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Review

The Energy Trilemma in the Low-Carbon Transition: From Static Trade-Offs to Dynamic Interactions

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Abstract

The transition towards low-carbon energy systems is fundamentally reshaping the relationships between energy security, affordability, and environmental sustainability. Although the energy trilemma has become a widely adopted framework for analysing these objectives, existing studies often examine individual dimensions or bilateral trade-offs in isolation, providing limited understanding of how interactions evolve throughout the transition process. This review synthesises recent evidence on the energy trilemma in the context of the low-carbon transition and develops a dynamic, context-sensitive interpretation of interactions between its three dimensions. A structured integrative literature review with thematic synthesis was conducted using systematic searches of the Scopus and Web of Science databases, followed by multi-stage screening and qualitative synthesis. Rather than evaluating individual studies separately, the review integrates evidence across complementary research streams to identify recurring interaction patterns, trade-offs, synergies, and the conditions under which they emerge. The findings demonstrate that interactions within the energy trilemma are neither static nor universally characterised by unavoidable trade-offs. Energy security increasingly depends on electricity system resilience, critical mineral supply chains, and institutional capacity rather than fossil fuel availability alone. Affordability is shaped primarily by distributional processes, adaptive capacity, and equitable access to low-carbon transition opportunities rather than average energy prices. Security–affordability interactions evolve across different risk regimes, highlighting the economic value of resilience under geopolitical uncertainty and market disruption. Across all three dimensions, technological innovation, infrastructure development, governance quality, temporal dynamics, and socio-economic context determine whether policy interventions generate trade-offs or mutually reinforcing outcomes. Building on these findings, the review reconceptualises the energy trilemma as a dynamic and context-sensitive analytical framework rather than a static balancing exercise. The proposed framework integrates technological, institutional, temporal, distributional, and geopolitical perspectives to explain how interactions among energy security, affordability, and environmental sustainability evolve under different transition conditions.

Keywords: energy trilemma; low-carbon transition; energy security; environmental sustainability; trade-offs; dynamic interactions

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1. Introduction

The transition towards low-carbon energy systems has fundamentally transformed the priorities of contemporary energy policy. Governments are no longer challenged solely by the need to reduce greenhouse gas emissions, but increasingly by the requirement to achieve climate objectives while maintaining reliable, resilient, and affordable energy systems under conditions of growing geopolitical uncertainty, accelerating electrification, and rapidly evolving technologies [1,2]. Recent geopolitical disruptions, increasing electricity demand, expanding renewable energy deployment, and the growing strategic importance of critical materials have further demonstrated that decarbonisation cannot be considered independently of wider energy system resilience and socio-economic stability [1,3,4]. At the same time, the transition creates new opportunities for reducing fossil fuel dependence, improving energy efficiency, and strengthening long-term sustainability, while simultaneously generating technological, institutional, and distributional challenges that require increasingly integrated policy responses [5–7]. These developments suggest that understanding the interactions among multiple energy policy objectives has become as important as pursuing the objectives themselves.

The growing complexity of the low-carbon transition has renewed attention towards the energy trilemma, commonly conceptualised through the interconnected dimensions of energy security, affordability (or energy equity), and environmental sustainability [2]. While this framework has traditionally been used to evaluate the balance among these three dimensions, recent research increasingly demonstrates that their relationships are neither static nor universally applicable. Instead, they evolve as technological innovation, electricity system transformation, changing geopolitical conditions, and institutional responses reshape both the opportunities and constraints of decarbonisation [8–10]. Energy security is no longer determined primarily by uninterrupted access to fossil fuels, but it increasingly depends on electricity system flexibility, grid resilience, critical mineral supply chains, and the secure deployment of low-carbon technologies [5,7]. Likewise, affordability extends beyond energy prices to encompass energy poverty, adaptive capacity, equitable access to low-carbon technologies, and the distribution of transition costs and benefits across different social groups [11–14]. Environmental sustainability increasingly requires a systems perspective that considers not only greenhouse gas mitigation but also resource use, life-cycle impacts, circularity, and the environmental implications of rapidly expanding clean energy value chains [6,15]. These developments make the relationships among the three trilemma dimensions increasingly dependent on the technological, institutional, temporal, distributional, and geopolitical conditions under which the transition unfolds.

Research on the energy trilemma and low-carbon transitions has significantly advanced understanding of individual trilemma dimensions and their interactions. Recent studies have examined renewable energy integration, electricity system resilience, and adaptive energy governance [5,8,10], while others have focused on critical minerals, energy justice, affordability, and geopolitical risks as increasingly important determinants of transition outcomes [7,13,16]. At the same time, methodological approaches have diversified considerably, encompassing composite indicator frameworks, optimisation models, scenario analysis, governance-oriented research, and interdisciplinary transition studies.

Despite these advances, the literature has largely evolved through specialised research streams that remain only partially integrated. Existing studies frequently examine individual trilemma dimensions or bilateral relationships, particularly those between energy security and environmental sustainability or affordability and sustainability, while comparatively fewer investigations analyse the multidirectional interactions among all three dimensions simultaneously [5,6,14]. Moreover, trilemma performance is still commonly evaluated using relatively static indicators or cross-sectional perspectives, despite growing recognition that transition outcomes depend on technological maturity, institutional capacity, temporal dynamics, geopolitical developments, and distributional conditions [7,8,17]. Consequently, there remains a need for a more integrated explanation of how interactions among energy security, affordability, and environmental sustainability evolve throughout the low-carbon transition. In particular, existing evidence needs to be synthesised to identify the mechanisms through which trade-offs and synergies emerge, the contextual conditions that shape their direction and intensity, and the circumstances under which initial trade-offs may weaken, persist, or develop into longer-term synergies.

Against this background, the objective of this review is to synthesise contemporary evidence on the evolving relationships among energy security, affordability, and environmental sustainability during the low-carbon transition. Rather than evaluating the relative performance of countries or proposing universally applicable policy solutions, the review develops a context-sensitive analytical framework that explains how technological, institutional, temporal, distributional, and geopolitical conditions shape trilemma interactions and influence the emergence of trade-offs and synergies across different transition pathways.

Guided by this objective, the review addresses the following research questions:

RQ1. *How should the energy trilemma be interpreted in the context of the low-carbon transition?*

RQ2. *How do interactions among energy security, affordability, and environmental sustainability generate trade-offs and synergies under different technological, institutional, temporal, distributional, and geopolitical conditions?*

RQ3. *How can current evidence be synthesised into a context-sensitive analytical framework that supports future research and policy development?*

Building on these research questions, this review makes four principal contributions to the existing literature. First, it integrates previously fragmented research streams on energy security, affordability, and environmental sustainability into a common analytical synthesis. This enables evidence on bilateral and multidimensional trilemma relationships to be considered jointly rather than as separate transition challenges.

Second, the review identifies recurring mechanisms and interaction patterns through which low-carbon transition processes generate trade-offs and synergies among the three trilemma dimensions. It shows that the direction and intensity of these interactions depend on technological, institutional, temporal, distributional, and geopolitical conditions and may change as energy systems progress through the transition.

Third, these findings are consolidated into a context-sensitive analytical framework that links trilemma interactions to the conditions under which they emerge and evolve. The framework provides a structured basis for examining why similar transition measures can produce different security, affordability, and sustainability outcomes across energy systems and over time.

Finally, the review translates the synthesis into implications for context-sensitive and adaptive energy governance and identifies empirically examinable questions for future comparative and longitudinal research.

The remainder of this article is organised as follows. Section 2 reviews the conceptual foundations of the energy trilemma and its evolution in the context of the low-carbon transition. Section 3 describes the review methodology. Section 4 synthesises the literature on trade-offs and synergies among energy security, affordability, and environmental sustainability. Section 5 presents the proposed context-sensitive analytical framework, while Sections 6 and 7 discuss policy implications and future research directions, respectively. Section 8 discusses the limitations of the review, and Section 9 concludes the article.

2. Conceptual Foundations of the Energy Trilemma in the Low-Carbon Transition

2.1. The Energy Trilemma as an Analytical Framework

The energy trilemma is commonly used to describe the challenge of balancing three central objectives of energy policy: energy security, energy equity, and environmental sustainability. In the World Energy Council framework, energy security refers to the ability of an energy system to meet current and future demand reliably and to withstand disruptions; energy equity concerns access to affordable and modern energy services; and environmental sustainability concerns the reduction in the environmental impacts of energy production and use. The World Energy Council presents the trilemma as a framework for assessing the balance and robustness of national energy systems, while the Energy Trilemma Index provides a comparative assessment of energy system performance across countries [2].

In this review, the energy trilemma is treated not only as a benchmarking framework but as an analytical lens for examining how trade-offs and synergies emerge under low-carbon transition conditions. This distinction is important because composite indicators can show whether countries perform differently across energy security, equity, and sustainability, but they do not necessarily explain why progress in one dimension supports or constrains another. A country may improve sustainability through renewable energy deployment while still facing affordability pressures or grid integration problems. Similarly, short-term energy security measures may weaken long-term sustainability if they extend fossil fuel dependence. Therefore, this review uses the trilemma as a relational framework: the focus is on the interactions between the three dimensions, not only on their separate measurement.

The relationship between the low-carbon transition and the environmental sustainability dimension requires an important conceptual distinction. Environmental sustainability represents one of the three objectives of the energy trilemma, whereas the low-carbon transition refers to the broader process of energy system transformation through which decarbonisation and related sustainability objectives are pursued. The transition is, therefore, not treated in this review as a fourth trilemma dimension or as an external objective separate from environmental sustainability. Rather, it represents the transformation context within which the pursuit of sustainability reshapes the conditions affecting all three trilemma dimensions.

This distinction makes a relational interpretation of the trilemma especially important. Earlier energy policy debates often framed the trilemma around securing fuel supply, maintaining acceptable energy prices and reducing environmental damage. These concerns remain relevant, but their substance changes as energy systems decarbonise. Energy security increasingly depends on electricity networks, system flexibility, critical minerals, and clean technology supply chains. Affordability increasingly depends not only on energy prices but also on access to low-carbon technologies and the distribution of transition costs. Environmental sustainability itself requires attention not only to emissions reduction but also to the life-cycle impacts, resource use, land use pressures, and waste associated with the technologies and infrastructures through which decarbonisation is pursued. The trilemma should, therefore, be understood as a dynamic framework whose interactions evolve as the energy system transformation progresses.

2.2. Energy Security: From Fuel Supply to System Resilience

Energy security has traditionally been associated with the availability, reliability, and affordability of energy supply. In many countries, this has meant reducing exposure to imported fuels, diversifying suppliers, maintaining sufficient infrastructure, and ensuring that energy markets can withstand geopolitical or technical disruptions. These concerns remain important, especially in the context of recent geopolitical instability and energy price volatility. However, the low-carbon transition broadens the meaning of energy security from fuel availability towards whole-system resilience.

This shift is most visible in electricity systems. Electrification of transport, buildings, industry, data centres, and advanced manufacturing makes reliable electricity supply increasingly central to economic and social life. The IEA projects that global electricity demand will grow strongly during 2026–2030 and that electricity consumption will increase much faster than total energy demand [3]. Under these conditions, electricity grids, flexibility resources, and system operation become core energy security issues. Renewable electricity can reduce dependence on imported fossil fuels, but high shares of solar and wind require adequate transmission and distribution networks, storage, demand response, balancing capacity, and supportive regulatory frameworks. The IEA notes that grids and flexibility are moving to the forefront of policymaking as power systems integrate changing patterns of generation, demand, and storage, while large volumes of renewables, storage, and new electricity demand remain delayed in grid connection queues [3].

Critical minerals further illustrate the changing nature of energy security. Low-carbon technologies depend on material inputs such as copper, lithium, nickel, cobalt, graphite, and rare earth elements. These materials are essential for electricity networks, batteries, electric vehicles, wind turbines, solar technologies, and digital infrastructure. As a result, energy security is increasingly connected to the resilience and diversification of mineral supply chains. The IEA argues that critical minerals have moved to the centre of energy, economic, and national security agendas because of supply chain concentration, trade restrictions, and the need for resilience and diversification [4]. Recent export controls and concentration in processing and refining have turned critical mineral supply chains into a direct economic security challenge [4].

Energy security in the low-carbon transition, therefore, involves both old and new risks. Fossil fuel dependence, geopolitical conflict and price volatility remain important, but electricity system adequacy, grid congestion, flexibility, technology dependence, digital vulnerabilities, and mineral supply concentration are becoming increasingly central. This does not mean that the low-carbon transition necessarily weakens energy security. Renewable energy, efficiency, storage, demand-side flexibility, and regional interconnection can strengthen security by reducing exposure to imported fuels and improving system resilience. However, these benefits depend on infrastructure, governance, investment capacity, and policy coordination.

2.3. Affordability, Equity, and Energy Justice

The second dimension of the trilemma is commonly described as energy equity. In this review, affordability is used as the main analytical entry point because the low-carbon transition directly affects energy prices, household energy burdens, investment costs, and access to low-carbon technologies. However, affordability is not treated as a narrow question of low prices. It is connected to wider questions of energy poverty, social vulnerability, distributional justice, procedural participation, and energy justice.

Energy justice scholarship provides an important conceptual bridge between affordability and equity. Heffron et al. [11] argue that energy justice can help balance the competing aims of the energy trilemma while addressing inequality across the energy sector and wider society. Heffron [12] further emphasises that energy justice has become an important interdisciplinary concept for ensuring that energy transitions are fair, equal, equitable, and inclusive. From this perspective, affordability concerns not only whether energy prices are low but also whether households can access adequate energy services, whether vulnerable groups are protected from excessive energy burdens, whether communities participate in energy decisions, and whether the benefits and costs of transition are shared fairly.

The recent global energy crisis illustrates why affordability has become a central part of the energy trilemma. High energy prices placed severe pressure on household budgets and brought affordability and fairness to the centre of energy policy debates, especially for low-income countries and households [18]. However, affordability debates can be misleading if recent price shocks are attributed primarily to climate policy or clean energy. The IEA argues that the 2022 global energy crisis was not caused by clean energy but was strongly linked to major reductions in Russian natural gas supply [18]. This distinction is important because it prevents affordability from being framed as inherently opposed to decarbonisation.

At the same time, clean energy transitions can create genuine affordability and equity risks. Many low-carbon technologies have lower operating costs over their lifetime but require higher upfront investment. Building renovation, heat pumps, rooftop solar, electric vehicles, and efficient appliances can reduce long-term energy costs, but households with low incomes, poor access to credit, rental housing, or inadequate buildings may be unable to benefit from them. The OECD notes that climate change and energy transition pathways have heterogeneous effects across countries, regions, households, and workers, and that both price-based and non-market policies can raise equity concerns depending on national context, affordability, and energy poverty conditions [19]. Affordability must, therefore, be analysed as a distributional issue: the key questions are not only whether average energy prices rise or fall but who pays, who benefits, when costs are incurred, and whether vulnerable groups can adapt.

2.4. Environmental Sustainability: Beyond Emissions Reduction

Environmental sustainability forms the third dimension of the trilemma. It is most commonly associated with reducing greenhouse gas emissions, limiting climate change, and decreasing the environmental impacts of energy production and consumption. Decarbonisation is, therefore, a central component of this dimension and a principal driver of the low-carbon transition, involving the expansion of renewable energy, improvements in energy efficiency, electrification of end uses, and the phasing down of fossil fuels. These objectives remain central because deep decarbonisation is necessary to meet climate goals.

However, sustainability cannot be reduced to operational emissions alone. A low-carbon technology may reduce emissions during use while generating environmental or social pressures elsewhere in its life-cycle. Renewable energy infrastructure, batteries, electric vehicles, electricity networks, and digital technologies require materials, land, water, processing facilities, and waste management systems. The extraction and refining of critical minerals can create environmental impacts, social tensions, and governance concerns. Similarly, large-scale deployment of renewables can raise land use, biodiversity, permitting, and local acceptance issues. These concerns do not undermine the need for decarbonisation, but they show that sustainability must be understood through a whole-system lens.

Critical minerals again illustrate this point. They are essential for low-carbon technologies, but their supply chains can create environmental and social risks if mining, processing, and recycling are poorly governed. The IEA's critical minerals outlook includes not only supply and demand analysis but also sustainability performance tracking and policy frameworks, reflecting the need to connect mineral security with responsible supply chain development [4]. Recycling, circular economy approaches, responsible sourcing, and improved material efficiency are, therefore, not only sustainability measures but also security measures. Sustainability in the low-carbon transition requires attention to the full energy system and the broader value chains that support it.

