clean energy deployment

Clean energy deployment varies greatly across different regions due to the interaction between geographic resource availability and technological readiness (see Fig. 3). Renewable technologies, especially solar, wind, and hydro power, tend to cluster in areas where environmental conditions make cost-effective generation possible. For example, high solar irradiance in the Middle East and North Africa, strong wind corridors in the North Sea and U.S. Great Plains, and large river systems in countries like Brazil, Canada, and China illustrate this pattern [95–98]. Conversely, traditional energy systems are still rooted in fossil-fuel-rich regions such as Russia, Venezuela, and India [99,100].

Hydrogen energy provides a complementary pathway within the broader renewable energy framework. Pal et al. [101] emphasize increasing investment in hydrogen R&D among the QUAD nations, with applications aimed at decarbonizing sectors that are difficult to electrify. However, large-scale deployment—especially in regions lacking industrial R&D infrastructure—faces challenges related to cost, transportation, and storage logistics. In the context of BRICS and the US, Kakran et al. [102] reveal differing national strategies, with China leading in production and the US focusing on green hydrogen at a project scale. These efforts remain mostly quantitative, with broader institutional integration still underway.

The link between innovation and renewable adoption is further supported by Han et al. [103], who establish a measurable relationship between innovation rates and renewable energy use within the G20. This evidence highlights the importance of innovation ecosystems in shaping deployment pathways. Policy coordination and investment in technological systems are crucial for building capacity, especially in countries striving to cut carbon intensity through targeted solar strategies [104].

Materials are an often overlooked factor influencing the scalability of renewables. Guo et al. [105] and others [106,107] point out that metals such as copper, aluminum, and nickel form the backbone of clean energy hardware. National decarbonization strategies, like those pursued by China [108,109], increasingly treat mineral access as a key planning component. These findings highlight the need for policies focused on resource management to address upstream supply challenges. In regions such as ECOWAS, renewable deployment directly connects with broader development goals. Mohsin et al. [110] show that, when combined with targeted R&D, expanding clean energy can generate significant economic benefits. However, low energy efficiency across the bloc reflects ongoing infrastructural and policy fragmentation. Coordinated innovation frameworks tailored to local institutions will be key to achieving

