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The Essential Contradiction and Solution of the Energy "Triangle Dilemma"

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Abstract

The "energy triangle dilemma," the inherent conflict among affordability, cleanliness and security/ reliability, poses a fundamental challenge to the global energy transition. This study proposes a novel "Super-additive Synergy Triangle" framework to overcome this dilemma through multidimensional integration. Through conceptual analysis and case studies, we deconstruct the dilemma's core contradictions and propose three synergistic dimensions: technological, model, and policy synergy. Case studies from China's Sichuan-Chongqing region validate the framework's efficacy: the Panxi Hydrogen Corridor shows reduced logistics costs and emissions through hydropower-based hydrogen; Chongqing Guoyuan Port's green initiative lowers operating costs and achieves approximately 100,000 metric tons of annual CO_2 reduction; and the Chengdu near-zero-carbon park demonstrates 15-25% lower energy costs for firms via geothermal and waste-heat recovery. These practical applications confirm the framework's ability to generate tangible economic and environmental co-benefits. Furthermore, we propose a phased implementation pathway: a short-term focus on technological integration and business model pilots, a medium-term emphasis on establishing market mechanisms and policy frameworks, and a long-term goal of achieving system-wide dynamic equilibrium through digital twins and AI optimization. The core value of this research lies in providing a systematic approach to transform the competing objectives of the energy trilemma into mutually reinforcing drivers, to ultimately achieve "1+1+1>3" super-additive outcomes.

Keywords: Energy triangle dilemma; Super-additive synergy; Energy transition; Technological synergy; Policy synergy; Sustainable Energy

1. Introduction

Energy is the lifeblood of a nation's economy, bearing critical significance for socioeconomic development and national security. However, the three core objectives of energy development—"security and reliability, cleanliness, and affordability"—have long been mutually constraining and interacting, creating what is known as the "energy trilemma." To achieve the "dual carbon goals"(carbon peak and carbon neutrality) and "energy independence" while building a modern energy powerhouse, resolving this energy trilemma represents an imperative challenge for China [1].

Existing research demonstrates that pursuing extreme optimization in a single dimension (e.g., maximal clean energy transition) frequently results in substantial compromises in other critical dimensions, such as techno-economic viability and system security. This phenomenon aligns with the "Energy Trilemma" framework, where the interdependent challenges of security, affordability, and sustainability form a persistent optimization boundary in energy systems [2-3].

This phenomenon has been widely validated globally, particularly under the dual pressures of geopolitical conflicts and environmental crises, where the actual effectiveness of national energy policies frequently faces severe challenges [3]. Additionally, the implementation of climate policies and technological innovations in recent years has also profoundly influenced the development of energy systems. As nations strive to achieve carbon neutrality goals, traditional fossil fuels are gradually being replaced by clean energy sources. However, this transition has also raised new energy security issues, such as risks associated with the supply of critical mineral resources and operational risks in new power systems [4].

Currently, addressing the "energy trilemma" has become a global challenge, and major economies have adopted distinct transition pathways accordingly. For instance, the European Union has established a series of policy instruments, including renewable energy targets, carbon pricing mechanisms (such as the Emissions Trading System, ETS), and energy efficiency directives [5]. In contrast, the United States relies more heavily on fiscal incentives like tax credits under the Inflation Reduction Act, emphasizing market-driven approaches and technology commercialization. While these international experiences offer valuable insights, they are highly dependent on specific political and economic contexts and often focus on single-policy tools. By comparison, China's energy system—characterized by its vast scale and significant regional disparities—requires a synergistic framework that can systematically integrate technology, business models, and policy. Studies reveal that effectively addressing the "energy trilemma" hinges on synergistic innovation [6-7].By integrating technological, systemic, and policy synergies, holistic optimization of energy systems can be achieved, moving beyond fragmented adjustments or single-objective prioritization. For instance, at the technological level, coupling green hydrogen production with hydrogen fuel cells can significantly reduce logistics costs while enhancing energy self-sufficiency, thereby bolstering system security, and delivering substantial decarbonization benefits [8].Crucially, establishing market-based mechanisms and policy frameworks enables the free flow of energy resources. In the medium term, this addresses challenges of equity and efficiency in energy allocation and trading. In the long term, the application of digital twins and AI optimization will enable real-time dynamic equilibrium in energy systems, further driving a breakthrough in the "trilemma" and enabling a transition to "super-additive synergy." super-additive synergy, a classic concept in systems synergy, posits that for any two non-intersecting subsystems, their integrated effect is greater than the sum of their individual parts (1+1>2). We posit that the key to addressing the energy trilemma lies in synergistic innovation that transcends fragmented adjustments. This study introduces the "Super-additive energy trilemma synergy (1+1+1>3)" framework, operationalized through three core dimensions: technological, model, and policy synergy. The Super-additive Synergy Triangle achieves synergistic value creation at every node, enabling a new balance among affordability, security, and sustainability.

This study employs conceptual analysis supported by illustrative case studies to explore this framework. Through in-depth analysis of practical cases from the Sichuan-Chongqing region, we demonstrate the application effects of "super-additive synergy." We then propose a phased implementation pathway, including technology integration and business model pilots in the short-term; market mechanism development and policy framework establishment in the medium-term; and digital twin implementation coupled with AI optimization in the long-term. This approach not only charts a novel pathway for energy transition but also provides critical insights for addressing global energy challenges.

2. Deconstructing the Fundamental Contradictions of the Energy Trilemma

The fundamental contradiction of the "energy trilemma" arises from the inherent tension among its three core attributes—affordability, cleanliness, and security—which exhibit strong trade-offs [9].