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2.5. Trade-Offs, Synergies, and Context Dependence

The three dimensions of the energy trilemma are interdependent. A policy designed to improve one dimension can support, weaken, or transform another. These interactions can take the form of trade-offs, where progress in one dimension creates costs or risks in another, or synergies, where a policy improves multiple dimensions at the same time. Understanding these interactions is the central analytical task of this review.

Trade-offs arise in several ways. Security-oriented policies may weaken sustainability if they extend the lifetime of fossil fuel infrastructure or support new carbon-intensive assets in the name of short-term reliability. Sustainability-oriented policies may weaken affordability if they impose high upfront costs or distribute transition costs regressively. Affordability-oriented policies may weaken sustainability and long-term security if they suppress price signals, reduce incentives for efficiency, or delay investment in clean infrastructure. External shocks can intensify these tensions. Opoku et al. [20] show that geopolitical risks may have positive effects on energy security and energy equity while creating negative pressures on environmental sustainability. Yosthongngam et al. [21] find that climate physical risk places pressure on energy security and environmental sustainability, while institutional quality moderates how countries absorb and adapt to these risks.

Synergies are also possible, but they are not automatic. Energy efficiency can reduce emissions, lower consumer bills, and decrease dependence on imported fuels. Renewable energy can improve sustainability and energy independence, but only when supported by adequate grids, flexibility, and storage. Targeted social protection can protect vulnerable households without fully weakening incentives for efficiency or demand response. Circular economy strategies can reduce waste, lower material dependence, and strengthen supply chain resilience. In each case, policy design determines whether an intervention reduces or worsens trilemma tensions.

For this reason, the energy trilemma should be understood as a context-sensitive framework. The same policy can have different effects depending on income level, energy mix, institutional quality, market design, infrastructure capacity, import dependence, climate exposure, and social vulnerability. Carbon pricing, for example, may be environmentally effective but politically fragile if compensation mechanisms are weak. Renewable subsidies may accelerate decarbonisation but become regressive if only higher-income households can access them. Grid investment may raise network costs in the short term but reduce congestion, improve reliability, and lower system costs over time. This context dependence is central to the contribution of the review: the trilemma is treated as a dynamic analytical framework for examining how the relationships among energy security, affordability, and sustainability evolve as the energy system transformation progresses and how policy measures can transform trade-offs into synergies under specific conditions.

The key conceptual shifts discussed throughout this section are consolidated in Table 1, which contrasts the conventional interpretation of each energy trilemma dimension with the broader interpretation emerging under low-carbon transition conditions. The columns should be read as a conceptual progression rather than as independent categories: changes in the underlying meaning and operational conditions of each trilemma dimension modify the types of risks and tensions associated with its pursuit. Thus, conventional concerns centred primarily on fuel availability, energy prices, and direct environmental impacts evolve into broader challenges involving electricity system resilience, critical material dependencies, distributional inequality, infrastructure requirements, and life-cycle impacts. The categories presented in the table reflect recurring conceptual shifts identified in the reviewed literature, including the movement from fuel supply security towards system resilience, from price-centred affordability towards distributional equity and adaptive capacity, and from emissions-centred sustainability towards whole-system and life-cycle considerations.

The final column translates these shifts into the principal trade-off risks that provide the conceptual basis for the interaction-oriented synthesis developed in Section 4. Together, these conceptual foundations inform the review methodology described in the following section and the subsequent synthesis of trade-offs and synergies across the literature.

Table 1. Conceptual evolution of the energy trilemma dimensions and associated trade-off risks under low-carbon transition conditions.

Dimension	Traditional Interpretation	Low-Carbon Transition Interpretation	Main Trade-Off Risks
Energy security	Fuel supply, import dependence, infrastructure reliability, price stability	Electricity system resilience, grid adequacy, flexibility, storage, demand response, critical minerals, clean technology supply chains	Fossil fuel lock-in, grid bottlenecks, mineral dependence, technology concentration, cyber and infrastructure risks
Affordability/equity	Low prices, access to energy, consumer protection	Energy burden, energy poverty, upfront costs of clean technologies, access to efficiency and electrification, distributional justice	Regressive transition costs, unequal access to clean technologies, affordability backlash, weak social acceptance
Environmental sustainability	Emissions reduction, renewable energy deployment, energy efficiency, reduced pollution	Whole-system sustainability, life-cycle impacts, land use, biodiversity, critical mineral extraction, recycling, circularity	Material extraction impacts, local environmental pressures, waste, land use conflicts, rebound effects

3. Review Methodology

3.1. Review Design

This study employed a structured integrative literature review with a systematic search strategy and thematic synthesis to examine the evolving relationships between energy security, affordability, and environmental sustainability within the context of the low-carbon transition. An integrative review was considered the most appropriate methodological approach because the research objective was not to estimate quantitative effects or synthesise evidence from a single study design but rather to integrate the diverse conceptual, empirical, and policy-oriented literature into a coherent analytical understanding of the energy trilemma [22–24]. This approach enabled the inclusion of studies employing different methodological traditions, while facilitating the identification of recurring mechanisms, emerging themes, and broader patterns across the literature.

Unlike conventional narrative reviews, the review followed a predefined and transparent search and screening strategy designed to ensure methodological rigour and reproducibility. At the same time, it did not seek the exhaustive coverage typically associated with full systematic reviews or meta-analyses. Instead, the review adopted a structured and concept-driven approach in which literature was selected according to its analytical relevance for explaining interactions among the three dimensions of the energy trilemma. Particular attention was paid to studies that advanced the understanding of trade-offs, synergies, contextual conditions, and policy responses associated with the low-carbon transition.

The review was further guided by thematic synthesis, which focused on identifying and integrating recurring analytical mechanisms rather than summarising individual publications in isolation. Instead of organising the evidence according to study characteristics or research designs, the synthesis examined how different studies explained relationships between energy security, affordability, and environmental sustainability under varying technological, institutional, geopolitical, and socio-economic conditions. This approach supported the development of a context-sensitive interpretation of the energy trilemma and ultimately informed the conceptual framework proposed later in the review.

3.2. Literature Search Strategy

The literature search was designed to capture both the core energy trilemma literature and the rapidly expanding body of research examining its individual dimensions within the context of the low-carbon transition. Because relevant studies are dispersed across multiple research domains—including energy policy, sustainability transitions, energy justice, electricity systems, and critical mineral supply chains—a single search strategy based exclusively on the term *energy trilemma* was considered insufficient. Consequently, the search strategy combined a broad conceptual search with targeted thematic searches addressing the principal interactions examined in this review.

Two multidisciplinary bibliographic databases, Scopus and Web of Science Core Collection, were selected as the principal sources for the structured peer-reviewed literature search because of their broad and complementary coverage of research across energy, sustainability, environmental science, economics, and public policy. The use of these established bibliographic databases also enabled a consistent search and screening procedure to be applied across the multidisciplinary literature relevant to the energy trilemma. Searches were limited to English-language journal articles and review papers published between 2015 and 2026. The 2015 starting point was selected to focus the structured search on the contemporary phase of the low-carbon energy transition, characterised by accelerating technological change, renewable energy deployment, and electrification, and increasingly complex interactions between decarbonisation, energy security, and affordability. The temporal boundary was, therefore, intended to capture the conditions most relevant to the contemporary energy trilemma rather than to provide a comprehensive historical account of energy transitions. Conference papers, editorials, book chapters, and other non-peer-reviewed publications were excluded from the structured database search in order to maintain a consistent peer-reviewed evidence base. However, the broader evidence used in the review was not restricted exclusively to publications retrieved through Scopus and Web of Science. A limited number of authoritative institutional publications, including reports published by the International Energy Agency (IEA), the Organisation for Economic Co-operation and Development (OECD), and the World Energy Council (WEC), were included selectively where they provided internationally recognised conceptual definitions, policy frameworks, or statistical evidence directly relevant to the review objectives. These institutional sources were treated as complementary contextual evidence rather than as part of the numerical screening workflow for peer-reviewed publications.

To ensure comprehensive coverage while maintaining a clear analytical focus, the search strategy was organised around six complementary thematic search blocks, each addressing a distinct component of the energy trilemma literature (Table 2). The first block captured the conceptual foundations of the energy trilemma, whereas the remaining blocks focused on the principal bilateral interactions among energy security, affordability, and environmental sustainability, together with two emerging themes that have become increasingly important under the low-carbon transition: critical minerals and electricity system resilience. This multi-block strategy reduced the risk of overlooking relevant studies that address individual trilemma dimensions without explicitly employing the term *energy trilemma*.

Table 2. Thematic structure of the literature search strategy.

Search Block	Primary Focus
B1	Conceptual foundations of the energy trilemma
B2	Energy security–environmental sustainability interactions
B3	Affordability–environmental sustainability interactions
B4	Energy security–affordability interactions
B5A	Emerging research area: critical minerals and strategic supply chains
B5B	Emerging research area: electricity security, grids, and system flexibility

The complete search strings for each thematic search block are presented in Appendix A (Table A1).

Following completion of the database searches, records retrieved from the six thematic blocks were merged into a single reference database prior to the screening process. Duplicate records were removed before title and abstract screening to ensure that each publication entered the review only once, irrespective of the number of search blocks in which it appeared.

3.3. Study Selection and Screening

Following database retrieval and within-block deduplication, 510 unique records underwent a multi-stage screening process designed to progressively identify studies providing the greatest analytical value for the objectives of this review (Figure 1). Rather than relying solely on keyword matching, the screening process emphasised each publication's capacity to contribute meaningful conceptual, empirical, or policy-related insights into the evolving relationships among energy security, affordability, and environmental sustainability under low-carbon transition conditions. At both the title/abstract and full-text stages, records were independently assessed by the two co-authors against the predefined eligibility and analytical relevance criteria. Any initial disagreements concerning inclusion, exclusion, or interpretation were subsequently discussed until consensus was reached, and no third-party arbitration was required. A formal inter-rater agreement coefficient was not calculated; the consensus-based procedure is, therefore, reported explicitly to provide a transparent account of how disagreements were resolved.

During the initial title and abstract screening, publications were assessed according to their topical relevance and anticipated analytical contribution to the review. Of the 510 records screened, 391 were retained for further assessment, whereas 119 were not advanced because they either fell outside the scope of the review or provided insufficient analytical value for the objectives of the study. Two general reasons accounted for non-advancement at this stage: thematic or scope mismatch, where publications did not substantively address the energy trilemma dimensions or their interactions under low-carbon transition conditions, and insufficient analytical relevance to the objectives of the review. Because these reasons were not recorded as mutually exclusive categories during the original screening process, they are reported qualitatively rather than as separate numerical counts.

During consolidation of the retained records, an additional 34 duplicate publications retrieved across multiple thematic search blocks were identified and removed. This resulted in 357 unique publications, which subsequently underwent a stricter analytical screening focused on conceptual relevance, analytical value, and redundancy. Following this stage, 112 publications were retained for targeted full-text assessment and detailed thematic analysis. The remaining 245 publications were not advanced at this stage, primarily because of insufficient conceptual relevance, insufficient analytical value in explaining the mechanisms, contextual conditions or policy implications associated with trilemma interactions, or substantial redundancy with evidence already represented by retained studies. As at the preceding stage, these reasons were not recorded as mutually exclusive categories during the original screening process and are, therefore, reported qualitatively rather than as separate numerical counts.

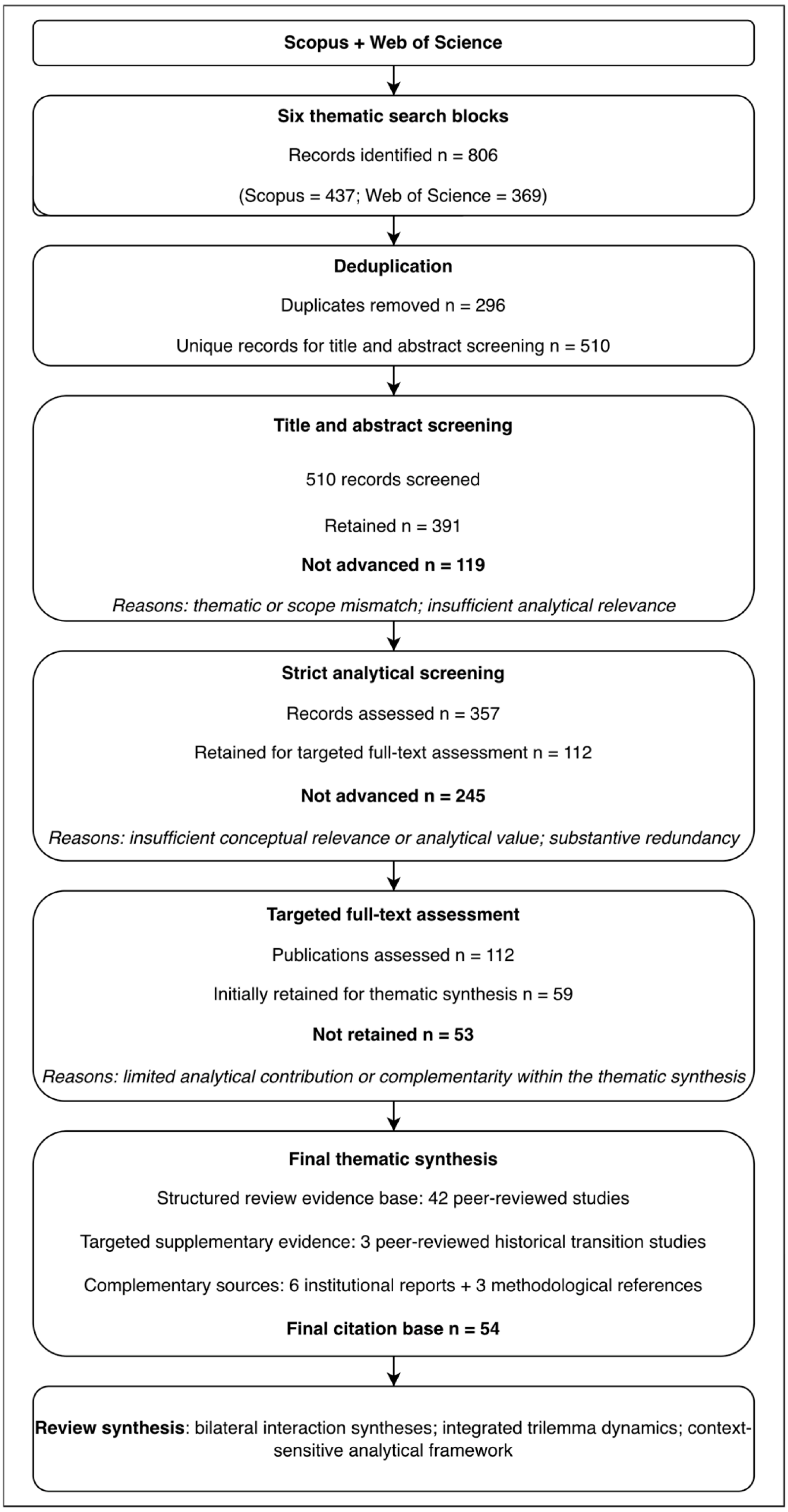

Figure 1. Workflow of the original structured literature search, study selection, and screening process, together with the supplementary evidence incorporated during manuscript revision and the resulting final thematic synthesis.

Because the review sought to develop a conceptual synthesis across heterogeneous evidence rather than evaluate intervention effectiveness, a formal methodological quality appraisal using standard critical appraisal tools was not undertaken. Instead, studies were evaluated during full-text assessment according to their analytical relevance, conceptual or empirical contribution, and alignment with the review questions, consistent with the interpretive objectives of integrative literature reviews [24].

The initial screening stage consisted of title and abstract assessment, during which publications were evaluated against the predefined scope of the review. Studies were retained when they addressed at least one of the three energy trilemma dimensions or their interactions within the context of energy transition, decarbonisation, electricity systems, critical minerals, energy justice, or related policy challenges. Publications focusing on unrelated topics, lacking substantive relevance to the review objectives, or failing to provide sufficient analytical content were excluded at this stage.