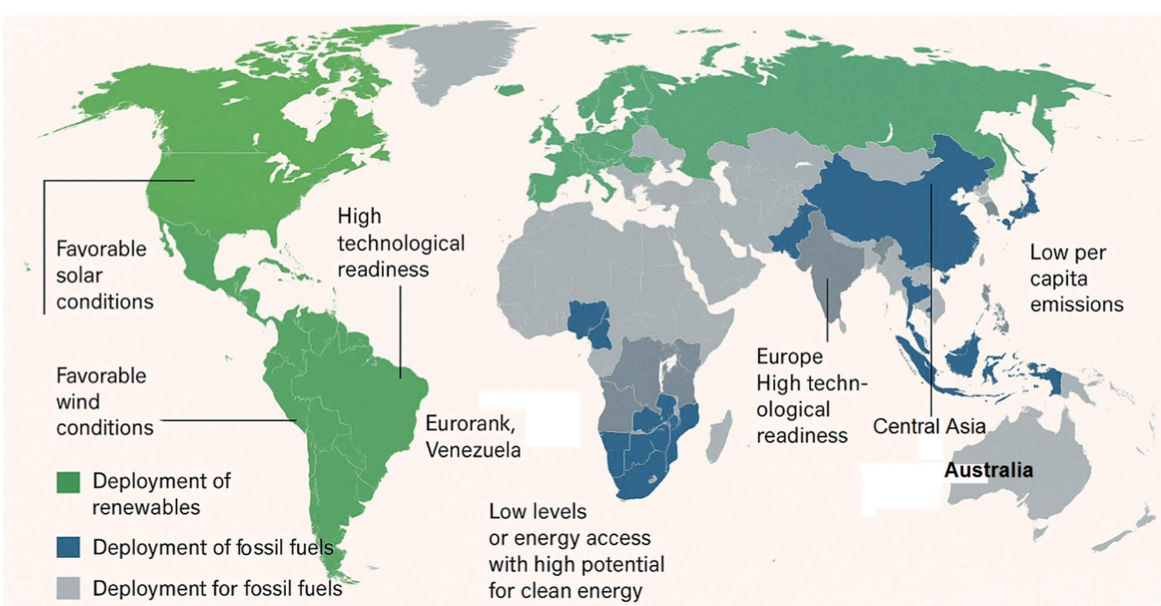

Fig. 3. Geographic distribution of renewable energy potential and technological readiness across regions. Notes: The map illustrates spatial patterns of clean energy deployment driven by natural resource endowments and technological infrastructure. High solar irradiance in North Africa and the Middle East, wind corridors in Northern Europe and North America, and hydro-rich regions in South America, Canada, and China mark key zones of renewable generation. It also highlights contrasts between regions with strong innovation ecosystems—such as East Asia and Scandinavia—and those where favourable environmental conditions remain underutilized due to limited grid capacity, technical expertise, or infrastructure, such as parts of Sub-Saharan Africa and South Asia.

energy and development synergies.

There is a reciprocal relationship between renewable energy investment (REI) and technological innovation. Zhao et al. [111] find that while REI can stimulate innovation within renewables, it may also divert resources from broader technological progress. These reciprocal effects indicate the importance of balanced strategies that support clean energy growth without hindering foundational innovation efforts. The overall review confirms that energy transitions depend not only on resource availability but also on the alignment of technological, economic, and institutional systems.

3.3. Capital structuring and financial market dynamics in clean energy transition

Capital structuring decisions critically influence the financial viability and scalability of renewable energy systems. A prevailing trend across energy sectors involves the dominance of debt-based financing, particularly project finance, over equity participation. This is exemplified in Spain's renewable sector, where long-term debt is preferred to align financial flows with extended project timelines and defined risk profiles [112]. While this alignment facilitates investment continuity, it also introduces limitations regarding financial adaptability and long-term resilience. The underuse of equity financing and retained earnings in clean energy investments suggests an imbalance that could affect project sustainability under volatile market conditions. Fiscal incentives and regulatory consistency have been identified as key enablers for diversifying capital structures and mitigating refinancing vulnerabilities [112].

Capital markets increasingly serve as conduits for climate-aligned investments. Instruments such as green bonds not only align environmental objectives with investor expectations but also generate structured income streams [113]. In parallel, financial innovations—including blockchain and digital finance—are reshaping the distribution and monitoring of capital across renewable energy supply chains. In China, digital finance has contributed to clean energy adoption by linking financial flows with industrial policy and infrastructure coordination [114]. Similar mechanisms in rural settings have supported decentralized energy deployment, reinforcing the relationship between financial access and localized energy security [115]. These platforms enhance transparency, which may increase investor confidence; yet, their institutional effectiveness remains uneven across regions.

An integrated assessment of clean energy financing necessitates attention to both structural systems and ethical dimensions. While Long et al. [116] outline a six-pronged framework encompassing financing instruments and institutional readiness, embedding this model within broader socio-technical and justice-centred perspectives enhances its explanatory value. The multi-level perspective (MLP), as discussed by Geels [117] and further conceptualized by Kanger [118], situates financing within dynamic interactions across niche innovations, regime practices, and landscape pressures, highlighting the temporal and systemic nature of energy transitions. These transitions are not purely financial or technological but also involve distributional effects, procedural fairness, and recognition of diverse stakeholder needs. Sovacool and Dworkin [119] and Correljé [120] emphasize that justice frameworks—attuned to ethics, capability, and institutional legitimacy—inform the design of financing tools that are equitable and context-sensitive. As such, effective financing strategies must accommodate both systemic transformation pathways and differentiated socio-economic realities across regions.

Public financial institutions, particularly Export Credit Agencies (ECAs), have adjusted their investment portfolios to include more renewable projects; however, fossil fuel funding persists in part due to policy inertia and national strategic interests [121]. These dynamics reflect the dual mandates ECAs often navigate—balancing commercial viability with environmental commitments. Despite new alliances such as the E3F seeking to reorient export finance toward low-carbon priorities, asymmetries in access to such funding continue to shape the energy transition landscape, particularly in lower-income countries. Institutional realignment and mandate revision may be necessary for ECAs to function as consistent agents of energy transformation.

In Sub-Saharan Africa, the interaction between financial development and resource endowments presents a nuanced picture. Osman et al. [122] observe that resource wealth does not preclude renewable energy adoption when supported by well-structured financial systems and coordinated policy efforts. Financial development in this context becomes an enabling factor rather than a constraint. Similarly, Achuo et al. [123] highlight the conditional impact of human capital, noting that its influence on energy outcomes strengthens when embedded within broader financial and institutional ecosystems. These findings point to the interdependence of capital structuring with national developmental baselines and governance quality.