The pursuit of carbon peaking and carbon neutrality ("dual carbon") targets is placing increasingly complex constraints on energy systems. Taking affordability as an example, the high upfront investment costs for low-carbon and clean energy technologies substantially raise short-term expenditures. Furthermore, during the initial deployment phase, these technologies often suffer from insufficient economies of scale and suboptimal technological maturity, resulting in elevated operational and maintenance expenses that directly undermine their economic competitiveness [10].While large-scale deployment of renewable energy significantly reduces greenhouse gas and pollutant emissions, its inherent intermittency and variability pose substantial challenges to grid frequency and voltage stability. Even with the construction of large-scale energy storage facilities to mitigate these issues, the associated additional costs remain non-trivial, further complicating the economic viability of clean energy systems [11-12].The increasing penetration of renewable energy in power systems has amplified operational complexity and uncertainty, exacerbating the inherent tension between reliability and economic viability. From a security perspective, the critical challenges center on system dispatchability and risk resilience. Conventional fossil-fuel power plants maintain inherent advantages in load-following flexibility and baseload provision, yet their environmental pollution and carbon emissions have become unsustainable liabilities. In contrast, while clean energy sources significantly reduce ecological impacts, their climate-dependent availability necessitates substantial investments in dispatch coordination and energy storage technologies to ensure uninterrupted and reliable power supply [13].

Within this complex web of contradictions, conventional single-attribute optimization strategies prove demonstrably inadequate. The fundamental challenge lies in transcending linear thinking and isolated system design paradigms. The prevailing trade-offs manifest as: Affordability currently relies on fossil fuels' low costs, achieved at the expense of sustainability; Security depends on centralized supply architectures that inherently limit flexibility; Sustainability necessitates high-cost clean technologies that strain economic viability. This zero-sum dynamic among critical dimensions constitutes the core contradiction in energy system optimization.

To resolve these contradictions, a systematic solution is urgently needed. Technological advancement is key to addressing this issue. By integrating various advanced technologies to create synergies—such as using artificial intelligence (AI) and big data analytics to optimize the scheduling and management of energy systems—it is possible to alleviate the conflicts between economic efficiency, cleanliness, and safety to some extent. Furthermore, support at the policy level is crucial; a comprehensive incentive mechanism and market-oriented reforms must be implemented to promote technological progress and industrial applications. At the local level, targeted pilot projects should be initiated to explore replicable and scalable paths and models by integrating regional resources and advantages.

Therefore, breaking through the constraints of the "energy trilemma" requires technological innovation, model innovation, and policy innovation. Through systematic restructuring and institutional innovation, we can achieve the coordinated coexistence of economic efficiency, safety, and cleanliness.

3. Three Innovation Dimensions for Building "Super-Additive Synergy" in the Energy Trilemma

As mentioned earlier, we posit that the key to addressing the energy trilemma lies in synergistic innovation that transcends fragmented adjustments. This study introduces the “Super-additive energy trilemma synergy (1+1+1>3)” framework (Figure 1), operationalized through three core dimensions: technological synergy, model synergy, and policy synergy. It is built on three pillars of innovation.

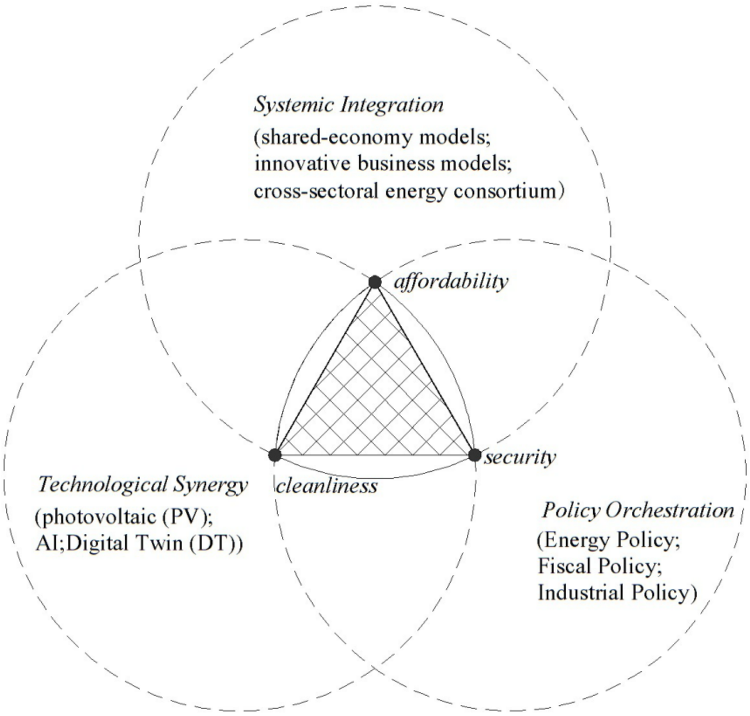

Figure 1: The Super-additive Synergy Triangle Conceptual Framework.

3.1. Technological Synergy

China has made significant strides in mitigating the energy trilemma through coordinated advancements in renewable energy technologies, particularly in photovoltaics (PV), electric vehicles, and ultra-high voltage (UHV) transmission networks. As a cornerstone renewable technology, PV systems combine low-carbon attributes with high energy conversion efficiency. Material science breakthroughs have pushed crystalline silicon PV conversion efficiency beyond 25%, while emerging perovskite-silicon tandem cells promise efficiencies up to 45%, substantially reducing levelized energy costs.