Publications passing the initial screening subsequently underwent targeted full-text assessment. Instead of reviewing every publication with equal depth, full-text analysis focused on extracting information directly relevant to the review questions. Particular attention was paid to studies explaining the mechanisms underlying trade-offs and synergies, contextual conditions influencing interactions among trilemma dimensions, proposed policy responses, and emerging analytical perspectives. Where multiple publications presented highly similar evidence or repeated equivalent analytical arguments, studies offering broader conceptual contributions, stronger empirical evidence, or greater thematic distinctiveness were retained to maximise analytical diversity while avoiding unnecessary redundancy.

Three complementary criteria guided the analytical screening. Conceptual relevance referred to the extent to which a publication contributed directly to understanding one or more energy trilemma dimensions or the relationships among them under low-carbon transition conditions. Analytical value referred to the extent to which a study provided explanatory insight into the mechanisms generating trade-offs or synergies, the contextual conditions shaping these interactions, their temporal or distributional characteristics, or associated policy responses. Redundancy referred to substantial duplication of an analytical argument or empirical insight already represented by other retained studies. Redundancy was not treated as an indication of lower study quality; rather, it was used to avoid overrepresenting repeatedly documented arguments when multiple publications offered substantively equivalent contributions.

The overall screening strategy, therefore, prioritised analytical relevance over publication quantity. Inclusion was determined not only by topical relevance but also by each study's contribution to explaining recurring mechanisms, contextual variation, and policy implications across the energy trilemma literature. This progressive screening process formed the basis for the subsequent evidence extraction and thematic synthesis presented in the following section.

3.4. Evidence Extraction and Thematic Synthesis

Following targeted full-text assessment of the 112 retained publications, 59 publications were initially retained for thematic synthesis based on conceptual relevance, analytical contribution, and complementarity within the emerging thematic structure (Figure 1). The remaining 53 publications were not retained because their contribution to the emerging synthesis was comparatively limited in terms of analytical contribution or complementarity with the evidence already represented. These reasons were not recorded as mutually exclusive exclusion categories and are, therefore, reported qualitatively rather than as separate numerical counts. During subsequent synthesis and manuscript preparation, a number of these publications were consolidated: several studies presenting highly similar evidence were merged into a single analytical account, a small number were superseded by more recent publications addressing the same mechanism, and others became redundant once the thematic structure of the review was finalised. As a result, the structured review evidence base comprised 42 peer-reviewed journal articles and review papers. During manuscript revision, a targeted supplementary search was conducted in response to the need for stronger representation of historical energy transition perspectives identified during peer review. This search resulted in the inclusion of three additional peer-reviewed studies addressing historical transition dynamics, temporal inertia, and path dependence, which were incorporated selectively into the synthesis in Sections 4.4 and 5. These supplementary studies were treated as complementary evidence and were not retrospectively incorporated into the original predefined Scopus and Web of Science screening workflow; accordingly, the original screening counts reported in Figure 1 remain unchanged. The final evidence base, therefore, comprised 45 peer-reviewed studies, complemented by six authoritative institutional reports providing internationally recognised conceptual definitions, policy frameworks, and statistical evidence, and three methodological references informing the review design and evaluation approach.

The extracted evidence subsequently underwent thematic synthesis. Thematic development proceeded iteratively from the structured evidence extraction. Relevant findings and arguments were first coded according to the trilemma interaction addressed and the mechanism through which that interaction was explained. Related codes were then compared across studies and consolidated into broader analytical themes where recurring mechanisms or contextual patterns were identified. The three bilateral trilemma relationships provided the higher-order structure for organising the synthesis, while cross-cutting subthemes emerged from recurring evidence concerning technological, institutional, temporal, distributional, and geopolitical conditions. The resulting themes were subsequently reviewed against the underlying studies to ensure that they reflected convergent or substantively distinctive evidence rather than isolated observations. The synthesis was initially structured around the three principal bilateral interactions comprising the energy trilemma—energy security–environmental sustainability, affordability–environmental sustainability, and energy security–affordability. These thematic syntheses were subsequently integrated to examine how interactions among all three dimensions evolve simultaneously under the low-carbon transition, providing the basis for the integrated analytical framework developed in Section 5.

Throughout the synthesis process, particular emphasis was placed on identifying cross-study convergence rather than reporting isolated findings. Where multiple publications advanced similar analytical arguments, evidence was synthesised to capture the underlying mechanism instead of describing each study individually. Conversely, studies offering distinctive conceptual perspectives, novel empirical evidence, or context-specific insights were retained to enrich the thematic interpretation and broaden the explanatory scope of the review. Where studies reported divergent or apparently conflicting findings regarding the same interaction, these differences were retained rather than resolved by selectively emphasising one study over another. Instead, they were interpreted in relation to the contextual conditions under which the respective findings were obtained, such as system flexibility, market design, institutional capacity, or transition stage. Divergent evidence was, therefore, treated as informative about the context-dependence of trilemma interactions rather than as an inconsistency to be eliminated from the synthesis. This approach allowed the review to move beyond descriptive literature summarisation towards an integrated explanation of the dynamic relationships underpinning the contemporary energy trilemma.

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Generative artificial intelligence (ChatGPT, OpenAI, model GPT-5.5) was used as a supporting tool during selected organisational and preliminary analytical stages of the review. Its use was limited to reference organisation, assistance with duplicate identification, preliminary screening support, and the organisation of candidate thematic codes. During preliminary screening, the tool was instructed to assess the apparent relevance of bibliographic records to the predefined review scope and to provide a provisional categorisation with a brief rationale; these outputs served only as decision support information and did not determine eligibility. During thematic organisation, the tool was used to compare author-extracted findings, identify potentially recurring mechanisms, and suggest candidate groupings of related codes. Representative prompt templates used for these tasks are reported in Appendix B to improve transparency and reproducibility.

Human verification was maintained throughout the review process. As described in Section 3.3, title/abstract and full-text eligibility decisions were independently assessed by both co-authors, and AI-generated screening suggestions were not treated as inclusion or exclusion decisions. Similarly, candidate thematic groupings suggested with AI assistance were checked against the underlying publications and retained, modified, or rejected on the basis of the authors' interpretation of the source evidence. To minimise the risk of AI-induced bias or unsupported content, the tool was not used as an evidence source, was not permitted to substitute for assessment of the underlying publications, and did not independently determine study eligibility, interpret study findings, establish the final thematic structure, or formulate the conclusions of the review. All final screening decisions, evidence interpretations, thematic synthesis, and manuscript content were evaluated and approved by the authors.

4. Interactions, Trade-Offs, and Synergies Within the Energy Trilemma

4.1. Energy Security–Sustainability Interactions

The relationship between energy security and environmental sustainability changes as decarbonisation objectives are pursued through the low-carbon transition. Traditionally, these objectives were often portrayed as competing policy priorities, with energy security primarily associated with secure and affordable fossil fuel supplies, while environmental sustainability focused on reducing greenhouse gas emissions. The more recent literature, however, increasingly challenges this conventional dichotomy by suggesting that decarbonisation can simultaneously strengthen and reshape energy security [25,26]. Rather than representing an inherent conflict, security–sustainability interactions appear to depend on the evolution of energy systems, the pace of technological change, and the institutional and geopolitical contexts within which transition pathways are implemented [5].

A growing body of evidence indicates that low-carbon transitions can generate important structural synergies by reducing dependence on imported fossil fuels, limiting exposure to fuel price volatility, and lowering vulnerability to geopolitical supply disruptions [25,26]. Improvements in energy efficiency, renewable energy deployment, electrification, and demand-side restructuring collectively reduce fossil fuel demand while strengthening the long-term resilience of energy systems. These benefits are particularly evident when electrification is accompanied by sustained expansion of low-carbon electricity generation and continued efficiency improvements, enabling countries to reduce external fuel dependence without compromising climate objectives [5].

Nevertheless, these benefits should not be interpreted as either immediate or universally guaranteed. The literature highlights a pronounced temporal asymmetry within the transition process: although long-term pathways substantially reduce dependence on fossil fuels, legacy infrastructures, existing technologies, and continuing fossil fuel demand create an extended period during which conventional energy security vulnerabilities remain significant [25]. At the same time, many of the investments required to support decarbonisation—including electricity networks, storage technologies, and flexibility resources—only deliver their full security benefits over longer time horizons. Consequently, energy security is increasingly understood not as a static end-state but as a dynamic process that requires different policy priorities at different stages of the transition [26].

A recurring finding across the reviewed literature is that the low-carbon transition transforms rather than eliminates energy security risks [26,27]. As dependence on fossil fuels gradually declines, new vulnerabilities emerge around electricity networks, system flexibility, digital infrastructure, critical material supply chains, and increasingly interconnected technologies. Consequently, the principal challenge shifts from ensuring uninterrupted access to fossil fuels towards maintaining the resilience of highly electrified, digitally enabled, and technologically complex socio-technical systems. This evolution fundamentally broadens the concept of energy security, extending it beyond traditional concerns over fuel availability towards the governance of interconnected infrastructures and emerging technological dependencies [5,28].

Rather than signalling a deterioration of energy security, these emerging vulnerabilities reflect a broader process of risk transformation. Measures designed to reduce one category of risk frequently generate new technological, institutional, geopolitical, or environmental challenges elsewhere in the energy system. Sovacool [6] conceptualises this process through four complementary mechanisms—risk offset, risk substitution, risk transfer, and risk transformation—demonstrating that energy transitions rarely eliminate risks altogether but instead redistribute them across infrastructures, technologies, and society. Viewed from this perspective, renewable deployment, electrification, and digitalisation should not be evaluated simply according to whether they increase or decrease energy security but according to how they reshape the balance of risks throughout the transition process. This conceptualisation provides the analytical foundation for understanding why security–sustainability interactions cannot be adequately described as either purely synergistic or inherently conflictual.

The practical implications of this evolving understanding of energy security become particularly evident in the deployment of renewable energy technologies, where the reviewed evidence points to contrasting outcomes. Whereas the evidence discussed above associates decarbonisation with reduced import dependence and greater long-term resilience [25,26], other studies indicate that increasing renewable capacity alone does not automatically generate security–sustainability synergies [29]. These apparently divergent findings can be understood in relation to differences in the underlying system conditions: while higher shares of renewable energy generally reduce dependence on imported fossil fuels and improve environmental performance, security outcomes depend critically on the ability of electricity systems to accommodate increasingly variable generation. Empirical studies consistently identify insufficient storage capacity, transmission bottlenecks, limited system flexibility, and overly deterministic planning assumptions as important constraints that may weaken the anticipated security benefits of renewable integration [30]. Consequently, the relationship between renewable deployment and energy security is neither linear nor automatic but mediated by the broader capacity of electricity systems to maintain reliability, resilience, and operational flexibility under changing generation profiles.

A similar pattern emerges in the literature on electrification. Replacing direct fossil fuel consumption with electricity is widely regarded as a cornerstone of low-carbon transition pathways [31]. Yet electrification itself does not necessarily improve either environmental sustainability or energy security. Rather, its benefits depend on whether growing electricity demand is accompanied by sufficiently rapid decarbonisation of electricity generation together with timely investments in storage technologies, demand-side flexibility, grid expansion, and digital system management. Where these developments are poorly coordinated, emissions and security risks may simply be displaced from end-use sectors towards electricity generation and network infrastructure. Electrification should, therefore, be understood as a system-level transition strategy whose success depends on coordinated transformation across the entire energy system rather than on changes in final energy consumption alone [25].

Taken together, these findings indicate that renewable deployment and electrification should not be viewed as independent technological solutions but as components of broader socio-technical transitions. Their contribution to both energy security and environmental sustainability depends on the capacity of energy systems to integrate new technologies while preserving reliability under increasingly complex operating conditions. This observation reinforces the broader conclusion that the transition modifies the conditions under which energy security is achieved rather than simply improving security through technological substitution.

The recent literature, therefore, increasingly shifts attention from individual technologies towards the institutional and governance arrangements that shape transition outcomes. The same technological pathway may generate either synergies or trade-offs depending on market design, regulatory frameworks, investment incentives, and long-term policy coordination. For example, capacity mechanisms introduced to safeguard electricity system adequacy may unintentionally prolong the operation of carbon-intensive backup generation if they continue to favour conventional fossil fuel technologies [32]. Conversely, market designs that reward storage, demand response, and low-carbon firm capacity can simultaneously enhance system reliability while supporting decarbonisation objectives. Likewise, tensions between energy security and environmental sustainability often arise not because the two objectives are inherently incompatible but because industrial policy, infrastructure planning, permitting procedures, and investment frameworks remain insufficiently coordinated throughout the transition process [5].

Collectively, these studies suggest that security–sustainability interactions are governed less by individual technologies than by the institutional and infrastructural systems within which those technologies operate. Renewable energy, electrification, and other low-carbon innovations undoubtedly create opportunities for simultaneous improvements in environmental performance and long-term energy security. However, these opportunities are realised only when technological deployment is accompanied by coherent policy frameworks, adequate infrastructure, sufficient flexibility resources, and effective institutional coordination. Consequently, successful low-carbon transitions cannot be understood as purely technological transformations; they also depend critically on governance and institutional coordination.

Beyond technological deployment and domestic policy coordination, the reviewed literature increasingly highlights the importance of international governance and strategic interdependence in shaping security–sustainability interactions. The transition towards low-carbon energy systems is accompanied by a gradual shift from dependence on internationally traded fossil fuels towards greater reliance on globally interconnected technology value chains, manufacturing capacities, and critical raw materials [7]. Consequently, energy security is increasingly embedded within broader industrial, trade, and innovation policies, requiring governments to consider resilience across entire supply chains rather than focusing exclusively on domestic energy production [5].

Importantly, the reviewed evidence does not suggest that these emerging dependencies simply replace one form of geopolitical vulnerability with another. Rather, the transition redistributes strategic dependencies across a more diversified portfolio of technologies, materials, and international partnerships. Critical minerals, therefore, illustrate a particularly clear security–sustainability interaction: expanding low-carbon technologies can reduce fossil fuel dependence and emissions while simultaneously increasing exposure to concentrated mineral supply chains and to the environmental impacts associated with extraction and processing. At the same time, renewable energy systems create opportunities to mitigate these vulnerabilities through technological innovation, recycling, material substitution, and international cooperation. Accordingly, strategic autonomy should not be interpreted as complete resource self-sufficiency but as the capacity to build resilient, diversified, and adaptive supply systems capable of responding to evolving geopolitical and technological uncertainties [7,33].

A related perspective is provided by Thaler and Hofmann [34] through the concept of the "Impossible Energy Trinity", which highlights a structural tension between energy security, environmental sustainability, and national energy sovereignty. In their formulation, increasing reliance on renewable electricity may strengthen sustainability and security through greater cross-border integration, but this can simultaneously constrain national energy autonomy. This perspective shares with the conventional energy trilemma an emphasis on competing energy policy objectives, but it differs in treating national energy sovereignty, rather than affordability or equity, as the third objective and in framing the interaction as an explicit prioritisation problem. The context-sensitive interpretation developed in this review takes a different but complementary perspective. Rather than assuming a structurally fixed incompatibility among objectives, it examines how the direction and intensity of trade-offs and synergies evolve with technological, institutional, temporal, distributional, and geopolitical conditions.

This tension between national autonomy and interdependence is also reflected in the literature on regional electricity markets and cross-border integration. Whereas interdependence has traditionally been viewed as a potential source of energy security vulnerability, more recent studies increasingly argue that appropriately governed interconnection can enhance both security and sustainability by improving system flexibility, facilitating renewable integration, and enabling more efficient balancing of variable renewable generation across wider geographical areas. From this perspective, resilience in low-carbon energy systems may increasingly depend on managed interdependence rather than complete national self-sufficiency, provided that robust governance arrangements, coordinated market design, and effective emergency response mechanisms are in place [33,34].

Overall, the reviewed literature suggests that the interaction between energy security and environmental sustainability is considerably more dynamic than traditionally assumed. Decarbonisation creates substantial opportunities to strengthen long-term energy security, yet these opportunities remain conditional upon the capacity of energy systems to anticipate, absorb, and adapt to evolving technological, institutional, and geopolitical risks. Consequently, the transition should not be understood as a process of eliminating energy security risks but of transforming and governing them through coordinated technological deployment, resilient infrastructure, effective institutions, and adaptive governance. From this perspective, the central challenge is no longer to maximise energy security and environmental sustainability independently but to develop governance arrangements capable of preserving long-term synergies while managing the inevitable trade-offs that arise throughout the transition process. While these findings demonstrate that security and sustainability can often be mutually reinforcing under appropriate technological and institutional conditions, the transition simultaneously generates important distributional consequences that determine how these benefits and costs are shared across societies. These affordability-related dimensions are examined in the following section.