The effectiveness of climate finance also seems to depend on the path taken. Amoah et al. [124] report that the adoption of clean energy in Sub-Saharan Africa often happens before, rather than after, increases in climate finance inflows. This order suggests that visible progress in energy is key to attracting subsequent funding, highlighting the importance of policy continuity and institutional credibility. These feedback loops challenge the idea that finance alone drives transitions, instead showing that policy frameworks and initial progress can be necessary conditions for ongoing investments [125]. Green finance works best for energy transitions when the financial ecosystems are above certain developmental levels. Deng et al. [126] demonstrate this in China, where regional differences—especially between eastern and western provinces—underline the need for localized institutional and infrastructural capabilities. In less developed financial settings, the potential of green finance is limited, requiring additional investments in administrative, technological, and policy capacity to support its role [127] (see Table 1).

3.4. Institutional and policy frameworks for clean energy development

Clean energy transitions are influenced by national policy orientations, legal frameworks, and the administrative capacity of public institutions (see Table 2). Throughout the Global South, institutional frameworks often mirror the impact of international agreements such as the Kyoto Protocol and the Paris Agreement, which have provided guidance for incorporating renewable energy targets into national strategies. Mechanisms like the Clean Development Mechanism and Nationally Determined Contributions (NDCs) have helped formalize clean energy commitments and steer domestic policy reforms [128,129].

3.4.1. Fiscal instruments and regulatory design

Countries have implemented various fiscal tools to encourage clean energy investments. High-income countries usually use advanced methods like emissions trading and renewable energy auctions [130,131]. Conversely, basic mechanisms such as feed-in tariffs, concessional loans, and risk-sharing programs are common in lower-income countries, where higher capital costs and greater institutional risks exist [132,133].

However, having these tools does not ensure successful results. For example, in Nigeria, legal ambiguity and overlapping responsibilities have hampered project implementation [134]. Evidence from Cameroon and other nations indicates that poorly organized institutions and unclear regulatory roles lead to delays and poor performance [135,136]. When national laws are revised to support decentralized systems like mini-grids and off-grid solar, policy implementation tends to improve [137,138]. Ensuring legal clarity is essential for attracting private sector involvement and building investor trust.

3.4.2. Cross-border and regional coordination

In regions with fragmented energy markets, cross-border

Table 1
Aligning the study search strategy with PRISMA items and checklist as of Page et al. [45].

Stage	Process	PRISMA checklist item (s)	Details
Identification	Database and register searches	Item 1: Identify information sources	Conducted comprehensive searches in Scopus, Web of Science, Google Scholar, and registers to gather literature on clean energy systems development (2009–2025).
Screening	Removal of duplicates and initial screening	Items 4 & 7: Study selection process	Removed duplicates and screened titles and abstracts for relevance to: technological capabilities, financial instruments, policy frameworks, and decentralized models in clean energy.
Eligibility	Full-text article review and application of inclusion/exclusion criteria	Items 6 & 8: Eligibility criteria and reasons for exclusion	Full-text articles were assessed against criteria focused on the four research questions about clean energy systems. Excluded studies were documented with specific reasons.
Included studies	Qualitative and quantitative synthesis	Item 12: Data synthesis methods	Synthesized studies to analyze the development of clean energy systems, financing mechanisms, governance frameworks, and community-driven energy models.
Synthesis	Narrative synthesis and comparative analysis	Items 13 & 15: Synthesis of results and additional analyses	Conducted narrative synthesis and comparative analysis to integrate findings related to technological, financial, policy, and decentralized energy dimensions.
Excluded studies	Documentation of exclusions and rationale	Item 7: Study selection process	Maintained detailed records of excluded studies after full-text review, specifying reasons such as irrelevance to research questions, unclear information, or unavailable full text.

coordination has become an essential reform. West Africa has taken early steps to harmonize standards and promote grid integration through regional regulatory bodies [139]. These efforts seek to facilitate electricity trade and reduce system inefficiencies. However, progress varies, with national legal systems often operating separately from regional goals.

International donors and multilateral agencies such as IRENA and the Green Climate Fund have supported capacity building and regulatory development. These organizations have also offered technical guidance on policy mechanisms and helped spread new technologies [128,129]. Nonetheless, donor fragmentation and inconsistencies between external funding sources continue to limit the impact of international cooperation [140].