The integration of novel energy storage solutions and UHV transmission infrastructure has effectively addressed the intermittency and geographical constraints of distributed renewable generation. This technological ecosystem enables efficient transmission of abundant solar resources from northwestern regions to load centers in central and eastern China, ensuring grid stability while optimizing the spatial allocation of clean energy. The synergistic development of these technologies demonstrates how innovation can simultaneously enhance energy affordability, sustainability, and security - the three dimensions of the energy trilemma [14].

Hydrogen energy has emerged as a critical component of the energy transition, with its value chain development warranting particular attention. As a high-efficiency, clean energy carrier, hydrogen can be produced through various methods including water electrolysis and natural gas reforming, while its combustion yields only water without carbon emissions. Within China’s carbon neutrality framework, hydrogen is projected to evolve from its current primary role as an industrial feedstock to a mainstream energy commodity by 2060. Projections indicate total hydrogen demand exceeding 90 million metric tons annually by the target year, with transportation and industrial applications each accounting for 47%

of consumption, while power generation constitutes the remaining 6%. This transition underscores hydrogen's growing significance in decarbonizing hard-to-abate sectors and its potential to address multiple dimensions of the energy trilemma [15].

The application of digital twins and artificial intelligence in energy systems has become increasingly prevalent, revolutionizing traditional energy management paradigms. These technologies enable the construction of virtual energy system models through real-time data acquisition and big data analytics, facilitating dynamic monitoring and optimized dispatch of energy networks. A prime example is the "smart energy brain" technology, which employs advanced AI algorithms to maintain real-time electricity supply-demand balance while optimizing energy allocation patterns. This digital transformation significantly enhances overall energy utilization efficiency, typically achieving 15-20% reductions in system operational costs while improving grid stability and renewable energy integration capacity. The convergence of these digital technologies with physical energy infrastructure represents a fundamental shift in how modern energy systems can simultaneously address the trilemma challenges of reliability, affordability, and environmental sustainability [16-18].The technology application not only enhances the intelligentization of energy systems through digital twin and AI-driven optimization frameworks, but also optimizes economic viability, security resilience and clean energy transition.

The strategic integration of photovoltaic systems, hydrogen energy, and artificial intelligence technologies is driving a fundamental revolution in energy systems, achieving the "super additive synergy triangle" that harmonizes economic viability, system resilience, and environmental sustainability. This technological convergence creates a robust foundation for the global green energy transition while simultaneously accelerating market-based reforms. The emergent paradigm enables novel market architectures, particularly through the coupling of regional electricity spot markets with carbon pricing mechanisms, providing dual policy support for both supply-side innovation and demand-side transformation.

3.2. Systemic Integration

Systemic Integration plays a pivotal role in addressing the "energy trilemma". Specifically, the adoption of a shared-economy models can substantially enhance the overall efficiency of energy systems, while the mechanism of intensive resource utilization strengthens their affordability, reliability, and sustainability [19-20].For instance, shared electric vehicle programs, through centralized procurement and intelligent dispatch systems, not only reduce users' vehicle ownership costs but also significantly decrease tailpipe emissions from private cars [21].From a technical perspective, the deep integration of Internet of Things (IoT) and blockchain technologies enables transparent data sharing and real-time monitoring in energy systems, thereby ensuring secure and highly efficient energy utilization [22-23].Furthermore, the establishment of energy communities enables intelligent redistribution of surplus energy through peer-to-peer sharing mechanisms, which not only enhances energy utilization efficiency but also reduces electricity costs for community members. Such decentralized, distributed energy management models also improve localized energy security[24].

Moreover, innovative business models offer novel solutions to these challenges. The Renewable Energy Investment Trust (REIT) mechanism enables public investment in large-scale renewable energy projects through capital markets, effectively addressing financing bottlenecks. This approach not only mobilizes broader social capital and reduces project financing costs but also diversifies investment risks and strengthens investor confidence—critical factors for accelerating the energy transition [25].

Simultaneously, the establishment of cross-sectoral Energy Consortium plays a pivotal role in advancing integrated energy systems. These collaborative platforms, exemplified by Integrated Energy Service Companies (IESCos), deliver comprehensive energy solutions encompassing the supply and management of diverse energy forms including electricity, heating, and cooling services [26]. IESCos transcend the conventional role of energy suppliers by leveraging synergistic effects to optimize integrated energy systems, thereby achieving a comprehensive equilibrium across economic viability, supply security, and environmental sustainability [27].

In summary, the integration of sharing economy models, energy communities, innovative business mechanisms, and cross-sectoral energy consortium enables multi-dimensional synergies across technological, economic, and policy domains. This systemic approach transcends the conventional energy "trilemma" constraints, propelling energy systems toward a new paradigm of "super-additive synergy" - representing not merely isolated technological breakthroughs or policy innovations, but rather a comprehensive optimization strategy that achieves system-wide co-benefits through multidimensional alignment.

3.3. Policy Orchestration

Policy Orchestration serves as the critical linchpin in establishing the "super-additive synergy triangle," integrating technological and systemic synergies through adaptive governance. Effective policy must be both flexible and forward-looking, extending beyond energy-specific measures to encompass integrated financial and industrial instruments. Financial tools—such as green bonds, tax incentives, and dedicated funds—can catalyze corporate investment in renewables. Concurrently, industrial policies, including clear R&D roadmaps and standards, build resilient supply chains and accelerate market penetration, creating a virtuous cycle of innovation and deployment.