4.2. Affordability–Sustainability Interactions

While the previous section demonstrated that security–sustainability interactions are largely shaped by technological change, system flexibility, and institutional coordination, the reviewed literature increasingly suggests that the long-term success of the low-carbon transition also depends on how its economic costs, benefits, and opportunities are distributed across society [6,13]. Environmental improvements achieved through decarbonisation do not automatically translate into socially equitable outcomes, as households, regions, and economic sectors differ substantially in both their exposure to transition costs and their ability to benefit from emerging low-carbon opportunities. Consequently, affordability should be understood not simply in terms of average energy prices or aggregate welfare impacts but as a fundamentally distributional dimension of the energy transition [14,35].

A central conclusion emerging from the reviewed literature is that affordability–sustainability trade-offs are primarily policy-contingent and distributional rather than inherent to decarbonisation itself [13,36]. Climate policies delivering comparable emission reductions may generate markedly different affordability outcomes depending on how transition costs are financed, how benefits are allocated, and which social groups are able to participate in low-carbon investments. Climate policy effectiveness and distributional fairness should, therefore, be regarded as analytically distinct dimensions rather than automatically complementary outcomes. As a result, policies that substantially reduce emissions may nevertheless intensify affordability pressures or reinforce existing socio-economic inequalities if financial burdens are widely shared while access to transition benefits remains uneven [13,37].

This perspective shifts the analytical focus from asking whether decarbonisation increases or decreases aggregate energy costs towards examining who bears transition costs, who captures transition benefits, and who possesses the capacity to adapt. The reviewed evidence indicates that affordability outcomes are shaped not only by income differences but also by housing tenure, property ownership, access to capital, technological opportunities, institutional arrangements, and broader socio-economic conditions that determine households' ability to respond [38,39]. Consequently, identical policy instruments may generate progressive outcomes in one context while producing regressive consequences in another. This variation highlights the importance of policy design in shaping affordability–sustainability interactions rather than treating such trade-offs as unavoidable consequences of ambitious climate action [13,36,40]. For example, carbon pricing accompanied by targeted revenue recycling may preserve the emissions reduction incentive while limiting burdens on low-income households, whereas the same price signal without effective compensation may intensify energy poverty [36]. Similarly, retrofit or clean-heating support may generate substantial long-term affordability gains for owner–occupiers able to co-finance investments, while tenants and households lacking access to credit may remain excluded from these benefits [39].

This interpretation also broadens the concept of affordability beyond short-term household expenditure. Rather than representing a static measure of energy prices, affordability increasingly reflects the ability of households and communities to maintain essential energy services while adapting to changing technologies, market conditions, and policy interventions. From this perspective, transition vulnerability depends not only on the magnitude of financial costs but also on unequal adaptive capacity—the extent to which households can modify energy consumption, invest in efficiency improvements, access financial support, or benefit from low-carbon technologies [38,40]. Understanding affordability, therefore, requires analysing both the distribution of economic burdens and the unequal opportunities available for responding to them, thereby linking affordability with broader questions of energy justice and social resilience [35,37].

The affordability dimension of the low-carbon transition becomes particularly visible through changes in energy prices. Carbon pricing, fossil fuel subsidy reform, and other market-based climate policies strengthen incentives for energy conservation, improve energy efficiency, and support emissions reduction by encouraging behavioural change and technological substitution [38]. However, the reviewed literature consistently shows that the same economic signals capable of accelerating decarbonisation may simultaneously impose disproportionate welfare costs on households with limited flexibility to reduce or modify essential energy consumption. Affordability–sustainability trade-offs, therefore, arise not because climate policies fail environmentally but because identical economic incentives affect social groups with markedly different capacities to respond [13,36].

Importantly, household vulnerability cannot be explained solely by differences in income or energy expenditure. Instead, affordability outcomes largely depend on households' ability to adjust to changing economic conditions through behavioural adaptation, investments in energy-efficient technologies, access to financial resources, and effective use of public support [38]. Households facing structural constraints experience energy price increases not only through higher utility bills but also through reduced disposable income, forcing difficult trade-offs between energy consumption and other essential needs such as food, healthcare, and mobility. Consequently, the regressive effects of energy price shocks reflect unequal opportunities for adaptation rather than differences in expenditure shares alone [13,40].

These findings suggest that the interaction between affordability and sustainability depends less on the magnitude of price increases than on the accompanying policy framework. Universal price suppression or broad energy subsidies may provide immediate financial relief, yet they often weaken incentives for energy conservation and reduce the effectiveness of demand-side decarbonisation [36]. Conversely, maintaining strong carbon price signals without adequate social protection risks exacerbating energy poverty while undermining public acceptance of climate policy. The recent literature, therefore, increasingly frames affordability not as an argument against carbon pricing itself but as a challenge of designing complementary measures capable of preserving environmental incentives while protecting vulnerable households [14,38].

Compensation mechanisms play a pivotal role in determining whether these tensions persist or evolve into long-term synergies. As highlighted by Büchs et al. [36], the effectiveness of compensation depends not only on its magnitude but also on its design. Direct cash transfers may reduce the regressive effects of higher energy prices, yet they rarely address the structural causes of energy vulnerability and may even partially offset environmental gains if additional income supports carbon-intensive consumption. By contrast, investments in low-carbon public transport, residential energy efficiency, renewable heating systems, and other essential low-carbon services simultaneously improve affordability, reduce emissions, and strengthen long-term resilience. Well-designed affordability protection should, therefore, be viewed not as an exception to climate policy but as an integral component of successful decarbonisation strategies [13,14].

Taken together, these findings demonstrate that affordability–sustainability trade-offs are neither fixed nor unavoidable. Rather, they emerge from the interaction between economic incentives, households' capacity to respond and policy design. Climate policies create the strongest synergies when they move beyond compensating households for rising energy costs and instead reduce the underlying sources of energy vulnerability. This shift from short-term financial protection towards structural resilience provides the conceptual bridge to the next part of the discussion, which examines how energy efficiency improvements, building retrofits, and broader access to low-carbon technologies can simultaneously strengthen affordability and environmental sustainability.

While compensation mechanisms can alleviate the immediate distributional impacts of climate policies, the reviewed literature increasingly argues that long-term affordability depends on addressing the structural drivers of energy vulnerability rather than continuously offsetting rising energy costs [38,39]. This represents an important shift in recent research, moving beyond short-term financial protection towards interventions that permanently strengthen households' ability to access affordable, low-carbon energy services. Consequently, long-term affordability is increasingly viewed as a function of structural resilience rather than disposable income or temporary financial support [36].

Among the structural interventions identified in the literature, investments in residential energy efficiency, building retrofits, and low-carbon heating technologies consistently emerge as some of the most effective measures for simultaneously improving affordability and environmental sustainability [39]. Unlike direct income transfers, these measures permanently reduce household energy demand, lower exposure to future energy price volatility, and contribute to sustained emissions reductions. Their benefits, therefore, extend beyond immediate financial relief by strengthening household resilience while improving the long-term environmental performance of the energy system. Energy efficiency investments thus represent one of the clearest examples of policies capable of transforming affordability–sustainability trade-offs into enduring synergies [13,14].

However, the reviewed evidence also demonstrates that access to these long-term benefits remains uneven. Higher-income households, property owners, and those with better access to credit are generally better positioned to invest in energy-efficient technologies and, therefore, capture a disproportionate share of the economic gains associated with the transition [39]. By contrast, low-income households, tenants, and other vulnerable groups often face financial and institutional barriers that restrict participation in retrofit programmes and other low-carbon investments. Consequently, policies intended to improve long-term affordability may inadvertently reinforce existing socio-economic inequalities unless opportunities to participate in the transition are more equitably distributed [35,41].

These findings suggest that affordability should be evaluated not only through household energy expenditure but also through access to transition opportunities. The availability of technologies, finance, and institutional support increasingly determines which households are able to benefit from decarbonisation and which remain exposed to persistent energy vulnerability [39]. Recent research, therefore, argues that successful climate policy requires moving beyond compensation for transition costs towards ensuring equitable participation in investments that generate lasting affordability gains. From this perspective, affordability becomes as much a question of opportunity allocation as of income distribution, further strengthening its links with energy justice and inclusive low-carbon development [35,37,40].

This broader perspective naturally extends beyond individual households. The reviewed literature increasingly demonstrates that affordability–sustainability interactions are also shaped by spatial and territorial inequalities [35,40]. Regional differences in income, housing quality, energy infrastructure, and access to public investment create substantial variation in how communities experience both the costs and the benefits of decarbonisation. As a result, transition outcomes differ not only across socio-economic groups but also between urban and rural areas, industrial regions, and economically disadvantaged territories, highlighting the need for context-sensitive policy responses rather than uniform national approaches [39].

The distributional dimension becomes even more pronounced at the international level. While advanced economies generally possess greater financial resources, institutional capacity, and technological capabilities to implement low-carbon transitions, many developing countries face considerably tighter affordability constraints despite contributing relatively little to historical greenhouse gas emissions [14,37]. Climate mitigation policies, therefore, cannot be separated from broader questions of international equity, financial assistance, and technological cooperation. Differences in fiscal capacity, access to investment, and technological capabilities increasingly influence not only the pace of decarbonisation but also countries' ability to simultaneously pursue affordability and sustainability objectives [35].

Beyond the allocation of economic costs and technological opportunities, recent research increasingly highlights the importance of procedural justice. Affordability outcomes depend not only on policy content but also on the processes through which climate policies are designed, communicated, and implemented [37]. Public acceptance is consistently found to be higher when affected communities perceive decision-making processes as transparent, inclusive, and procedurally fair. Moreover, meaningful participation can improve policy effectiveness by incorporating local knowledge, strengthening public trust, and facilitating long-term implementation. Conversely, even environmentally effective policies may encounter substantial political resistance when transition costs are perceived as unfairly distributed or when vulnerable groups have limited opportunities to participate in decision-making [13].

Taken together, the reviewed literature indicates that affordability–sustainability interactions are fundamentally shaped by the allocation of resources, opportunities, and adaptive capabilities across households, regions, and countries. Rather than representing an inevitable consequence of ambitious climate policy, affordability challenges primarily arise from the interaction between existing socio-economic inequalities and the design of transition policies. Successful decarbonisation, therefore, requires more than reducing energy prices or compensating vulnerable groups. It depends on governance arrangements that expand access to low-carbon technologies, strengthen long-term resilience, and ensure that both the costs and the benefits of the transition are shared more equitably across society. From this perspective, affordability should be understood not merely as a question of economic burden but as a broader issue of distributive and procedural justice that ultimately shapes the social legitimacy, political durability, and long-term effectiveness of the low-carbon transition.

Finally, although many affordability–sustainability tensions can be mitigated through equitable policy design and stronger adaptive capacity, they remain closely intertwined with energy security considerations. Measures intended to improve affordability influence investment incentives, infrastructure development, and the pace of decarbonisation, while security-oriented policies frequently generate important distributional consequences. These multidirectional interactions illustrate the limitations of analysing the three dimensions of the energy trilemma in isolation and provide the foundation for the integrated trilemma perspective developed in the following section.

4.3. Energy Security–Affordability Interactions

The interaction between energy security and affordability has traditionally been framed as a trade-off between maintaining low energy costs and ensuring reliable energy supplies. Under stable market conditions, access to inexpensive imported fuels may simultaneously support affordability and economic competitiveness, creating the impression that greater external dependence represents an economically efficient energy strategy [16,42]. In contrast, other evidence reviewed here indicates that import-dependent systems may experience disproportionate welfare losses when supply conditions deteriorate [17,43]. These apparently conflicting findings can be understood in relation to differences in the prevailing risk environment: the security–affordability relationship is contingent rather than fixed. Energy systems that appear economically optimal during periods of stable supply may become particularly vulnerable when geopolitical tensions, supply disruptions, or prolonged price volatility materialise, rapidly transforming low-cost dependence into a source of significant welfare losses [17].

A central conclusion emerging from the reviewed studies is, therefore, that the relationship between energy security and affordability is fundamentally state-dependent rather than static. Affordability cannot be evaluated solely on the basis of average energy prices observed under normal market conditions because these prices frequently fail to reflect the economic costs associated with supply disruptions, geopolitical instability, and fuel price volatility [16]. Conversely, investments intended to strengthen energy security—including supply diversification, domestic energy production, renewable deployment, and broader resilience measures—may increase costs in the short term while substantially reducing exposure to severe price shocks over the longer term. Consequently, security and affordability should not be interpreted as inherently competing objectives but as dimensions whose interaction changes across different risk regimes [17,43].

This perspective shifts the analytical focus from comparing the average costs of alternative energy systems towards evaluating their performance under uncertainty. Rather than asking which energy system delivers the lowest prices during normal conditions, the reviewed literature increasingly examines how different energy configurations respond to geopolitical shocks, supply interruptions, and persistent fuel-price volatility [16]. From this perspective, energy security functions less as a source of immediate economic efficiency than as a form of resilience insurance, whereby additional investments undertaken during stable periods may reduce the likelihood and severity of future affordability crises. This interpretation provides the conceptual foundation for understanding the dynamic interactions between security and affordability explored in the remainder of this section [43].

The reviewed literature consistently demonstrates that energy affordability and energy security frequently reinforce one another under stable market conditions but diverge during periods of disruption. Energy systems relying heavily on inexpensive imported fossil fuels may provide low consumer prices and support short-term economic competitiveness when international markets function efficiently [16]. However, this apparent affordability often reflects favourable market conditions rather than intrinsic system resilience, leaving countries highly exposed to external shocks beyond domestic policy control. Consequently, energy affordability achieved through import dependence may prove considerably more fragile than conventional price-based indicators suggest [43].

This distinction highlights an important asymmetry between affordability and security. While the economic benefits of low-cost energy are immediately visible through lower household expenditure and reduced production costs, the value of energy security often remains largely invisible until disruptions occur. Investments in supply diversification, strategic reserves, domestic energy production, or renewable capacity may, therefore, appear economically inefficient during periods of stable supply because their principal benefits lie in reducing the probability and severity of future crises rather than lowering present-day energy prices [16]. From this perspective, energy security functions as a form of resilience investment whose economic value becomes fully apparent only under adverse conditions [17].

The reviewed studies further suggest that this apparent trade-off reflects differences in analytical time horizons rather than an inherent incompatibility between security and affordability. Policies prioritising the lowest short-term energy costs may inadvertently increase long-term exposure to geopolitical instability, supply interruptions, and extreme price volatility [16]. Conversely, strategies involving higher upfront investments in renewable energy, domestic generation capacity, storage, or system flexibility may temporarily increase system costs while substantially reducing future affordability risks. Accordingly, the interaction between security and affordability should be understood as an intertemporal trade-off in which short-term economic efficiency is balanced against long-term resilience [17,43,44].

Recent research, therefore, increasingly argues that conventional assessments based solely on average energy prices provide an incomplete picture of affordability. Energy systems should instead be evaluated according to their capacity to maintain acceptable energy costs under conditions of uncertainty [16]. This broader perspective shifts attention from static price comparisons towards system robustness, highlighting that affordability depends not only on the level of energy prices but also on their stability, predictability, and resistance to external shocks. As a result, resilient energy systems may ultimately provide more sustainable affordability outcomes than systems optimised exclusively for minimum short-term cost [17].

The reviewed literature indicates that major energy crises fundamentally alter the relationship between energy security and affordability by exposing vulnerabilities that remain largely hidden under stable market conditions. The 2022 global energy crisis demonstrated that energy systems optimised primarily for short-term economic efficiency may experience abrupt and substantial affordability losses when fuel supplies are disrupted or when international prices become highly volatile [17,42,45]. Under such conditions, concerns traditionally associated with energy security—including import dependence, supply diversification, and domestic generation capacity—rapidly become affordability concerns as escalating wholesale prices are transmitted to households, businesses, and public finances [16].

This shift has important implications for the economic evaluation of low-carbon transitions. Prior to major supply disruptions, investments in renewable energy, storage technologies, and domestic low-carbon generation were frequently criticised for increasing electricity system costs or requiring substantial public support. However, the reviewed studies suggest that energy crises fundamentally reshape this assessment by revealing the economic value of technologies that reduce exposure to imported fossil fuels and volatile international energy markets [17]. Measures previously regarded primarily as environmental investments increasingly become recognised as instruments for stabilising energy prices and strengthening long-term affordability [43].