3.4.3. *Participatory and multi-level governance*

Participatory frameworks have developed as a supplement to fiscal and regulatory reforms. In many cases, governance models that involve local actors in planning and implementation improve legitimacy and service delivery. Evidence from Ethiopia and Cameroon shows that clean energy programs connected to development goals are more likely to gain public support and lead to lasting adoption [141,142]. Research in Southeast Asia and sub-Saharan Africa also indicates that credibility and transparency in governance enhance macroeconomic outcomes in energy sectors [143,144].

Not all participatory models have produced consistent results. When administrative capacity is weak or legal mandates are unclear, decentralized approaches might remain limited. For instance, legislation for mini-grids in Nigeria is still developing, which restricts the expansion of off-grid systems despite increasing demand [134]. Broader reforms are needed to connect bottom-up efforts with national planning and fiscal tools.

3.4.4. *Cross-sectoral integration and system adaptability*

Energy policy should be considered alongside related fields like agriculture, water, and infrastructure. In Kenya's Tana River Basin, a lack of cross-sector coordination has hindered the potential for integrated resource planning, especially during times of climate stress [145]. Alignment across sectors is not only a planning challenge but also key to long-term system resilience [146].

Adaptive regulatory models are increasingly being explored to manage complexity and uncertainty. Dynamic tools such as system dynamics models have been used to simulate subsidy design, fiscal exposure, and implementation timelines under different scenarios [147]. These approaches offer more flexibility than static policy tools and may be better suited to contexts marked by volatility or rapid technological change.

3.4.5. *Institutional capacity and ecosystem support*

Technological change has reshaped the institutional landscape, especially with the decreasing costs of renewables and the growth of decentralized energy systems. However, adoption of these technologies relies on more than just market signals. Institutional capacity, ecosystem development, and policy stability all play a role in determining results. In many lower-income countries, shortages of skilled labor and limited entrepreneurial ecosystems have hampered deployment [138,148].

International cooperation in technology transfer has yielded mixed outcomes. Projects that combine technology access with capacity-building and institutional support tend to perform better than those that treat technology as a standalone resource [148]. Ecosystem design—including training, business development, and circular economy linkages—must be incorporated into institutional planning.

3.5. *Integrative approaches to optimization, digitalization, and governance in decentralized energy systems*

Decentralized energy systems are increasingly used to address energy access challenges in areas where expanding the centralized grid is not economically or logistically feasible. These systems, often based on off-grid and community-focused infrastructure, provide localized solutions that support socio-economic growth and energy independence. Evidence from Tanzania and Kenya shows the transformative power of decentralized solar setups, including mini-grids and home systems, in boosting rural livelihoods. Documented results include longer commercial activity, better service delivery in schools and clinics, and new

Table 2
Institutional and policy frameworks for clean energy development.

Theme	High-income countries	Developing countries	Key comparative insights
1. Fiscal instruments and regulatory design	Advanced tools such as carbon pricing, renewable energy auctions, and green bonds; strong policy stability (e.g., Germany, South Korea)	Basic instruments dominate: feed-in tariffs, subsidies, concessional loans; often inconsistent implementation (e.g., Nigeria, Cameroon)	Effectiveness depends on institutional clarity, regulatory coherence, and local risk mitigation mechanisms
2. Cross-border and regional coordination	Mature electricity markets with regional interconnections (e.g., EU Energy Union)	Fragmented markets; emerging regional bodies (e.g., West Africa Power Pool) with limited enforcement power	Regional harmonization can reduce duplication and improve grid reliability, but requires legal and institutional alignment
3. Participatory and multi-level governance	Institutionalized public engagement, civil society roles, and participatory budgeting (e.g., Denmark)	Growing emphasis on community engagement in planning; mixed outcomes due to capacity gaps (e.g., Ethiopia, Southeast Asia)	Decentralized planning improves legitimacy but must be coupled with local administrative capacity
4. Cross-sectoral integration and adaptability	Integrated planning across energy, water, transport, and climate sectors; adaptive policy frameworks	Weak coordination across ministries; siloed planning hampers resilience (e.g., Kenya's Tana River Basin)	System adaptability improves with cross-sector frameworks and dynamic policy tools (e.g., simulation modeling)
5. Institutional capacity and ecosystem support	Strong R&D ecosystems, skilled labour, and technology commercialization (e.g., US, Japan)	High dependence on external technology; limited local manufacturing and skills pipelines (e.g., Sub-Saharan Africa)	Ecosystem development (training, entrepreneurship, local supply chains) is essential for scaling deployment
6. Legal and regulatory architecture	Clear, enforceable mandates; stable legal environments attract investment	Frequent legal overlaps, unclear mandates, and slow legislative reforms (e.g., Nigeria)	Legal certainty and streamlined regulations underpin effective policy execution
7. Decentralization and mini-grid integration	Fully integrated into national energy plans in some contexts (e.g., Australia)	Legal recognition growing, but often lacks coordination with national utilities (e.g., Nigeria, Burkina Faso)	Dedicated regulatory frameworks are critical for scaling decentralized and off-grid solutions
8. Role of international institutions	Donors, lenders, and norm-setters; shape global technology and finance norms	Recipients of finance, technology transfer, and institutional models (e.g., via GCF, IRENA)	Multilateral engagement enhances early-stage deployment but must avoid donor fragmentation