Harnessing market-based mechanisms is pivotal for reconciling the trilemma's inherent tensions.. Carbon emissions trading and renewable electricity spot markets optimize resource allocation through price signals effectively balancing affordability, security, and sustainability. These mechanisms accelerate the commercialization of clean technologies while steering industries toward higher-value, lower-emission production paradigms, creating synergistic wins for both economic competitiveness and environmental performance.

Finally, effective orchestration requires international alignment. Active participation in global energy partnerships facilitates technology transfer and domestic system modernization. Concurrently, aligning domestic policy with international trade governance—through mechanisms like Carbon Border Adjustment (CBAM)—enhances the global competitiveness of local enterprises and ensures regulatory parity with major trading partners. In essence, policy orchestration acts as the crucial nexus that bridges technological, economic, and systemic dimensions. By implementing integrated policies coupled with market mechanisms, it transforms competing objectives into synergistic co-benefits, accelerating the transition to a decarbonized energy future and setting a global precedent for systemic change.

4. Case Study: Sichuan-Chongqing “Super additive Synergy” Practice in Energy Transition

4.1. Technology-Mode Synergy Mechanisms

The Panzhihua-Xichang Hydrogen Corridor project demonstrates a successful technology-model integration by establishing a closed-loop system combining hydropower-based hydrogen production with fuel cell heavy truck transportation, achieving dual improvements in both environmental performance and economic viability for freight logistics. Technically, the project leverages the region's abundant hydropower resources for low-cost, low-carbon hydrogen production through water electrolysis. A hybrid electrolysis system incorporating both conventional bipolar alkaline electrolyzes and advanced polymer electrolyte membrane (PEM) electrolyzes enhances production efficiency while minimizing energy consumption. The produced hydrogen is compressed for storage in high-pressure vessels and distributed via an optimized pipeline network to refueling stations.

The project's operational framework incorporates advanced fuel cell technology in heavy-duty truck transportation, utilizing innovative platinum-based catalysts and high-performance proton exchange membranes (PEM) to achieve efficient hydrogen-to-power conversion. This zero-emission powertrain demonstrates exceptional energy efficiency and reliability under demanding freight conditions, while an intelligent energy management system at each transport node enables optimal energy allocation through real-time monitoring and dynamic adjustment. Furthermore, the implementation of a multimodal operation strategy - integrating logistics demand patterns with energy supply characteristics - systematically optimizes both routing configurations and load management protocols.

The project's implementation extensively employs digital twin technology for comprehensive lifecycle management of the hydrogen corridor. By establishing real-time virtual-physical system mapping, this approach enables continuous monitoring and optimization of operational parameters and energy flows across all processes, thereby enhancing both system safety and stability. Advanced data analytics and AI algorithms further facilitate predictive maintenance and dynamic resource allocation, achieving significant reductions in operational costs and risk exposure while maintaining peak performance standards.

This synergistic innovation achieves dual environmental and economic benefits across the entire freight transport chain, simultaneously reducing carbon emissions while enhancing regional competitiveness through improved logistics efficiency and energy self-sufficiency. The deep integration of technological and operational models establishes a pioneering pathway for hydrogen applications in heavy-duty logistics, offering transferable insights for achieving comprehensive system-level optimization in energy transitions.

4.2. Policy-Economy Synergy Mechanisms

Chongqing Guoyuan Port's green port initiative demonstrates how renewable energy self-supply systems coupled with carbon tariff exemptions can enhance international trade competitiveness. The port's electricity supply primarily integrates solar PV (20MW installed capacity) and shore power systems, achieving both low-carbon operations and improved energy autonomy. Notably, this green power infrastructure enables annual CO_2 emission reductions of approximately 100,000 metric tons by eliminating auxiliary engine use during vessel berthing, while meeting all operational power demands through clean energy sources.

The port's carbon tariff exemption policy further strengthens its competitive advantage by eliminating indirect emission costs for goods transported via green shipping methods. This strategic mechanism grants carbon duty relief per ton of cargo for vessels meeting low-carbon standards-as exemplified by Europe-Chongqing routes -creating dual incentives for cleaner maritime transport adoption while enhancing the port's global market positioning. By systematically linking emission performance with trade policy benefits, this approach establishes a replicable model for aligning international shipping economics with decarbonization objectives.

The synergistic implementation of these measures achieves significant port operation cost reductions while driving substantial economic returns, demonstrating the financial viability of emission-reduction strategies in maritime logistics. This integrated policy approach not only validates the economic benefits of green port transformation but also establishes a transferable framework for coastal ports globally seeking to balance environmental and commercial objectives.

This study demonstrates that the policy-economic synergy between port renewable energy self-supply systems and carbon tariff exemptions yields dual competitive and environmental advantages, offering both strategic guidance and practical implementation value for future green port development. The model substantiates how targeted policy support coupled with technological innovation can achieve low-carbon transformation within existing regulatory frameworks, while simultaneously advancing energy structure optimization and emission reduction objectives—providing a replicable paradigm for maritime decarbonization that balances economic and sustainability imperatives [28].

4.3. Cross-Sector Synergy Mechanisms

The Chengdu Eastern New Area's "near-zero carbon industrial park" demonstrates how synergistic geothermal energy deployment and data center waste heat recovery achieve both environmental and economic benefits. Geothermal systems-utilizing multiple wells with geothermal heat pumps (GHPs) exhibiting coefficients of performance (COP) exceeding 4.0-provide stable, low-carbon renewable energy while transforming waste heat into operational cost savings. This configuration yields exceptional energy efficiency, with each unit of electrical input generating four units of thermal output, establishing a replicable model for industrial park decarbonization.