Importantly, the reviewed evidence does not suggest that renewable energy automatically guarantees affordable or secure energy systems. Rather, crisis experience demonstrates that affordability gains depend on whether renewable deployment is accompanied by adequate investments in electricity networks, storage capacity, system flexibility, and institutional preparedness [17,44]. Without these complementary measures, new forms of price volatility and reliability risks may emerge even as dependence on imported fossil fuels declines. Consequently, the economic benefits of decarbonisation arise not from renewable technologies alone but from the development of resilient energy systems capable of maintaining reliable and affordable energy services under changing market conditions [16,43].

The reviewed literature, therefore, increasingly frames recent energy crises not simply as temporary market disturbances but as critical learning events that have reshaped both academic and policy perspectives on the interaction between security and affordability. Rather than demonstrating a conflict between decarbonisation and economic performance, the evidence suggests that crises expose the hidden costs of fossil fuel dependence while highlighting the long-term economic value of resilience-oriented investments [17,42,45]. In this sense, periods of disruption accelerate a broader transition from evaluating energy systems according to short-term price efficiency towards assessing their capacity to provide stable, affordable, and secure energy under conditions of uncertainty [16].

While the preceding discussion has focused primarily on energy systems and market dynamics, the reviewed literature demonstrates that the interaction between energy security and affordability ultimately materialises at the household level. Supply disruptions, geopolitical instability, and wholesale price volatility influence affordability not only through macroeconomic indicators but also through rising retail energy prices, increased living costs, and heightened risks of energy poverty [16,42]. Consequently, large-scale energy security challenges are translated into everyday economic pressures that directly affect household welfare and social resilience.

The reviewed studies further suggest that households experience energy insecurity primarily through increased price volatility rather than permanent increases in average energy prices. Periods of rapid market disruption create substantial uncertainty regarding future energy expenditure, reducing households' ability to plan consumption, allocate financial resources, and maintain essential energy services [42]. This uncertainty disproportionately affects vulnerable consumers with limited financial reserves or restricted opportunities to adjust energy use, thereby reinforcing the economic consequences of broader supply shocks [17].

Importantly, the reviewed evidence indicates that policies strengthening energy security may simultaneously enhance long-term household affordability when they reduce exposure to future price instability. Investments in renewable electricity generation, domestic energy resources, storage capacity, and system flexibility not only improve the resilience of national energy systems but also contribute to more stable and predictable energy costs for consumers over time [16,43]. Accordingly, affordability should be evaluated not only according to current price levels but also in relation to the stability and reliability of future energy expenditure under changing geopolitical and market conditions [17].

These findings also help explain why public perceptions of the low-carbon transition frequently change following major energy crises. During periods of stable markets, investments in energy security may be perceived primarily as additional economic costs. Following supply disruptions, however, the capacity to maintain affordable and reliable energy increasingly becomes recognised as a direct social and economic benefit [42]. In this sense, crises not only reshape the objective interaction between security and affordability but also alter public understanding of the economic value of resilient energy systems [17].

Taken together, the reviewed literature suggests that the relationship between energy security and affordability cannot be adequately understood through static comparisons of energy prices or supply indicators alone. Instead, both dimensions evolve dynamically as energy systems respond to changing geopolitical conditions, market disruptions, and technological transformation. Strategies that minimise costs under stable conditions may substantially increase vulnerability during crises, whereas investments that initially appear more expensive often improve affordability by reducing future exposure to severe price shocks. Consequently, energy security and affordability should be viewed as mutually reinforcing dimensions of resilient low-carbon energy systems rather than as permanently competing policy objectives. This dynamic perspective provides the final conceptual bridge towards the integrated trilemma framework developed in the following section.

4.4. From Bilateral Trade-Offs to Integrated Trilemma Dynamics

The bilateral interactions reviewed in the preceding sections provide important insights into the relationships between energy security, affordability, and environmental sustainability. However, the reviewed evidence also demonstrates that these dimensions cannot be fully understood in isolation. Improvements in one objective frequently alter the conditions under which the remaining two operate, creating indirect effects, feedback mechanisms, and evolving trade-offs that extend beyond simple pairwise relationships. Consequently, the low-carbon energy transition should be analysed as an integrated system in which security, affordability, and sustainability continuously interact rather than as three independent policy objectives linked only through bilateral trade-offs.

Evidence from multi-objective energy system studies reinforces this perspective by demonstrating that the three dimensions evolve simultaneously rather than sequentially [46,47]. Instead of forming a fixed triangle in which progress in one objective necessarily comes at the expense of another, the energy trilemma is more accurately represented as a dynamic and nonlinear possibility frontier. Within this frontier, significant simultaneous improvements in security, affordability, and environmental sustainability are often achievable before increasingly ambitious policy objectives generate steeper marginal trade-offs. Consequently, the compatibility between trilemma objectives changes as energy systems evolve rather than remaining constant across all transition pathways [48].

This interpretation helps reconcile many of the apparent contradictions identified in the previous sections. Security–sustainability interactions demonstrated that technological innovation and institutional coordination can transform traditional energy security risks rather than simply reducing them. Affordability–sustainability interactions showed that distributional outcomes depend on how transition costs, benefits, and opportunities are allocated across society. Security–affordability interactions further illustrated that the economic value of resilience becomes apparent primarily under conditions of uncertainty and disruption. Considered individually, these findings describe different bilateral relationships. Considered together, however, they indicate that changes affecting one trilemma dimension inevitably reshape the others through multiple interconnected mechanisms rather than through isolated trade-offs.

Across these bilateral relationships, four recurring interaction patterns can be identified. First, risk substitution occurs when reductions in fossil fuel dependence create new vulnerabilities associated with grids, flexibility, technologies, or critical material supply chains. Second, temporal trade-offs arise when transition costs and infrastructure requirements materialise before longer-term security, affordability, or environmental benefits are realised. Third, distributional mediation occurs when similar policies generate different affordability outcomes because households, regions, and countries differ in their capacity to absorb costs and access transition benefits. Fourth, conditional synergy emerges when complementary infrastructure, institutional coordination, and policy design allow improvements in one trilemma dimension to reinforce rather than constrain the others. These patterns, summarised in Table 3, indicate that dynamic outcomes can be identified through changes in the direction, intensity, and distribution of interactions as underlying technological, institutional, and socio-economic conditions evolve.

A historical perspective further reinforces the importance of temporal dynamics in interpreting contemporary trilemma interactions. Evidence from previous energy transitions indicates that large-scale changes in energy systems have typically unfolded over several decades, reflecting the scale, infrastructural requirements, and technological interdependencies of energy systems [49,50]. Transition speed has nevertheless varied substantially across technologies and national contexts, with later adopters sometimes benefiting from accumulated technological learning while early adopters remain constrained by sunk investments and established infrastructures [49]. These historical patterns suggest that contemporary trade-offs should not be interpreted solely as properties of particular technologies or policies but also as outcomes conditioned by the stage and inherited structure of the transition.

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Table 3. Recurring interaction patterns shaping energy trilemma outcomes.

Interaction Pattern	Brief Definition	Typical Triggering Conditions
Risk substitution	Improvement in one trilemma dimension reduces an existing vulnerability but creates or increases a different risk elsewhere in the energy system.	Technological substitution; shifts in import dependence; growing reliance on electricity networks, critical materials, or clean-technology supply chains; insufficient system adaptation.
Temporal trade-offs	Costs, risks, and benefits across trilemma dimensions emerge over different time horizons, producing tensions between short-term adjustment and longer-term gains.	Rapid transition measures; infrastructure investment cycles; temporary capacity constraints; technology deployment ahead of supporting infrastructure or institutional adaptation.
Distributional mediation	The direction and intensity of a trilemma interaction depend on how transition costs, benefits, and adaptive opportunities are distributed across households, regions, or socio-economic groups.	Unequal household resources; energy price exposure; differences in access to low-carbon technologies; regional economic dependence; uneven incidence of policy costs and benefits.
Conditional synergy	Improvements in two or more trilemma dimensions become mutually reinforcing when enabling technological, institutional, or infrastructural conditions are present.	Adequate grid flexibility and infrastructure; effective governance and policy coordination; supportive market design; technological maturity; sufficient adaptive capacity.

Rather than representing a fixed balance between competing objectives, the reviewed literature increasingly suggests that the energy trilemma should be understood as a dynamic possibility frontier whose shape continuously evolves in response to technological progress, institutional change, and shifting external conditions [46,48]. Consequently, the interaction between security, affordability, and sustainability is not determined by immutable trade-offs but by the characteristics of the energy system within which these objectives are pursued. Technological innovation, infrastructure development, policy design, and geopolitical conditions may all expand or constrain the range of feasible policy outcomes, allowing some trade-offs to be transformed into synergies while simultaneously creating new constraints elsewhere [47]. This interpretation of the trilemma as a dynamic possibility frontier is developed further in Section 5, where the concept is explicitly linked to the contextual conditions identified in the review and translated into an operationally interpretable framework.

An important implication of this perspective is that the intensity of trade-offs is rarely constant. Evidence from multi-objective optimisation studies demonstrates that substantial simultaneous improvements across all three trilemma dimensions are often achievable when energy systems move away from inefficient baseline configurations [46]. However, as policy ambitions become progressively more demanding—whether through increasingly stringent decarbonisation targets, higher levels of energy autonomy, or maximum reliability requirements—the marginal compatibility between objectives gradually declines. Under these conditions, additional gains in one dimension are increasingly likely to require disproportionate sacrifices in another, indicating that trade-offs emerge progressively rather than existing from the outset of the transition [51,52].

This nonlinear interpretation also helps explain why similar policy instruments frequently produce different outcomes across countries and regions. As demonstrated throughout the preceding sections, technological deployment alone does not determine trilemma performance. The effectiveness of renewable energy, energy efficiency, electrification, or diversification strategies depends on existing infrastructure, resource endowments, market structures, institutional quality, and geopolitical conditions [9,53]. Consequently, policies that successfully generate synergies in one energy system may produce more pronounced trade-offs in another, not because the technologies themselves differ but because the surrounding system conditions fundamentally alter the feasible balance between security, affordability, and sustainability [10,47].

This perspective also reconciles the temporal and distributional dynamics identified in the previous sections. Trade-offs frequently arise because transition costs, security risks, and environmental benefits materialise over different time horizons, while their economic and social consequences are distributed unevenly across households, regions, and countries. As a result, the position of an energy system within the trilemma frontier is determined not only by technological performance but also by when benefits emerge, who bears transition costs, and how institutions manage the resulting distributional and geopolitical tensions. Rather than representing external complications, these temporal and distributional dimensions constitute integral components of trilemma dynamics that shape the feasibility of different transition pathways.

Taken together, the reviewed evidence suggests that no universal relationship exists between energy security, affordability, and environmental sustainability. Rather than being governed by fixed trade-offs, trilemma outcomes emerge from the interaction of technological, institutional, economic, and geopolitical conditions that shape both the opportunities and constraints of individual transition pathways. Consequently, similar policy interventions may generate markedly different outcomes depending on the characteristics of the energy system in which they are implemented, the timing of the transition, and the external conditions under which policy decisions are made [9,46,53].

This interpretation has important implications for both research and policy. Much of the existing literature continues to evaluate trilemma performance through static indicators or average national-level outcomes. However, the evidence synthesised in this review indicates that such approaches risk obscuring the mechanisms through which trade-offs and synergies evolve over time. Identical aggregate outcomes may arise through fundamentally different transition pathways, while similar policy instruments may produce contrasting results depending on technological maturity, infrastructure availability, governance arrangements, and exposure to external shocks. Understanding the energy trilemma, therefore, requires moving beyond static performance assessment towards analysing the dynamic conditions under which interactions between the three dimensions are strengthened, weakened, or fundamentally transformed.

Accordingly, the findings synthesised across Sections 4.1–4.4 support a broader conceptual interpretation of the low-carbon energy trilemma. Rather than representing a fixed optimisation problem, the trilemma should be understood as a dynamic and context-sensitive decision space in which trade-offs and synergies continuously evolve as technologies mature, institutions adapt, transition pathways progress, and geopolitical conditions change. Within this perspective, temporal dynamics, distributional processes, and institutional context are not external influences acting upon an otherwise stable trilemma. Instead, they constitute fundamental mechanisms through which interactions between security, affordability, and sustainability are produced and reshaped over time.

This conceptual interpretation provides the foundation for the analytical framework proposed in the following section. Building on the evidence synthesised throughout this review, the framework seeks to explain not only whether trade-offs or synergies emerge, but also when, for whom, and under which contextual conditions they are most likely to arise. By explicitly incorporating temporal, distributional, and contextual dimensions, the proposed framework aims to provide a more comprehensive basis for analysing low-carbon transition pathways than approaches relying solely on static representations of the energy trilemma.

5. A Context-Sensitive Framework for the Low-Carbon Energy Trilemma

5.1. From Static Trade-Offs to Dynamic Interactions

Traditional interpretations of the energy trilemma have frequently conceptualised energy security, affordability, and environmental sustainability as three competing policy objectives requiring continuous balancing. Within this perspective, improvements in one dimension are often assumed to occur at the expense of another, leading to the widespread perception that trade-offs constitute an inherent characteristic of energy transitions. While this representation has provided a useful heuristic for analysing competing policy priorities, the synthesis presented in this review suggests that such a static interpretation no longer adequately captures the complexity of contemporary low-carbon transitions.

Rather than identifying universal relationships between the three dimensions of the trilemma, the reviewed evidence consistently demonstrates that interactions among energy security, affordability, and environmental sustainability vary according to the broader context within which transition pathways unfold. Across the three pairwise interactions examined in Section 4, similar policy measures were shown to generate markedly different outcomes depending on technological maturity, institutional capacity, distributional characteristics, geopolitical conditions, and the temporal stage of the transition. Consequently, trade-offs and synergies emerge not as fixed properties of the energy trilemma itself but as context-dependent outcomes shaped by evolving socio-technical systems.

This observation represents a common thread linking the findings across all three interaction dimensions. In the case of energy security and environmental sustainability, renewable energy deployment and electrification were found to strengthen long-term resilience while simultaneously introducing new dependencies associated with electricity networks, critical materials, and digital infrastructure. Likewise, affordability–sustainability interactions were shown to depend less on the environmental ambition of climate policies than on how transition costs, benefits, and adaptive opportunities are distributed across households, regions, and countries. Similarly, the relationship between energy security and affordability proved highly contingent on changing geopolitical conditions, illustrating how strategies that minimise costs under stable market conditions may substantially increase vulnerability during periods of disruption. Taken together, these findings indicate that neither trade-offs nor synergies are predetermined outcomes of decarbonisation; instead, they emerge through the interaction between transition pathways and the contextual conditions under which they are implemented.

Across these interactions, the synthesis draws on the four recurring patterns already identified in Section 4.4—risk substitution, temporal trade-offs, distributional mediation, and conditional synergy—through which dynamic trilemma outcomes emerge. These recurring patterns provide the analytical link between the bilateral evidence synthesised in Section 4 and the contextual dimensions incorporated into the framework.

The framework components were derived from recurring mechanisms identified across these bilateral and integrated syntheses. Technological conditions emerged primarily from evidence concerning renewable integration, electrification, grid flexibility, and critical material dependencies; distributional conditions from differences in household adaptive capacity, access to low-carbon technologies, and the allocation of transition costs and benefits; and geopolitical conditions from evidence concerning import dependence, supply chain exposure, and energy price shocks. Institutional conditions repeatedly appeared across all three bilateral interactions as determinants of whether technological and economic changes translated into trade-offs or synergies, while temporal conditions reflected both the recurrent distinction between short-term transition costs and longer-term resilience, affordability, and sustainability gains and the historical evidence that energy system transformation is shaped by long transition periods, infrastructure inertia, and accumulated technological and institutional legacies [49,50]. These recurring cross-cutting mechanisms were, therefore, consolidated into the five contextual dimensions represented in the framework.