job opportunities [149–151]. The "Off-Grid Energy Access" project in Kenya highlights how small-scale photovoltaic systems enhance rural productivity and resilience [152]. These initiatives also promote skill development and the involvement of local businesses in energy supply [153].

Strong governance structures are crucial for fair deployment and long-term success of such systems. Land use governance, benefit-sharing plans, and community consultation are critical areas where governance quality directly affects project results. In regions where land rights are unclear or farming is dominant, conflicts over land access and compensation have slowed project progress [68,154–156]. The South African Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) is known for handling such tensions relatively well through collaborative frameworks that include government agencies, investors, and civil society groups [157]. Also, digital innovations like mobile payments and smart meters help expand energy access and financial inclusion, but their success depends heavily on inclusive governance and adaptable regulation [158].

Energy system planning has evolved to address uncertainty and contextual differences. Recent research highlights a shift toward optimization models that balance reliability with computational efficiency under diverse socio-technical conditions. Prabatha et al. (2024) provide a comparative analysis of robust optimization, linear programming, and Monte Carlo simulations, finding that robust methods are especially effective for dynamic environments and early-stage project screening. These techniques increase resilience in planning by managing uncertainty without needing exhaustive scenario specification. The growth of energy communities adds a socio-political dimension to decentralized energy. Ahmed and Ali [159] describe these communities as mechanisms for integrating citizen agency into national clean energy strategies. Their roles go beyond energy production, including environmental stewardship, economic inclusion, and participatory governance. Despite differences in policy support across regions, the contribution of energy communities to democratic energy transitions is clear. Kubli and Puranik [160] support this view with their morphological analysis of 90 community energy cases. This classification identifies 25 modular business model designs, providing a toolkit for adapting economic strategies to local resource profiles and institutional settings. This modular approach boosts both financial sustainability and social equity.

Technological innovation is bringing new efficiencies and capabilities to decentralized systems. Swarm electrification, which connects solar home systems into modular microgrids, has emerged as a scalable and adaptable solution. Radvilė and Urbonas [161] detail how AI and IoT technologies support predictive maintenance, optimize energy flows, and provide real-time diagnostics, while blockchain platforms enable secure peer-to-peer (P2P) trading. Shen et al. [78] contribute by proposing a layered smart contract framework for blockchain-enabled energy transactions, which enhances cost-efficiency and consumer protection. Telagi and Pedapenki [162] offer a broader review of trading architectures—including bilateral, cooperative, and virtual power plant models—and highlight the regulatory changes needed to support such digital ecosystems. These changes include rules on cybersecurity, market transparency, and governance of decentralized transactions.

Local ownership and operational independence are equally vital for long-term success. Field research from Indonesia highlights the effectiveness of community-led renewable energy systems, where involvement in design and maintenance fosters stronger ownership and durability [163]. These findings are echoed in the hybrid governance model proposed by Araujo-Vizuete and Robalino-López [164], which combines centralized planning with localized implementation. Their study in Ecuador shows that decentralization benefits from phased deployment, where national frameworks enable gradual transfer of control to community levels within a cohesive regulatory environment.