The integrated waste heat recovery system (WHRS) further enhances system-wide energy efficiency through heat exchangers that repurpose data center thermal byproducts for geothermal heating networks. When combined with thermal energy storage (TES) facilities-which store heat during off-peak periods to address demand fluctuations-the system achieves annual recovery exceeding 10,000 GJ of waste heat, translating to CO_2 emission reductions surpassing 1,000 metric tons. This cascading energy utilization framework exemplifies circular thermal management in industrial applications.

This technological synergy generates substantial economic advantages, with the innovative near-zero carbon model reducing corporate energy expenditures by 15-25% daily while maintaining operational output—directly converting energy savings into profit margins. Complementary government policies, including renewable energy tax incentives and capital subsidies, effectively mitigate both initial investments and long-term operating costs, creating a competitive market position that demonstrates the financial viability of deep decarbonization in industrial operations.

The Chengdu Eastern New Area's near-zero carbon industrial park exemplifies how cross-sectoral synergy achieves dual technological and systemic breakthroughs—advancing energy efficiency through technical innovation while establishing a replicable green development model via multidimensional economic and policy coordination. This case study empirically validates the practical applicability and transformative potential of the "super-additive synergy triangle" framework in real-world decarbonization initiatives, demonstrating its capacity to unlock co-benefits that exceed the sum of individual interventions.

The case of the Sichuan-Chongqing region demonstrates the practical application of the "super-additive synergy triangle" framework through various synergistic approaches. A comparison of the key outcomes is provided in Table 1.

Table 1： Comparing the Case Studies of Synergy Effectiveness

Case Name	Primary Synergy Dimension	Technologies/Models	Key Outcomes
Panzhihua-Xichang Hydrogen Corridor	Technological Synergy, Model Synergy	Hydropower-based H_2 production, Fuel Cell Heavy Trucks, Digital Twin	Reduced logistics costs & emissions; validated H_2 business model for heavy transport.
Chongqing Guoyuan Port	Policy Synergy, Economic Synergy	Solar PV+Shore Power, Carbon Tariff Exemption	Lower operating costs; Enhance international competitiveness through a green trade advantage
Chengdu Near-Zero Carbon Park	Cross-Sectoral Synergy	Geothermal, Data Center Waste Heat Recovery, Smart Management	15-25% lower energy costs for firms; high clean energy penetration.

5. The Pathways to Achieving the "Super-Additive Synergy Triangle"

5.1. Core Value Proposition

The study's core proposition advocates transcending the traditional trilemma paradigm through synergistic value creation—where technological synergy, systemic integration, and policy orchestration transform energy affordability, security, and sustainability from competing priorities into mutually reinforcing drivers, ultimately achieving super-additive outcomes (1+1+>3).

To resolve the contradictions of the “energy trilemma,” the three synergistic dimensions of the “super-additive synergy triangle”—technological synergy, systemic integration, and policy orchestration—advance simultaneously across the short, medium, and long term, though each stage differs in strategic focus and emphasis. The overall pathway is visualized in Figure 2.Short-term (Breakthrough and Piloting) focuses on technology integration and business model innovation, aiming to verify feasibility and establish a commercial closed loop. Policy efforts center on creating an enabling environment for pilot projects. Medium-term (Scaling and Restructuring) emphasizes policy coordination and market model restructuring, with the goal of overcoming scaling barriers and establishing new market rules and standards. Technology efforts shift toward standardization and cost optimization. Long-term (Integration and Leadership) prioritizes disruptive technological innovation and deep systemic integration, targeting fundamental transformation of the energy system and leadership in a new industrial ecosystem. Policy and model measures focus on ensuring system stability and encouraging frontier exploration.

At the technological core of super-additive synergy lies data-driven intelligent energy management platforms that holistically optimize multiple energy carriers and their dynamic interactions to simultaneously enhance energy affordability, security, and sustainability. These platforms employ big data analytics for real-time optimization across generation, transmission, and consumption networks—incorporating smart sensors at critical nodes to detect operational anomalies, coupled with machine learning algorithms for predictive maintenance that minimize downtime through equipment failure anticipation and preemptive intervention.

This systematic technological approach ensures the levelized cost of renewable electricity progressively reaches parity with—and ultimately undercuts—fossil fuels, thereby achieving economic competitiveness. On the policy front, institutional innovation and targeted support mechanisms establish market-aligned incentive structures that accelerate the development and deployment of energy technologies. Exemplified by performance-based carbon mitigation policies and environmental key performance indicators (KPIs), such frameworks motivate voluntary corporate upgrades while creating competitive advantages—not only driving traditional energy providers toward cleaner alternatives but also fostering negative emissions technologies through carbon market mechanisms. Through such synergistic innovation, the energy system transcends the trilemma paradigm, evolving toward super-additive synergy where systemic coordination amplifies the value of individual components. The ultimate outcome manifests in threefold dividends: cost-competitive green electricity, enhanced risk resilience, and value creation from carbon removal technologies—collectively charting the course for the coming energy revolution.

The future energy paradigm thus transcends the conventional "trilemma" through synergistic integration of technological synergy, systemic integration, and policy orchestration—transforming the traditionally competing priorities of affordability, security, and sustainability into mutually reinforcing dimensions of super-additive synergy. In this framework, systemic coordination creates value amplification at every nodal point, ultimately constituting the foundational strategy for the global energy revolution.