Building upon this synthesis, the present review proposes a context-sensitive analytical framework that conceptualises the energy trilemma as a dynamic system of interactions rather than a static balance among competing objectives. Instead of treating energy security, affordability, and environmental sustainability as independent policy targets linked by fixed trade-offs, the framework emphasises that their interactions continuously evolve in response to changing technological, institutional, geopolitical, distributional, and temporal conditions. In this perspective, contextual conditions do not merely influence the severity of individual challenges but actively shape how the three dimensions interact, determining whether particular transition pathways generate reinforcing synergies or conflicting trade-offs.

Accordingly, the framework positions low-carbon transition pathways as the starting point of an adaptive process in which technological development, governance arrangements, market structures, social conditions, and external geopolitical factors jointly influence the configuration of trilemma interactions. These interactions subsequently produce different combinations of trade-offs and synergies, which inform adaptive policy and governance responses. Importantly, such responses do not simply mitigate undesirable outcomes but also reshape the contextual conditions under which future transition pathways evolve, creating a continuous process of institutional learning and system adaptation rather than a one-directional transition.

The proposed framework should, therefore, be understood as an analytical synthesis derived from the reviewed literature rather than as a new theoretical model of the energy trilemma. Its primary contribution lies in integrating previously fragmented evidence into a coherent conceptual structure capable of explaining why similar decarbonisation strategies often produce different outcomes across countries, sectors, and time periods. By shifting attention from static policy trade-offs towards context-dependent interactions and adaptive governance, the framework provides a foundation for analysing low-carbon transitions as dynamic socio-technical processes characterised by continuous feedback between technological change, institutional development, and policy responses.

5.2. The Context-Sensitive Analytical Framework

The proposed framework is presented in Figure 2. It conceptualises the energy trilemma as a dynamic system of interactions in which relationships among energy security, affordability, and environmental sustainability are continuously shaped by evolving contextual conditions rather than determined by fixed relationships between the three dimensions. Instead of representing the trilemma as a static balance among competing policy objectives, the framework highlights that transition outcomes emerge through successive interactions between decarbonisation pathways, contextual factors, trilemma dynamics, and adaptive policy responses. This perspective reflects the central finding of the present review that neither trade-offs nor synergies should be regarded as predetermined characteristics of low-carbon transitions; rather, they arise from the interaction between transition pathways and the technological, institutional, temporal, distributional, and geopolitical conditions under which these pathways unfold.

The framework begins with low-carbon transition pathways, representing the broad processes through which energy systems evolve towards lower carbon intensity. These pathways encompass different combinations of decarbonisation measures, including renewable energy deployment, electrification, energy efficiency improvements, infrastructure development, and changes in energy supply and demand. Rather than prescribing a single transition trajectory, the framework recognises that countries may pursue diverse technological and policy pathways depending on their resource endowments, institutional capacities, and development priorities. Consequently, transition pathways constitute the starting point of the analytical process rather than its desired endpoint, acknowledging that different routes towards decarbonisation may generate substantially different trilemma outcomes.

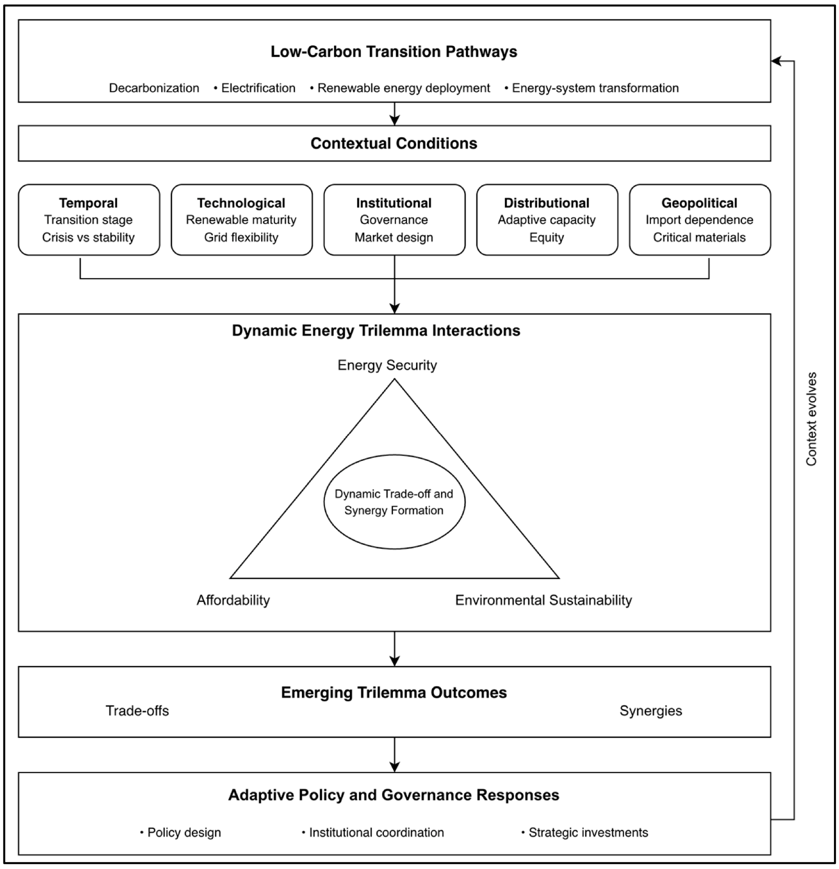

Figure 2. Context-sensitive analytical framework of the low-carbon energy trilemma derived from the thematic synthesis. The framework illustrates how low-carbon transition pathways interact with technological, institutional, temporal, distributional, and geopolitical conditions to shape evolving trade-offs and synergies among energy security, affordability, and environmental sustainability, which, in turn, inform adaptive policy and governance responses.

The second component of the framework comprises contextual conditions, which function as the principal moderators of trilemma interactions. The synthesis presented in this review identifies five interrelated contextual dimensions that consistently influence transition outcomes: temporal, technological, institutional, distributional, and geopolitical conditions. Temporal conditions recognise that trade-offs and synergies frequently evolve over different time horizons, with short-term adjustment costs often preceding longer-term resilience and sustainability gains. Technological conditions reflect differences in renewable maturity, electricity system flexibility, and infrastructure readiness that determine the capacity of energy systems to integrate low-carbon technologies. Institutional conditions encompass governance quality, market design, and policy coherence, shaping the effectiveness with which transition strategies are implemented. Distributional conditions capture variations in adaptive capacity, equity, and access to transition opportunities across households, regions and countries, while geopolitical conditions reflect external dependencies associated with fuel imports, critical materials, and international supply chains. Collectively, these contextual dimensions determine how similar transition pathways may produce markedly different outcomes across different socio-economic and political settings.

For empirical application, these five contextual dimensions can be translated into observable system characteristics rather than treated solely as abstract analytical categories. Technological conditions may be represented by measures of renewable energy penetration, electrification, storage, and system flexibility, grid adequacy, and technological maturity. Institutional conditions may be captured by indicators of governance effectiveness, regulatory quality, policy stability, and coordination capacity. Temporal conditions may be represented by transition stage, deployment trajectories, and investment cycles. Distributional conditions may be examined through household energy burdens, energy poverty, access to low-carbon technologies, and the incidence of transition costs and benefits, while geopolitical conditions may be represented by energy import dependence, supplier concentration, and exposure to critical-material and clean technology supply chains. These measures are illustrative rather than prescriptive, as their appropriate operationalisation will depend on the geographical scale, transition context, and specific research question. Nevertheless, they provide observable counterparts through which the contextual relationships proposed by the framework can be examined empirically in subsequent research.

Rather than acting independently, these contextual conditions jointly shape the dynamic interactions among the three dimensions of the energy trilemma. At the centre of the framework, energy security, affordability, and environmental sustainability are, therefore, represented not as isolated policy objectives but as mutually interacting system characteristics. Their relationships continuously evolve as contextual conditions change, creating dynamic patterns of reinforcement and tension throughout the transition process. This representation shifts analytical attention away from identifying universal trade-offs towards understanding the mechanisms through which interactions develop under different contextual circumstances. In doing so, the framework emphasises that successful low-carbon transitions depend less on optimising individual objectives than on managing the evolving relationships between them. In empirical applications, changes in the three outcome dimensions could correspondingly be assessed using established measures of supply and system security, household and system-level affordability, and environmental performance, with indicator selection adapted to the specific analytical context.

Within this operational interpretation, the "dynamic possibility frontier" discussed in Section 4.4 represents the boundary of feasible combinations of energy security, affordability, and environmental sustainability attainable under a given set of contextual conditions. The three trilemma dimensions define the outcome space, while the technological, institutional, temporal, distributional, and geopolitical conditions described above influence the position and shape of this frontier. The position and evolution of this frontier may also be path-dependent, as inherited energy infrastructures, technologies, and institutional arrangements can constrain the feasible direction and pace of subsequent energy system transformation [54]. Movement along the frontier represents a change in the balance among the three objectives under broadly unchanged contextual conditions, whereby improvement in one dimension may require a deterioration in another. By contrast, an outward shift of the frontier occurs when technological innovation, infrastructure development, institutional improvement, or other favourable contextual changes expand the set of simultaneously attainable outcomes, allowing one or more trilemma dimensions to improve without an equivalent deterioration elsewhere. Conversely, adverse contextual changes may constrain the feasible set and shift the frontier inward. The frontier is, therefore, used here as an analytical representation of changing feasible trade-offs rather than as an empirically estimated efficiency frontier.

The interaction of these three dimensions subsequently generates emerging trilemma outcomes, represented by different configurations of trade-offs and synergies. Importantly, these outcomes should not be interpreted as fixed or binary states. Instead, they represent evolving system responses that may coexist, overlap, or change over time as technologies mature, institutions adapt, and external conditions evolve. Policies that initially generate affordability challenges may ultimately strengthen long-term resilience and sustainability, while measures enhancing energy security under one set of geopolitical conditions may create new vulnerabilities under another. Accordingly, the framework conceptualises trade-offs and synergies as dynamic outcomes that emerge from the interaction between transition pathways and contextual conditions rather than as inherent properties of specific technologies or policy instruments.

The final component of the framework consists of adaptive policy and governance responses, which translate emerging transition outcomes into institutional learning and strategic action. Operationally, this adaptive cycle involves monitoring emerging trilemma outcomes, identifying the contextual constraints responsible for significant trade-offs, adjusting the relevant policy or investment response, and reassessing how the resulting changes in contextual conditions affect subsequent trilemma interactions. Rather than viewing policy intervention as a one-off response to isolated trade-offs, the framework conceptualises governance as a continuous adaptive process encompassing policy design, institutional coordination, and strategic investments. These responses seek not only to mitigate undesirable outcomes but also to strengthen the conditions under which future synergies become more likely. Through this adaptive process, governance progressively modifies technological capabilities, institutional arrangements, distributional conditions, and broader system resilience, thereby reshaping the contextual environment within which subsequent transition pathways evolve.

The feedback loop incorporated within the framework represents this process of continuous adaptation. Instead of depicting the low-carbon transition as a linear progression from policy implementation to predefined outcomes, the framework recognises that each round of policy intervention alters the contextual conditions influencing future decisions. Consequently, the energy trilemma is conceptualised as an evolving socio-technical system characterised by iterative learning, institutional adaptation and continuous adjustment to changing technological, economic, and geopolitical conditions. This dynamic perspective provides a more comprehensive basis for analysing low-carbon transitions than conventional static representations of the trilemma, while remaining sufficiently flexible to accommodate diverse national contexts and future technological developments. The framework, therefore, generates empirically examinable expectations rather than fixed causal predictions: similar transition measures should produce different trilemma outcomes where the relevant technological, institutional, temporal, distributional, or geopolitical conditions differ. Comparative and longitudinal research can subsequently examine whether changes in these contextual conditions systematically correspond to changes in the direction or intensity of observed trade-offs and synergies.

6. Policy Implications

The findings synthesised in this review suggest that effective management of the low-carbon energy trilemma requires a shift away from policy approaches that seek to optimise energy security, affordability, and environmental sustainability as separate objectives. Instead, the proposed analytical framework highlights that policy outcomes emerge from the dynamic interactions among these dimensions under evolving technological, institutional, distributional, and geopolitical conditions [9,46]. Consequently, successful low-carbon transitions depend less on identifying universally optimal policy instruments than on designing governance arrangements capable of responding to changing contextual conditions. From this perspective, the principal challenge for policymakers is not to eliminate trade-offs altogether but to manage their evolution while creating conditions under which long-term synergies become increasingly attainable [5,6].

A first implication concerns the importance of context-sensitive policy design. The synthesis presented in this review demonstrates that similar decarbonisation measures may produce substantially different outcomes depending on transition stage, institutional capacity, technological maturity, distributional characteristics, and geopolitical conditions. Policy priorities should, therefore, reflect the structural position of individual energy systems rather than follow a uniform transition template. In relatively advanced transition systems with mature renewable deployment and stronger institutional capacity, priorities increasingly shift towards grid expansion, storage, system flexibility, and the management of emerging material dependencies [26]. By contrast, fossil fuel- and import-dependent systems facing more rapid structural change may need to place greater emphasis on sequencing diversification and low-carbon investment with measures that limit short-term affordability and security risks. Where institutional or investment capacity is more constrained, implementation feasibility, access to finance, and protection against energy exclusion become particularly important. Context-sensitive policy design, therefore, requires not simply transferring successful instruments between countries but assessing whether the technological, institutional and socio-economic conditions necessary for their effectiveness are present [5,7].

A second implication relates to integrated and adaptive governance. Throughout the review, technological innovation, infrastructure development, industrial policy, social protection, and market regulation were repeatedly shown to influence multiple dimensions of the energy trilemma simultaneously. Energy policy should, therefore, be coordinated with industrial, social, and environmental policy, particularly where decarbonisation creates new infrastructure requirements, employment effects, or exposure to strategic supply chains [7,13]. The appropriate policy mix should also change as transitions progress. Early transition stages may require investment support, infrastructure development, and protection against concentrated adjustment costs, whereas more mature systems may increasingly require flexibility markets, network reinforcement, demand-side participation, and measures addressing new dependencies created by electrification. Effective governance, therefore, requires continuous monitoring, institutional learning, and periodic policy adjustment rather than assuming that a single policy configuration will remain appropriate throughout the transition [5,32].

A third implication concerns the management of trade-offs themselves. The evidence reviewed in this study indicates that many trade-offs emerge not because policy objectives are fundamentally incompatible but because they materialise over different temporal horizons or affect different social groups [38,40]. Consequently, policy evaluation should extend beyond short-term economic efficiency towards a broader assessment of long-term system resilience, distributional fairness, and adaptive capacity. Investments that appear economically costly during early transition stages may substantially reduce future exposure to supply disruptions, price volatility, or social vulnerability, thereby generating benefits that are not captured by conventional short-term evaluation frameworks. Managing the energy trilemma, therefore, requires recognising trade-offs as dynamic transition phenomena that can often be moderated, redistributed, or transformed through appropriate policy sequencing and complementary interventions rather than accepted as fixed constraints [6,36].

A fourth implication concerns the geopolitical asymmetries created and transformed by the low-carbon transition. Reducing dependence on imported fossil fuels can strengthen energy security, but greater reliance on critical minerals, clean technology supply chains, and increasingly interconnected electricity systems may generate different forms of external dependence [7,33]. These risks are distributed unevenly. Import-dependent energy systems, countries controlling strategic resources or processing capacity, and economies strongly exposed to fossil fuel revenues occupy different positions within emerging low-carbon supply chains and, therefore, face different combinations of security and adjustment risks [34]. Diversification should consequently extend beyond fuel suppliers to critical materials, technologies, processing capacity, and infrastructure, while avoiding the replacement of one concentrated dependency with another. For resource-dependent economies, diversification also has a domestic dimension, as declining fossil fuel demand may create fiscal, employment, and regional adjustment pressures that require economic and industrial transition strategies alongside energy policy. Geopolitical resilience should, therefore, be assessed in terms of both external supply exposure and the capacity of domestic economies to adapt to changing patterns of energy production and trade.

A fifth implication concerns the distributional management of transition trade-offs. The evidence reviewed in this study indicates that many apparent conflicts between affordability and sustainability arise because transition costs, benefits, and adaptive opportunities are unevenly distributed across households, regions, and social groups [37,39]. Energy justice should, therefore, be treated as an integral condition of transition feasibility rather than solely as a compensatory concern. Policy assessment should consider not only aggregate costs and benefits but also who bears upfront investment costs, who can access efficiency improvements and low-carbon technologies, and which households, workers, or regions remain particularly exposed to energy price or structural adjustment risks. Targeted social protection, equitable access to transition technologies, and place-sensitive support for adversely affected regions can reduce these asymmetries without abandoning longer-term decarbonisation objectives. These distributional choices also affect social acceptance: transition measures that are efficient at the system level may encounter persistent resistance when their costs are concentrated among groups with limited capacity to adapt or when affected communities have little influence over implementation [14,40]. Managing affordability and public acceptance, therefore, requires incorporating distributional considerations into policy design from the outset rather than addressing them only after adverse effects emerge.