The multi-scalar synthesis of governance models, institutional coordination, and socio-technical dynamics emphasizes the need to combine different frameworks to facilitate decentralized energy transitions. In Nigeria, for example, ongoing carbon lock-in and policy stagnation are addressed through community-led renewable energy projects and multi-level governance [165], highlighting the importance of locally rooted institutional mechanisms. Similarly, Ecuador's hybrid approach of national directives, supported by community involvement, shows how bottom-up participation can align energy policies with local needs, promoting inclusivity and flexibility [164]. The Greek example further demonstrates that meso-level institutional dynamics, when effectively connected to macro policies and micro behaviors, improve policy relevance and infrastructure responsiveness [166]. Meanwhile, cross-country analysis in OECD nations indicates that governance factors can influence energy transition results even when economic and AI-related challenges exist, underscoring the importance of integrated, context-aware policy design [167]. These findings collectively support the idea that decentralized energy systems thrive through hybrid, participatory, and governance-enhanced strategies.

4. Pathways for implementation in developing countries

This section presents a Theory of Change that outlines the interconnected processes driving clean energy transitions in low- and middle-income countries. Drawing from the literature review and guided by the four research questions, the framework identifies how technological capabilities, financial mechanisms, institutional structures, and decentralized models interact to produce measurable energy outcomes. Fig. 4 illustrates the relationships between key inputs, intermediate outputs, and longer-term outcomes across four primary pathways.

4.1. Underlying assumptions

The framework relies on four assumptions that guide how each pathway functions. First, clean energy technologies can be adapted to local environments when combined with domestic innovation systems, skilled labor, and region-specific technical solutions. Second, blended finance mechanisms, including concessional capital and risk-sharing tools, can reduce high investment risks and encourage private sector participation. Third, institutional reforms that simplify regulatory environments and improve cross-sector coordination help create more stable and scalable energy investments. Fourth, decentralized and participatory energy systems are more likely to succeed when supported by suitable governance structures and digital infrastructure that promote local control and accountability.

4.2. Causal pathways

The technological capability pathway, aligned with RQ1, starts with inputs such as resource mapping, knowledge transfer, and capacity-building initiatives. These foundational elements support the development of localized clean energy infrastructure tailored to specific regional conditions. The pathway progresses through establishing operational systems that lower technology costs, foster innovation ecosystems, and expand energy access, especially in areas underserved by traditional grids. Technological diffusion alone doesn't guarantee equitable outcomes, but when linked to local adaptation strategies and supportive policy frameworks, it leads to sustainable infrastructure growth.

In the financial mobilization pathway, corresponding to RQ2, the starting point includes tools like concessional loans, sovereign guarantees, and blended finance facilities designed to reduce perceived investment risk. These inputs enable the creation of financially viable project pipelines and strengthen local capital markets. As financial structures become more robust and accessible, investment flows increase, project financing becomes more affordable, and clean energy becomes more competitive in price-sensitive environments. This pathway shows that financial architecture must evolve alongside policy frameworks to achieve scale and inclusion in energy investments.

The institutional alignment pathway, related to RQ3, focuses on how policy coherence, legal clarity, and administrative capacity influence energy governance. The process starts with regulatory reforms and institutional restructuring aimed at integrating energy policy with land use planning, environmental safeguards, and economic development strategies. These efforts create more coherent policy frameworks and improve enforcement capabilities, reducing project uncertainty and boosting stakeholder confidence. Ultimately, this pathway demonstrates that durable energy transitions require not only capital and technology but also well-functioning institutions that ensure transparency, accountability, and long-term stability.

The decentralization and participation pathway, addressing RQ4, emphasizes the role of community-driven models in promoting inclusive energy access. This pathway begins with inputs such as participatory planning, digital tools, and enabling regulations that support decentralized systems. These conditions lead to the creation of mini-grids, solar home systems, and community-owned cooperatives that meet local needs. Over time, decentralized models enhance system resilience, foster social inclusion, and generate local economic benefits. However, their success depends on how well they are integrated within broader regulatory and institutional systems that provide continuity and technical support.