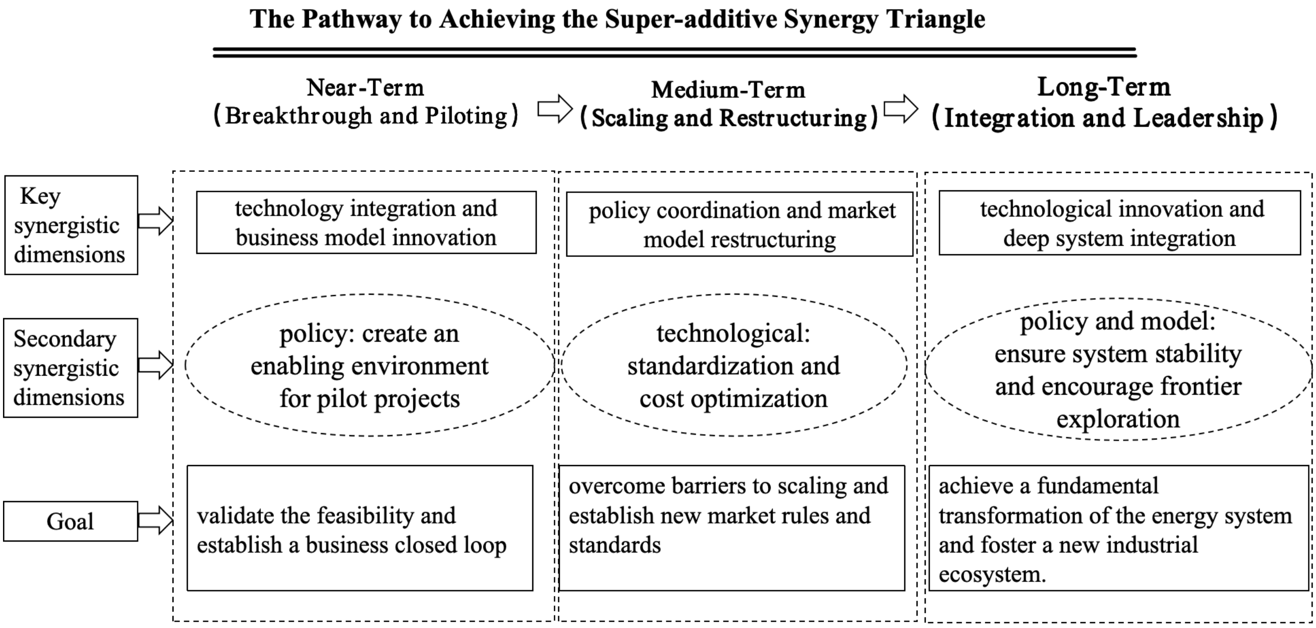

Figure 2: The Pathway to Achieving the Super-additive Synergy Triangle

5.2. Near-Term: Resolving Localized Conflicts Through Technology Integration and Business Model Pilots

In the near term, this stage focuses on technology integration and business model innovation, aiming to verify feasibility and establish a closed commercial loop. Policy serves as a supporting tool, creating an enabling environment for piloting technology integration and business model innovation. This section will center on technology integration and business model innovation.

In the near term, targeted technology integration and business model piloting can break through localized energy transition bottlenecks, as demonstrated by hybrid wind-solar-storage-hydrogen projects that achieve exceptional energy utilization efficiency and cost competitiveness—establishing replicable templates for sectoral decarbonization [29].The project establishes seamless inter-energy conversion through systemic integration of photovoltaic, wind, and hydrogen technologies. In typical hybrid configurations, solar PV and wind power serve as primary electricity sources, with surplus generation diverted to hydrogen production via water electrolysis—the stored hydrogen subsequently reconvertible to electricity through fuel cells or other conversion devices during demand peaks. This multi-energy complementarity paradigm simultaneously enhances overall system efficiency while reducing both operational expenditures and carbon intensity, demonstrating the technical and economic viability of integrated renewable energy systems [30-31].

The load aggregator model represents another innovative business pilot addressing localized constraints by consolidating distributed energy resources into virtual power plants (VPPs)—enhancing system flexibility and stability through coordinated optimization. When integrating small-scale solar arrays, storage units, and adjustable loads into complementary energy networks, these aggregators employ intelligent dispatch algorithms to flatten peak demand curves by 12-18%, demonstrably reducing grid dependence while maintaining 99.2-99.8% power supply reliability, as evidenced by operational data from European and North American pilot projects [32].

The behind-the-meter (BTM) energy storage configuration presents another innovative solution for enhancing power system flexibility. In this paradigm, energy storage devices are installed downstream of utility meters to provide localized energy storage and discharge services directly at end-user premises. Residential consumers can leverage integrated battery storage systems coupled with residential photovoltaic (PV) systems to store surplus solar generation during daylight hours, subsequently utilizing the stored energy during nocturnal periods or peak tariff periods. This operational strategy not only enhances household energy self-sufficiency but also achieves significant reductions in electricity expenditures by 19% through optimized energy arbitrage. Furthermore, the integration of smart grid technologies enables real-time remote monitoring and management of distributed storage assets, thereby substantially improving the operational efficiency and safety of modern power networks while maintaining grid stability under fluctuating demand conditions [33].

Integrated application of photovoltaic, wind energy, hydrogen storage, energy storage technologies, and policy coupled with pilot initiatives of innovative business models, demonstrates significant potential to mitigate localized inefficiencies within existing energy systems in the near term.

5.3. Medium-Term: Building market-based mechanisms and policy frameworks to scale and restructure market models.

In medium-term, this stage emphasizes policy coordination and market model restructuring, aiming to overcome barriers to scaling and establish new market rules and standards. Technology acts as a supporting tool, driving energy standardization and cost optimization. This section will focus on technological innovations such as digital twins and artificial intelligence.