Finally, the proposed framework provides a practical analytical structure for supporting strategic decision-making under conditions of uncertainty. Its principal policy value lies not in prescribing a universal set of instruments but in identifying the conditions that should be considered when selecting and sequencing transition measures. Policymakers can use the framework to assess how transition stage, technological readiness, institutional capacity, distributional vulnerability, and geopolitical exposure are likely to shape interactions among security, affordability, and environmental sustainability. This requires assessing not only whether a policy contributes to decarbonisation but also when its costs and benefits will materialise and which groups will bear them. Policy assessment should also consider the new dependencies a measure may create and whether existing institutions have the capacity to manage the resulting adjustment. Such assessment should be repeated as transition conditions evolve, allowing policy mixes to adapt when previously beneficial synergies weaken or new trade-offs emerge. In this way, the framework supports a shift from static trilemma optimisation towards context-sensitive and adaptive transition governance.

7. Research Gaps and Future Research Directions

The synthesis presented in this review demonstrates that research on the energy trilemma has expanded considerably during the low-carbon transition, reflecting growing recognition of the complex interactions between energy security, affordability, and environmental sustainability. At the same time, the reviewed literature reveals several recurring limitations that extend beyond individual studies and characterise the field more broadly. These limitations do not necessarily reflect weaknesses in existing research; rather, they illustrate the rapid evolution of the energy transition itself, where technological innovation, geopolitical change, and emerging policy challenges continuously reshape research priorities. Building upon the evidence synthesised throughout this review, three research priorities appear particularly important for advancing understanding of the low-carbon energy trilemma.

A first priority concerns the need to move beyond static assessments towards dynamic and longitudinal analyses of trilemma interactions. Much of the existing literature continues to evaluate relationships between energy security, affordability, and environmental sustainability using cross-sectional indicators or fixed policy scenarios. While these approaches provide valuable snapshots of transition performance, they often overlook the temporal evolution of trade-offs and synergies throughout the transition process. This limitation becomes increasingly important as electrification expands, renewable penetration increases, and energy systems progressively shift from fossil fuel dependence towards more infrastructure- and electricity-intensive configurations. Longitudinal and scenario-based research is, therefore, needed to distinguish temporary adjustment costs from persistent structural trade-offs and to identify how relationships among the three dimensions change as technologies mature, institutions adapt, and geopolitical conditions evolve. Two research questions are particularly relevant: How do trade-offs and synergies among energy security, affordability, and environmental sustainability evolve across different stages of the low-carbon transition? How does the feasible balance among the three dimensions change as electrification and renewable energy penetration increase?

A second priority is to advance integrated analysis of all three trilemma dimensions while explicitly accounting for contextual heterogeneity. Although recent studies increasingly examine pairwise interactions—particularly between energy security and sustainability or affordability and sustainability—comparatively few investigations explicitly analyse reciprocal relationships among all three dimensions within a unified analytical framework. At the same time, the findings synthesised in this review consistently indicate that similar transition measures may generate substantially different outcomes depending on institutional capacity, technological maturity, infrastructure readiness, distributional characteristics, and geopolitical conditions. These factors should, therefore, be treated not merely as background variables but as potential moderators of trilemma interactions. Comparative cross-country analyses, longitudinal case studies, and other context-sensitive empirical designs could help explain why similar transition pathways generate synergies in some settings while intensifying trade-offs in others. Future research should consequently move beyond demonstrating that context matters towards identifying the conditions under which the direction or intensity of particular interactions changes. Two questions follow directly from this gap: Under what institutional, technological, and infrastructural conditions do particular trilemma trade-offs weaken or develop into mutually reinforcing interactions? Are there identifiable thresholds in institutional capacity, system flexibility, import dependence, or other contextual conditions beyond which the direction or intensity of trilemma interactions changes?

A third priority concerns the distributional and implementation dimensions of trilemma interactions. National-level indicators and aggregate system assessments may conceal substantial differences in how transition costs, benefits, and risks are experienced across households, regions, and socio-economic groups. These differences become particularly important as decarbonisation increasingly affects household technologies, mobility, heating, infrastructure, employment, and regional economic structures. Future research should, therefore, examine whether particular transition pathways improve aggregate energy security, affordability, or environmental sustainability. It should also assess how the resulting benefits and adjustment costs are distributed and how differences in adaptive capacity influence transition outcomes. Greater attention is also required to the relationship between these distributional effects and policy implementation, including social acceptance, policy sequencing, and institutional responses to concentrated transition costs. This gives rise to two further questions: How are the costs, benefits, and risks generated by changing trilemma interactions distributed across households, regions, and socio-economic groups? How do these distributional effects influence social acceptance and the effectiveness of different policy sequences across transition contexts?

Addressing these three priorities will also require broader methodological approaches. Existing research remains dominated by indicator-based assessments, optimisation models, and scenario analyses, each providing important but partial perspectives on transition processes. Future work would benefit from combining quantitative assessments with longitudinal analysis, qualitative governance research, comparative policy evaluation, and systems-oriented approaches capable of capturing institutional learning, behavioural adaptation and socio-technical change. Such methodological pluralism would strengthen the ability of researchers to examine not only whether trade-offs and synergies occur, but also when they emerge, the conditions under which they change, and how their consequences are distributed. It would also provide a stronger empirical basis for testing the contextual relationships and potential thresholds proposed by the analytical framework developed in this review.

Taken together, these three research priorities suggest that future energy trilemma scholarship should move beyond refining individual indicators or evaluating isolated policy instruments. Greater attention is needed to the dynamic, contextual, and distributional processes through which interactions among energy security, affordability, and environmental sustainability evolve. The analytical framework proposed in this review provides one possible foundation for such work by emphasising contextual conditions, adaptive governance, and continuously evolving interactions among the three dimensions. Rather than representing a final conceptual model, it is intended to guide further theoretical development and empirical validation across countries, energy systems, and stages of the low-carbon transition, including investigation of when trade-offs and synergies emerge, under which conditions they change, and how their consequences differ across transition contexts.

8. Limitations

This review has several limitations that should be considered when interpreting its findings and the proposed analytical framework. First, the literature search was restricted to English-language journal articles and review papers indexed in Scopus and Web of Science and published between 2015 and 2026. Although these databases provide broad multidisciplinary coverage, this strategy may have excluded relevant research published in other languages, indexed elsewhere, or disseminated through other academic formats. The geographical distribution of the available evidence may also be uneven. Energy transition research is more extensively documented for some countries and energy systems than for others, particularly where institutional capacity, data availability, and research infrastructure are stronger. Consequently, the synthesis may not capture the full diversity of transition experiences in lower-income and less extensively studied economies. The contextual relationships identified in this review should, therefore, not be assumed to apply uniformly across countries with substantially different institutional, technological, and socio-economic conditions.

The review is also organised around interactions among the three energy trilemma dimensions rather than around individual economic or end-use sectors. Although evidence concerning buildings, transport, industry, and other sectors is incorporated where it contributes to the identified interaction mechanisms, the review does not provide a systematic sector-by-sector comparison. This distinction is important because technological options, infrastructure requirements, investment structures, and distributional consequences of decarbonisation may differ substantially across sectors. Future applications of the proposed framework could, therefore, examine how the identified trilemma interactions and contextual conditions vary across specific sectoral transition pathways.

Second, the evidence base is characterised by considerable methodological heterogeneity. The studies synthesised in this review employ diverse approaches, including indicator-based assessments, econometric analyses, optimisation and scenario models, comparative policy analyses, and qualitative or governance-oriented research. Such diversity is consistent with the integrative purpose of the review and enables the energy trilemma to be examined from complementary analytical perspectives. However, it also limits direct comparability across studies. Similar concepts may be operationalised using different indicators, spatial and temporal scales, or assumptions, while the strength of evidence supporting particular relationships varies across research designs. Accordingly, convergence across heterogeneous studies can indicate that particular mechanisms or contextual influences recur across different analytical traditions, but it should not be interpreted as demonstrating a common effect magnitude or establishing causal relationships.

Third, the thematic synthesis and the resulting context-sensitive framework are necessarily interpretive. The framework consolidates recurring mechanisms identified across the reviewed literature into five contextual dimensions—technological, institutional, temporal, distributional, and geopolitical—and illustrates how these conditions may shape evolving interactions among energy security, affordability, and environmental sustainability. It should, therefore, be understood as a literature-derived analytical framework rather than an empirically estimated or validated causal model. The review does not quantify the relative importance of individual contextual conditions, establish causal coefficients, or identify empirical thresholds at which particular trade-offs become synergies. These relationships require further testing through longitudinal, comparative, and other appropriate empirical designs. The framework consequently provides hypotheses and analytical propositions for future investigation rather than predetermined relationships expected to hold across all transition contexts.

Finally, the energy transition is evolving rapidly, particularly in areas such as electricity system integration, energy storage, critical material supply chains, industrial decarbonisation, and geopolitical energy relations. Relationships identified from the current literature may, therefore, change as technologies mature, infrastructure expands, institutions adapt, and new geopolitical or market conditions emerge. This temporal limitation is particularly relevant to the central argument of the review itself: if trilemma interactions are dynamic and context-sensitive, the evidence used to interpret them must also be periodically reassessed. The framework and associated policy implications should consequently be regarded as reflecting the present state of knowledge rather than as a fixed representation of future low-carbon energy systems. These limitations define the scope within which the findings should be interpreted and reinforce the need for continued empirical testing and refinement across diverse transition contexts.

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9. Conclusions

The low-carbon transition is fundamentally reshaping the way the energy trilemma should be understood and analysed. Rather than representing a static balance between energy security, affordability, and environmental sustainability, the evidence synthesised in this review demonstrates that the relationships among these three dimensions evolve continuously in response to technological innovation, electricity system transformation, changing geopolitical conditions, institutional development, and socio-economic change. Consequently, the principal challenge facing contemporary energy policy is no longer simply to optimise individual trilemma dimensions but to understand how their interactions change over time and under different contextual conditions. This review, therefore, argues that the energy trilemma should be interpreted as a dynamic and context-sensitive analytical framework through which trade-offs and synergies emerge, evolve and, under appropriate conditions, can be transformed through adaptive policy and governance.

The review further demonstrates that interactions among the three dimensions of the energy trilemma are considerably more complex than the traditional view of competing policy objectives suggests. Across the reviewed literature, energy security–sustainability interactions increasingly revolve around electricity system resilience, grid infrastructure, flexibility resources, and critical mineral supply chains, reflecting the transformation of energy systems from fuel-based to electricity-centred paradigms. Affordability–sustainability interactions are shown to depend not only on energy prices but also on the distribution of transition costs and benefits, access to low-carbon technologies, and the ability of households, regions, and industries to adapt to structural change. Meanwhile, energy security–affordability interactions illustrate that policies designed to strengthen resilience or shield consumers from short-term price shocks may create unintended long-term consequences if they weaken investment incentives, delay decarbonisation, or reinforce dependence on existing energy systems. Collectively, these findings demonstrate that trade-offs are rarely fixed or universal but emerge from the interaction of technological, institutional, economic, and geopolitical conditions.

A central contribution of this review lies in moving beyond the traditional interpretation of the energy trilemma as a framework for balancing three competing policy objectives towards a more dynamic understanding of how interactions among energy security, affordability, and environmental sustainability are shaped by contextual conditions. Rather than treating trade-offs and synergies as predetermined outcomes of particular technologies or policy instruments, the review demonstrates that they emerge through the interaction of technological development, institutional capacity, governance arrangements, geopolitical dynamics, and socio-economic conditions. This perspective provides a more flexible analytical foundation for interpreting energy transition pathways and helps explain why similar policy measures may produce markedly different outcomes across countries, regions, and time horizons. By synthesising evidence across previously fragmented research streams, the review connects conceptual developments in energy security, energy justice, critical minerals, and electricity system transformation within a single analytical framework. In doing so, it extends the contemporary interpretation of the energy trilemma.

The proposed context-sensitive analytical framework provides a structured basis for interpreting the energy trilemma under rapidly changing transition conditions. Rather than prescribing universal policy solutions, it emphasises that effective energy policy should be adaptive to evolving technological, institutional, geopolitical, and socio-economic contexts. The framework highlights that policy outcomes depend not only on the choice of individual instruments but also on the broader conditions under which they are implemented, including electricity system maturity, governance capacity, infrastructure availability, market design, and societal acceptance. From this perspective, successful energy transitions require integrated and adaptive governance capable of balancing short-term resilience with long-term sustainability objectives while ensuring that the costs and benefits of transition are distributed in a socially equitable manner. The framework, therefore, offers both a conceptual foundation for future research and a practical perspective for policymakers seeking to reduce persistent trade-offs and promote more durable synergies across the three dimensions of the energy trilemma.

Ultimately, the findings of this review suggest that the central challenge of the low-carbon transition is not to maximise energy security, affordability, and environmental sustainability independently but to understand and manage the evolving relationships among them. As energy systems become increasingly electrified, interconnected, and shaped by new technological, geopolitical, and societal realities, simplistic interpretations of the energy trilemma are becoming progressively less adequate. Instead, effective energy transition strategies require continuous adaptation, integrated governance, and context-sensitive decision-making capable of responding to changing circumstances rather than pursuing universally applicable policy solutions. The energy trilemma should, therefore, be viewed not as a static policy triangle to be balanced but as a dynamic analytical framework through which policymakers, researchers, and practitioners can better understand how trade-offs emerge, how synergies can be fostered, and how more resilient, equitable, and sustainable energy systems can be achieved over time.

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Appendix A

Database Search Strategies and Retrieval Details

The structured literature search was conducted in the Scopus and Web of Science Core Collection databases on 30 July 2026 using six thematic search blocks. The same eligibility filters were applied to all search blocks in both databases: publication years, 2015–2026; document type, Article or Review; and English language. The database-specific Boolean search expressions are reported below without these common filters to improve readability. The searches retrieved 437 records from Scopus and 369 records from Web of Science Core Collection before duplicate removal (n = 806 in total).

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Table A1. Scopus search strategies and records retrieved by thematic search block.

Thematic Block	Syntax	Records Retrieved
B1. Core energy trilemma literature	TITLE-ABS-KEY (“energy trilemma” OR “energy policy trilemma”) AND (“energy transition” OR “low-carbon transition” OR decarboni* OR “clean energy transition”) AND (trade-off OR trade-offs OR tradeoff OR tradeoffs OR synerg* OR tension* OR conflict*)	31
B2. Energy security–environmental sustainability interactions	TITLE-ABS-KEY (“energy security” OR “electricity security” OR “security of supply”) AND (“environmental sustainability” OR decarboni* OR ”low-carbon transition”) AND (trade-off OR trade-offs OR synerg* OR tension* OR conflict*) AND (policy OR governance OR “policy mix”)	169
B3. Affordability–environmental sustainability interactions	TITLE-ABS-KEY (“energy affordability” OR “energy poverty” OR “energy justice”) AND (“low-carbon transition” OR “clean energy transition” OR decarboni*) AND (“trade-off” OR “distributional impact*” OR “just transition”)	82
B4. Energy security–affordability interactions	TITLE-ABS-KEY (“energy security” OR “electricity security” OR “security of supply”) AND (“energy affordability” OR affordability OR “energy prices” OR “price volatility” OR “energy crisis”) AND (“trade-off” OR tension* OR “policy mix” OR subsidies OR “price cap*”)	79
B5A. Critical minerals and strategic supply chains	TITLE-ABS-KEY (“critical minerals” OR “critical raw materials”) AND (“energy security” OR “supply security”) AND (“clean energy transition” OR “low-carbon transition”) AND (“supply chain risk*” OR concentration OR dependence OR diversification OR geopolitical)	35
B5B. Electricity security, grids, and system flexibility	TITLE-ABS-KEY (“electricity security” OR “power system security” OR “energy security”) AND (“grid flexibility” OR “power system flexibility” OR “demand response” OR “energy storage” OR “grid congestion”) AND (“renewable integration” OR “variable renewable energy” OR “low-carbon transition”)	41
Total		437

Note: * denotes the wildcard (truncation) operator used in the database search syntax to capture different word endings and variants.