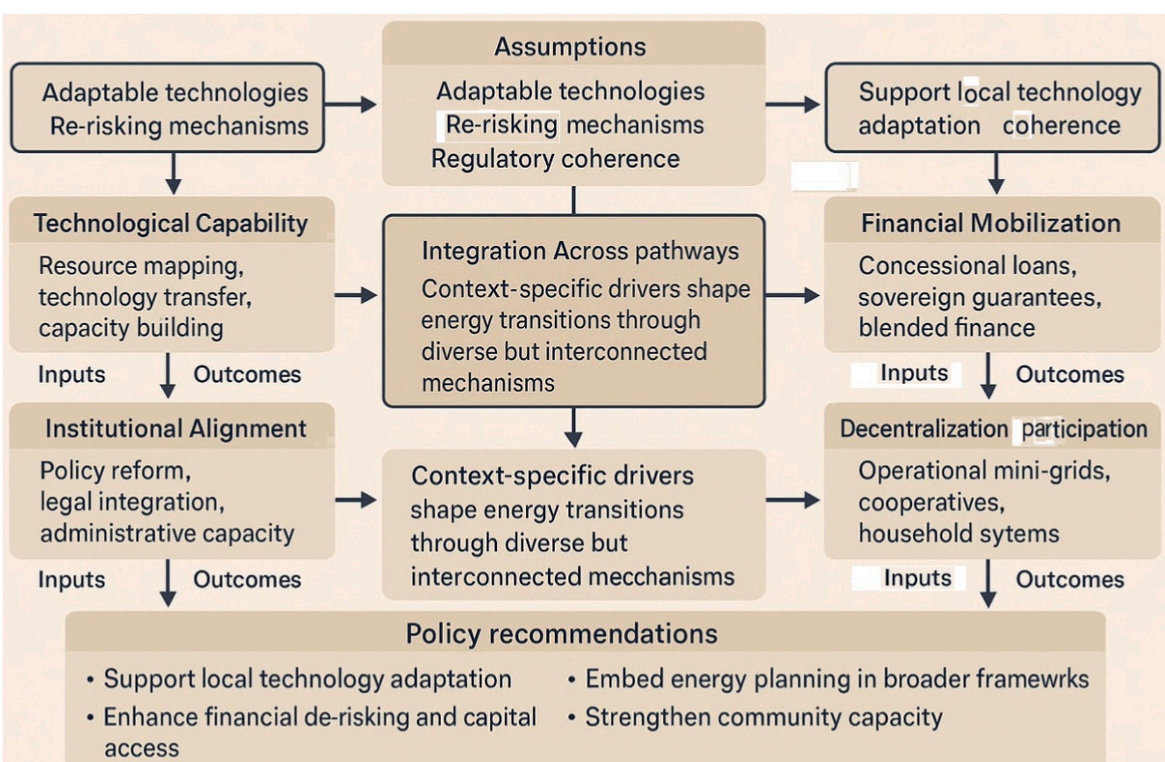

Fig. 4. Pathways for implementation of clean energy transitions in developing contexts.

4.3. Integration across pathways

These four pathways demonstrate that clean energy transitions in developing countries are not driven by single policy tools or one-size-fits-all approaches. Instead, they result from the interaction of specific drivers that depend on local factors, including natural resource availability, macroeconomic conditions, political institutions, and community capacity. The review's evidence highlights several common patterns. Countries with high renewable resource potential often lack the technical and institutional capacity to turn this potential into reliable infrastructure. When risk-adjusted financing is unavailable or poorly structured, viable projects fail to secure funding. Weak or fragmented governance delays implementation or leads to subpar outcomes. Meanwhile, decentralized systems have the potential to improve access but need ongoing institutional support and alignment with national plans.

4.4. Policy recommendations

Several implications arise from this analysis. Supporting local technology adaptation requires investing in regional innovation ecosystems, technical education, and public procurement strategies that favor local suppliers. Financial risk reduction must be complemented by developing long-term capital markets to improve affordability and scalability. Institutional coherence is best achieved by integrating energy planning into broader frameworks that include land rights, environmental regulation, and social protection. Decentralized systems need participatory governance, digital monitoring tools, and capacity-building at the community level to remain sustainable. Regional coordination and harmonized standards can further decrease transaction costs and draw cross-border investments, especially in smaller markets.

Clean energy transitions in developing countries depend on aligning various policy and market forces. The pathways outlined in this framework offer an understanding of how different countries navigate these transitions, rather than prescribing a specific model. Although country contexts vary greatly, the findings indicate that combining technological readiness, accessible finance, institutional strength, and community participation results in more durable and equitable outcomes. Future progress hinges on how these elements are prioritized, scaled, and governed in response to changing political and economic conditions.

5. Publisher's note

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CRediT authorship contribution statement

EKN: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. AJM: Methodology, Visualization, Writing – review & editing. LLM: Visualization, Writing – review & editing. FKF: Visualization, Writing – review & editing. CAK: Writing – review & editing. GMT: Writing – review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2025.101909.

Data availability

No data was used for the research described in the article.

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