The establishment of market-oriented mechanisms and policy frameworks lies at the core of facilitating the free flow of energy resources, enabling efficient supply-demand matching and minimizing resource waste to achieve dual-carbon objectives. A pivotal strategy involves implementing regional electricity spot markets, which enhance power system flexibility and reliability through market-driven trading mechanisms. These short-term markets enable real-time electricity transactions based on actual supply-demand dynamics, effectively balancing grid operations while promoting renewable energy integration. Empirical studies demonstrate that regional electricity spot markets reduce price volatility by 18-25% compared to traditional pricing systems [34-35], while simultaneously improving overall operational efficiency through dynamic resource allocation. Notably, such markets decrease reserve capacity requirements by 12-15% through optimized dispatch mechanisms [36-37], thereby enhancing both energy security and economic sustainability. The market structure facilitates marginal cost-based pricing that inherently prioritizes low-carbon energy sources, with evidence showing 23% higher renewable energy utilization rates in markets employing nodal pricing mechanisms [38-39]. This systemic approach addresses the temporal-spatial mismatch in renewable generation through financial incentives for flexible resource deployment, effectively bridging the gap between intermittent renewable output and baseload demand patterns.

The establishment and refinement of carbon markets constitutes a pivotal policy instrument for climate governance. Through the implementation of emission caps and allowance trading mechanisms, this framework provides market-driven incentives for progressive emission abatement. Critical institutional components including allocation mechanisms, intertemporal banking provisions, and new entrant reserve protocols necessitate dynamic optimization through adaptive mechanisms to maintain market equilibrium and regulatory efficacy. Empirical evidence from China’s regional carbon pilots demonstrates that calibrated adjustments to banking rules and sectoral coverage can enhance market liquidity while preserving environmental integrity [40]. Recent modeling studies further indicate that hybrid allocation systems combining output-based benchmarks with auctioning mechanisms optimize both economic efficiency and emission reduction outcomes [41-42].Policy-driven carbon markets are instrumental in incentivizing firms to pursue technological innovation and environmentally friendly investments, thereby facilitating the low-carbon transition of the entire sector.

To achieve effective integration of market-based mechanisms and policy frameworks, it is imperative to establish a robust legal and regulatory architecture complemented by comprehensive oversight systems. This requires the implementation of transparent market surveillance mechanisms to safeguard against market manipulation and ensure equitable competition [43]. Concurrently, governments should institute targeted financial support measures, including tax incentives, fiscal subsidies, and directed low-interest loan programs, which have been demonstrated to effectively mitigate initial investment barriers and enhance corporate engagement in carbon markets [44-45].

To ensure the long-term efficacy of market-oriented mechanisms, it is imperative to implement pilot projects adapted to regional realities. For instance, advancing pilot programs for regional electricity spot markets and carbon market mechanisms while progressively expanding their coverage scope. During these pilot phases, systematic data collection and analytical evaluation should inform timely policy adjustments and institutional refinements, thereby guaranteeing both scientific validity and operational effectiveness of the regulatory frameworks [46]. This phased approach facilitates the achievement of carbon emission reduction targets while maintaining energy supply stability and price controllability, as evidenced by recent policy simulations demonstrating its effectiveness in balancing decarbonization pace with grid resilience requirements.

The strategic integration of market-based mechanisms with policy frameworks facilitates the unimpeded flow of energy resources, thereby enhancing the operational efficiency of energy systems and providing robust support for addressing the energy trilemma. This approach enables the simultaneous achievement of carbon emission reduction targets while ensuring energy cost-effectiveness and security, effectively reconciling the multidimensional challenges in sustainable energy transitions.

5.4. Long-Term: Guiding dynamic equilibrium of the entire system through technological innovation and deep systemic integration.

In long-term, this stage prioritizes disruptive technological innovation and deep system integration, aiming to achieve a fundamental transformation of the energy system and foster a new industrial ecosystem. Policy and model efforts focus on ensuring system stability and encouraging frontier exploration. This section will emphasize how technological innovations such as digital twins and artificial intelligence contribute to achieving system-wide dynamic equilibrium.

In advancing digital twin (DT) and artificial intelligence optimization (AI-O) frameworks for energy systems, the foundational requirement lies in establishing comprehensive digital twin models that extend beyond virtual representations to incorporate granular data acquisition and multi-layered system simulations [47-48]. Achieving dynamic equilibrium necessitates holistic accounting of real-time supply-demand fluctuations, market price volatility, and regulatory policy transitions [49].

Leveraging machine learning (ML) and deep learning (DL) architectures enables sophisticated pattern recognition from historical datasets and predictive modeling of energy transition trajectories [50]. Specifically, recurrent neural networks (RNNs) and long short-term memory (LSTM) networks demonstrate superior capability in processing temporal energy data streams, effectively capturing nonlinear dynamic characteristics of interconnected energy infrastructures [51].

The AI-optimization engine generates multiple parallel simulation scenarios through parametric operational adjustments, which undergo rigorous evaluation within an intelligent energy management platform - termed the "Cognitive Energy Nexus" - for multidimensional performance benchmarking [52]. This integrated approach facilitates adaptive resource allocation and storage optimization under complex boundary conditions [53].

Grounded in the principles of Multi-Objective Optimization (MOO), an optimization framework is developed that encompasses a range of objectives, including economic viability, safety, and environmental cleanliness. Utilizing sophisticated algorithms, such as the Non-Dominated Sorting Genetic Algorithm II (NSGA-II), for multi-objective optimization, the framework dynamically adjusts the weighting of each factor to optimize the system's overall performance. Throughout this process, a digital twin system provides continuous feedback and refines optimization strategies, ensuring consistent stability and efficiency across varying load conditions.