Table A2. Web of Science Core Collection search strategies and records retrieved by thematic search block.

Thematic Block	Syntax	Records Retrieved
B1. Core energy trilemma literature	TS = ("energy trilemma" OR "energy policy trilemma") AND ("energy transition" OR "low-carbon transition" OR decarboni* OR "clean energy transition") AND (trade-off OR trade-offs OR tradeoff OR tradeoffs OR synerg* OR tension* OR conflict*)	22
B2. Energy security–environmental sustainability interactions	TS = ("energy security" OR "electricity security" OR "security of supply") AND ("environmental sustainability" OR decarboni* OR "low-carbon transition") AND (trade-off OR trade-offs OR synerg* OR tension* OR conflict*) AND (policy OR governance OR "policy mix")	115
B3. Affordability–environmental sustainability interactions	TS = ("energy affordability" OR "energy poverty" OR "energy justice") AND ("low-carbon transition" OR "clean energy transition" OR decarboni*) AND ("trade-off" OR "distributional impact*" OR "just transition")	90
B4. Energy security–affordability interactions	TS = ("energy security" OR "electricity security" OR "security of supply") AND ("energy affordability" OR affordability OR "energy prices" OR "price volatility" OR "energy crisis") AND ("trade-off" OR tension* OR "policy mix" OR subsidies OR "price cap*")	82
B5A. Critical minerals and strategic supply chains	TS = ("critical minerals" OR "critical raw materials") AND ("energy security" OR "supply security") AND ("clean energy transition" OR "low-carbon transition") AND ("supply chain risk*" OR concentration OR dependence OR diversification OR geopolitical)	25
B5B. Electricity security, grids, and system flexibility	TS = ("electricity security" OR "power system security" OR "energy security") AND ("grid flexibility" OR "power system flexibility" OR "demand response" OR "energy storage" OR "grid congestion") AND ("renewable integration" OR "variable renewable energy" OR "low-carbon transition")	35
Total		369

Note: * denotes the wildcard (truncation) operator used in the database search syntax to capture different word endings and variants.

Appendix B

Appendix B.1. Representative Prompts for GenAI-Assisted Review Tasks

Appendix B.1.1. Preliminary Title/Abstract Screening

Task: Assess the title and abstract of the following publication against the predefined scope of a review examining interactions among energy security, energy affordability, and environmental sustainability under low-carbon transition conditions. Identify whether the publication appears directly relevant, potentially relevant, or outside the review scope. Consider whether it contributes evidence or conceptual insight concerning trade-offs, synergies, contextual conditions, transition mechanisms, or policy responses. Provide a provisional classification and a brief rationale. Do not make a final inclusion or exclusion decision.

Appendix B.1.2. Analytical Relevance Assessment

Task: Based only on the information provided from the publication, identify its potential analytical contribution to the review. Consider whether it helps explain: (1) mechanisms generating trade-offs or synergies among energy security, affordability and environmental sustainability; (2) technological, institutional, temporal, distributional, or geopolitical conditions shaping these interactions; or (3) relevant policy responses. Indicate the principal contribution and flag substantial overlap with analytical mechanisms already represented in the supplied study set. Do not infer findings that are not explicitly supported by the provided material.

Appendix B.1.3. Candidate Thematic Code Organisation

Task: Compare the following author-extracted findings from the included publications and identify recurring analytical mechanisms or contextual patterns. Suggest candidate thematic groupings for substantively related findings, distinguishing among the three bilateral energy trilemma interactions where appropriate. Preserve contradictory or context-specific findings rather than forcing them into a common category. Base all suggested groupings exclusively on the supplied extracted evidence and do not introduce external information.

Appendix B.1.4. Duplicate/Reference Organisation

Task: Compare the supplied bibliographic records and identify records that appear to represent the same publication on the basis of title, authorship, publication year, journal, and DOI where available. Flag potential duplicates for author verification rather than deleting or merging records automatically.

References

1. International Energy Agency. *World Energy Outlook 2025*; IEA: Paris, France, 2025. Available online: https://www.iea.org/reports/world-energy-outlook-2025 (accessed on 25 June 2026).
2. World Energy Council. *World Energy Trilemma 2024: Evolving with Resilience and Justice*; World Energy Council: London, UK, 2024. Available online: https://www.worldenergy.org/publications/entry/world-energy-trilemma-report-2024 (accessed on 25 June 2026).
3. International Energy Agency. *Electricity 2026: Analysis and Forecast to 2030*; IEA: Paris, France, 2026. Available online: https://www.iea.org/reports/electricity-2026 (accessed on 25 June 2026).
4. International Energy Agency. *Global Critical Minerals Outlook 2026*; IEA: Paris, France, 2026. Available online: https://www.iea.org/reports/global-critical-minerals-outlook-2026 (accessed on 25 June 2026).
5. Kivimaa, P.; Entsalo, H. Synergies and tensions between decarbonisation, security and strategic autonomy in EU energy policy. *Environ. Innov. Soc. Transit.* **2026**, *59*, 101109. [CrossRef]
6. Sovacool, B.K. The low-carbon risk society: Dilemmas of risk–risk tradeoffs in energy innovations, transitions, and climate policy. *Risk Anal.* **2025**, *45*, 78–107. [CrossRef] [PubMed]
7. Le Billon, P.; Deberdt, R.; Trombetta, J. From resource security to resource securitisation: Materialities, latent securitisation, and the politics of (in)security in low-carbon transitions. *Crit. Stud. Secur.* **2025**, 1–32. [CrossRef]

8. Shirazi, M. Complex links between the energy trilemma dimensions in top 25 energy trilemma performers: The role of the UN plan of action for 2030. *Energy Strategy Rev.* **2025**, *57*, 101623. [CrossRef]
9. Wang, Y.; Li, Y.; Deng, J. Do energy transition goals encounter conflicts under geopolitical risk? Evidence of nonlinearity. *Energy Econ.* **2026**, *158*, 109320. [CrossRef]
10. Gad, K.S.; Crevani, G.; Colombo, E. An integrated modelling framework to address the energy trilemma in Egypt and Nile East Basin. *Energy Strategy Rev.* **2025**, *58*, 101689. [CrossRef]
11. Heffron, R.J.; McCauley, D.; de Rubens, G.Z. Balancing the energy trilemma through the Energy Justice Metric. *Appl. Energy* **2018**, *229*, 1191–1201. [CrossRef]
12. Heffron, R.J. Applying energy justice into the energy transition. *Renew. Sustain. Energy Rev.* **2022**, *156*, 111936. [CrossRef]
13. Lamb, W.F.; Antal, M.; Bohnenberger, K.; Brand-Correa, L.I.; Müller-Hansen, F.; Jakob, M.; Minx, J.C.; Raiser, K.; Williams, L.; Sovacool, B.K. What are the social outcomes of climate policies? A systematic map and review of the ex-post literature. *Environ. Res. Lett.* **2020**, *15*, 113006. [CrossRef]
14. Newell, P.J.; Geels, F.W.; Sovacool, B.K. Navigating tensions between rapid and just low-carbon transitions. *Environ. Res. Lett.* **2022**, *17*, 041006. [CrossRef]
15. Riofrancos, T. The security–sustainability nexus: Lithium onshoring in the Global North. *Glob. Environ. Polit.* **2023**, *23*, 20–41. [CrossRef]
16. Muhammad, S.; Hoffmann, C.; Müsgens, F. Assessing energy security risks: Implications for household electricity prices in the EU. *Energy* **2025**, *327*, 136201. [CrossRef]
17. Meng, W.; Nieto, J.; Guan, D.; Meng, J.; Sander, R.; Pöschl, U.; Hubacek, K.; Su, H.; Tao, S.; Cheng, Y. Rethinking energy transition strategies for the European Union amid rising energy prices. *Proc. Natl. Acad. Sci. USA* **2026**, *123*, e2609606123; Correction in *Proc. Natl. Acad. Sci. USA* **2026**, *123*, e2622923123. https://doi.org/10.1073/pnas.2622923123. [CrossRef] [PubMed]
18. International Energy Agency. *Strategies for Affordable and Fair Clean Energy Transitions*; IEA: Paris, France, 2024. Available online: https://www.iea.org/reports/strategies-for-affordable-and-fair-clean-energy-transitions (accessed on 25 June 2026).
19. OECD. *Distributional Impacts of Energy Transition Pathways and Climate Change*; OECD Economics Department: Paris, France, 2024; OECD Economics Department Working Papers. Available online: https://www.oecd.org/en/publications/2024/09/distributional-impacts-of-energy-transition-pathways-and-climate-change_212834fc.html (accessed on 25 June 2026).
20. Opoku, E.E.O.; Acheampong, A.O.; Frempong, J. Geopolitical risks, financial system and the energy trilemma. *Energy Econ.* **2025**, *149*, 108724. [CrossRef]
21. Yosthongngam, S.; Tansuchat, R.; Yamaka, W. Do institutions mitigate climate risk in energy systems? Evidence from the energy trilemma. *Energy Econ.* **2026**, *160*, 109479. [CrossRef]
22. Torraco, R.J. Writing integrative literature reviews: Guidelines and examples. *Hum. Resour. Dev. Rev.* **2005**, *4*, 356–367. [CrossRef]
23. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [CrossRef]
24. Whittemore, R.; Knafl, K. The integrative review: Updated methodology. *J. Adv. Nurs.* **2005**, *52*, 546–553. [CrossRef] [PubMed]
25. Tang, X.; Ren, K.; Wang, J.; Zhang, L.; Ding, Y.; Jiang, Y.; Ma, Z.; Ji, H.; Feng, C.; Höök, M. Assessing oil security and system resilience under China's low-carbon energy transition. *Engineering* **2026**. [CrossRef]
26. Zhang, S.; Sovacool, B.K.; Wei, C. Do clean energy transitions enhance global energy security? A comparative analysis of trends and tradeoffs across eight major economies, 1990–2020. *Energy Policy* **2026**, *212*, 115164. [CrossRef]
27. Månsson, A. Energy security in a decarbonised transport sector: A scenario based analysis of Sweden's transport strategies. *Energy Strategy Rev.* **2016**, *13–14*, 236–247. [CrossRef]
28. Khan, M.I.; Asfand, F.; Asif, M.; Al-Ansari, T.; Farooq, M.; Kurniawan, T.A.; Al-Ghamdi, S.G. Energy system resilience as an all-hazards system-of-systems property under climate and security challenges. *Appl. Energy* **2026**, *418*, 128033. [CrossRef]
29. Huang, H.; Wang, W.; Cai, G. Balancing energy security and carbon emissions in China: The roles of renewable energy and environmental regulation. *Energy Rep.* **2026**, *15*, 109007. [CrossRef]
30. Quitoras, M.R.; Cabrera, P.; Campana, P.E.; Rowley, P.; Crawford, C. Towards robust investment decisions and policies in integrated energy systems planning: Evaluating trade-offs and risk hedging strategies for remote communities. *Energy Convers. Manag.* **2021**, *229*, 113748. [CrossRef]
31. Shao, Z.; Liu, Y.; Zheng, B.; Zhao, J. Exploring carbon peak and carbon neutrality pathways for megacities from the perspective of supply and demand synergy: A LEAP simulation of the Beijing case. *Energy* **2026**, *347*, 140129. [CrossRef]
32. Kozlova, M.; Huhta, K.; Lohrmann, A. The interface between support schemes for renewable energy and security of supply: Reviewing capacity mechanisms and support schemes for renewable energy in Europe. *Energy Policy* **2023**, *181*, 113707. [CrossRef]
33. Jerzyniak, T. The EU de-risking of energy dependencies: Towards a new clean energy geopolitical order? *Politics Gov.* **2024**, *12*, 8285. [CrossRef]
34. Thaler, P.; Hofmann, B. The impossible energy trinity: Energy security, sustainability, and sovereignty in cross-border electricity systems. *Polit. Geogr.* **2022**, *94*, 102579. [CrossRef]

35. Garvey, A.; Norman, J.B.; Buchs, M.; Barrett, J. A "spatially just" transition? A critical review of regional equity in decarbonisation pathways. *Energy Res. Soc. Sci.* **2022**, *88*, 102630. [CrossRef]
36. Büchs, M.; Ivanova, D.; Schnepf, S.V. Fairness, effectiveness, and needs satisfaction: New options for designing climate policies. *Environ. Res. Lett.* **2021**, *16*, 124026. [CrossRef]
37. Sovacool, B.K.; Turnheim, B.; Hook, A.; Brock, A.; Martiskainen, M. Dispossessed by decarbonisation: Reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways. *World Dev.* **2021**, *137*, 105116. [CrossRef]
38. Varal, S.; Reaños, M.A.T. Energy price shocks in Europe and its impacts on vulnerable households: A demand system approach. *Energy Econ.* **2026**, *160*, 109429. [CrossRef]
39. Behr, S.M.; Kucuk, M.; Longmuir, M.; Neuhoff, K. Worst first: Thermal retrofits, carbon prices, and inequality. *Energy Policy* **2026**, *213*, 115145. [CrossRef]
40. Trépanier, M.P.; Rouleau, J.; Gosselin, L. How does energy transition impact vulnerable populations? A review of challenges, determinants, and solutions for a just transition. *Annu. Rev. Environ. Resour.* **2025**, *50*, 511–537. [CrossRef]
41. Tang, T.; Kim, H.J. Linking energy policy, energy insecurity, and health outcomes. *Front. Sustain. Energy Policy* **2023**, *2*, 1231821. [CrossRef]
42. Carfora, A.; Scandurra, G. Boosting green energy transition to tackle energy poverty in Europe. *Energy Res. Soc. Sci.* **2024**, *110*, 103451. [CrossRef]
43. Chan, Y.T.; Punzi, M.T.; Zhao, H. Navigating geopolitical crises for energy security: Evaluating optimal subsidy policies via a Markov switching DSGE model. *J. Environ. Manag.* **2024**, *349*, 119619. [CrossRef] [PubMed]
44. Vaiaso, T.V.J.; Jack, M.W. Quantifying the trade-off between percentage of renewable supply and affordability in Pacific Island Countries: Case study of Samoa. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111468. [CrossRef]
45. Mersch, M.; Markides, C.N.; Mac Dowell, N. The impact of the energy crisis on the UK's net-zero transition. *iScience* **2023**, *26*, 106491. [CrossRef] [PubMed]
46. Srinivasan, A.; Gabrielli, P.; Sansavini, G. Trade-offs of affordability, sustainability and security in the optimal design of multi-energy systems. *Appl. Energy* **2025**, *383*, 125299. [CrossRef]
47. Wu, R.; Sansavini, G. Energy trilemma in active distribution network design: Balancing affordability, sustainability and security in optimization-based decision-making. *Appl. Energy* **2021**, *304*, 117891. [CrossRef]
48. Tanoto, Y.; Haghdadi, N.; Bruce, A.; MacGill, I. Clustering based assessment of cost, security and environmental tradeoffs with possible future electricity generation portfolios. *Appl. Energy* **2020**, *270*, 115219. [CrossRef]
49. Grubler, A. Energy transitions research: Insights and cautionary tales. *Energy Policy* **2012**, *50*, 8–16. [CrossRef]
50. Smil, V. Examining energy transitions: A dozen insights based on performance. *Energy Res. Soc. Sci.* **2016**, *22*, 194–197. [CrossRef]
51. Jing, R.; Lin, Y.; Khanna, N.; Chen, X.; Wang, M.; Liu, J.; Lin, J. Balancing the energy trilemma in energy system planning of coastal cities. *Appl. Energy* **2021**, *283*, 116222. [CrossRef]
52. Mersch, M.; Caton, P.; Markides, C.N.; Mac Dowell, N. Energy import security in optimal decarbonization pathways for the UK energy system. *Cell Rep. Sustain.* **2024**, *1*, 100236. [CrossRef]
53. Yang, Z.; Liu, H.; Yuan, Y.; Li, M. Can renewable energy development facilitate China's sustainable energy transition? Perspective from energy trilemma. *Energy* **2024**, *304*, 132160. [CrossRef]
54. Fouquet, R. Path dependence in energy systems and economic development. *Nat. Energy* **2016**, *1*, 16098. [CrossRef]

https://doi.org/10.3390/en19184474