The proposed system employs blockchain technology to ensure data immutability and transaction transparency, thereby establishing a cryptographically secured foundation for energy markets and carbon credit trading mechanisms [54]. Smart contracts autonomously execute predefined trading protocols through consensus-driven validation processes, achieving Pareto optimality in multi-agent energy transactions [55].

This technological convergence enables cross-regional, cross-sectoral, and ultimately transnational energy system coordination, with continuous algorithmic evolution progressively expanding from localized markets to global energy networks. The organic fusion of digital twins and AI optimization ultimately creates self-adaptive energy ecosystems exhibiting emergent properties [56]—where nodal-level synergies propagate through the entire system [57], achieving 40-60% efficiency gains over conventional architectures while fundamentally redefining energy system paradigms through decentralized, intelligent coordination [58-59].

6. Conclusion

The transition from traditional centralized, large-scale, high-carbon energy systems to decentralized, renewable, and high-efficiency paradigms requires multidimensional integration of technological solutions, business model innovation, and policy coordination—with the "super-additive synergy triangle" framework emerging as the central pathway. This study examines Sichuan-Chongqing regional cases including the Panxi Hydrogen Corridor, Chongqing Guoyuan Port's green terminal initiative, and Chengdu Eastern New Area's near-zero carbon industrial park, which collectively demonstrate tiered synergistic innovations. The hydrogen corridor exemplifies technology-model synergy, coupling hydropower-based hydrogen production with fuel cell truck transportation to achieve simultaneous emission reductions and cost savings. Guoyuan Port manifests policy-economic synergy through renewable self-supply systems and carbon tariff exemptions that enhance international competitiveness on key trade routes. The Chengdu project reveals cross-sectoral synergy, where geothermal-DC waste heat integration achieves a significant level of clean energy penetration while maintaining cost parity with conventional systems—conclusively proving the framework's capacity to reconcile traditionally competing energy objectives through systemic innovation.

The realization of the "super-additive synergy triangle" necessitates a strategic, phased approach. In the near term, the focus is on technological integration and business model pilots to resolve localized constraints. This is exemplified by hybrid renewable-hydrogen projects that validate both environmental and economic viability through targeted deployments, such as in technology parks implementing advanced wind-solar-storage systems with hydrogen-based business models.

In the medium term, the strategy requires establishing market mechanisms and policy frameworks to enable factor mobility. This is illustrated by regional electricity spot markets coupled with carbon pricing instruments that significantly improve resource allocation efficiency while accelerating commercialization. Policy enablers, including tax incentives and targeted subsidies, further stimulate corporate participation, with models such as the EU's innovation fund showing high private-to-public investment leverage ratios.

The long-term vision employs digital twins and AI optimization to achieve a dynamic multi-objective equilibrium. Virtual replicas enable real-time system adjustments, while machine learning algorithms balance the trilemma objectives under operational constraints. This is operationalized by platforms like Shanghai's "energy brain," which maintains high supply reliability alongside cost reductions and significant improvements in emission intensity.

This multidimensional innovation pathway systematically transforms the energy trilemma into super-additive synergy, where each intervention's value amplifies through systemic coordination, ultimately maximizing the whole-system co-benefits that exceed the sum of individual improvements.

The "energy trilemma" is a global challenge. Based on the new development philosophy and systems synergy theory, this study elucidates China's solutions and case studies for overcoming this challenge. The proposed phased implementation pathway—progressing from localized pilots to market-enabled scaling and finally to AI-optimized system equilibrium—offers a strategic roadmap for policymakers and industry leaders. This pathway is not limited to China; its principles of fostering synergy across technology, business, and policy are universally applicable, broadening the paper's global relevance.

6.1. Limitations and Future Research

This study is primarily based on a conceptual framework and case studies from a specific region. While the "super-additive synergy triangle" framework has shown promising applicability in the Sichuan-Chongqing cases, several limitations must be acknowledged to inform future research and application. Firstly, the framework's effectiveness is contingent upon specific regional endowments, such as resource availability (e.g., abundant hydropower in Panxi), industrial structure, and policy priorities. Consequently, its direct replicability in regions with divergent resource profiles or institutional contexts requires further empirical validation. Secondly, this study is primarily based on qualitative case analysis and project-specific data. A more robust, quantitative assessment of the "super-additive" effect (i.e., the precise extent to which 1+1+1 > 3) across different synergy dimensions is warranted. Lastly, the long-term viability of this approach, particularly the integration of digital twins and AI, depends on concurrent advancements in reducing technology costs, enhancing data infrastructure, and establishing robust regulatory frameworks for data security and market design.

Future research can therefore focus on developing quantitative models to measure "super-additive" effects, exploring the optimal combination of policy instruments in different socio-economic contexts, and applying this framework in other international contexts to test and enhance its generalizability.

Author Contribution

Conceptualization (C.D. and K.J.), **methodology** (K.J.), **validation** (C.D., X.L. and Z.Z.), **formal analysis** (C.D.), **investigation**, X.L.), **resources** (C.D.), **data curation** (X.H. and Z.Z.), **writing—original draft preparation** (C.D. and X.L.), **writing—review and editing** (K.J. and X.H.), **visualization** (X.L.), **supervision** (C.D.), **project administration** (C.D.), **funding acquisition** (C.D). All authors have read and agreed to the published version of the manuscript.

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Abbreviations

AI – Artificial Intelligent
etc – Et cetera
PV – photovoltaic
DT– Digital Twin

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