Designing Closed-Loop Energy Supply Chains under Lean Economy: Co-optimization of Resource Efficiency and Social Adaptability

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***Abstract*—Against the backdrop of the global energy transition and the advancement of "dual carbon" goals, building energy supply chain systems that are both efficient and sustainable has become a shared priority for researchers and industry practitioners alike. In reality, however, many existing energy supply chains still struggle with low resource utilization, notable environmental side effects, and increasingly complex social challenges. Much of the current research has concentrated on improving single objectives — such as cost reduction or environmental performance — while paying limited attention to how resource efficiency and social adaptability can be developed in a coordinated manner under the framework of a Lean Economy. This has left an important gap in the literature.**

To address this issue, this study develops a closed-loop energy supply chain network optimization model that incorporates multiple objectives, multiple time periods, and multiple energy types, including photovoltaic power, wind energy, hydrogen, and energy storage. The model is designed to explore how lean principles can be innovatively applied within modern energy systems. The Augmented Epsilon-Constraint (AUGMECON) method is used to solve the model, and a major industrial province in China is selected as a representative case study. The model's feasibility and practicality are verified using publicly available official statistics and open-access industry data.

The results show clear nonlinear trade-offs among the three core objectives: economic cost, resource efficiency, and social adaptability. Quantitative analysis indicates that a systematic application of lean strategies can reduce total supply chain costs by about 15% while increasing the recycling rate of key resources by more than 8%. At the same time, the findings suggest that certain lean measures may temporarily reduce employment in traditional energy sectors. This highlights the need for policymakers to introduce effective cushioning measures, such as targeted skills retraining programs and strengthened social security policies.

Overall, this research provides a comprehensive decision-support framework for energy enterprises and public authorities, helping them balance energy security, economic performance, resource conservation, and social equity. It offers both strong theoretical contributions and practical insights for accelerating the transition toward a lean, circular, and socially adaptive future energy system.

Keywords—Closed-loop supply chain; Lean economy; Integrated energy system; Multi-objective optimization; Social adaptability; Circular economy

I. INTRODUCTION

The increasing intensity of global climate change and the rapid reshaping of international energy geopolitics have created a strong global consensus and a clear national strategic mandate to accelerate the transition toward low-carbon, clean, and sustainable energy systems [1]. Within this broader context, the Closed-Loop Supply Chain (CLSC) model has attracted growing interest from both academia and industry as a key mechanism for advancing the principles of the Circular Economy (CE), particularly due to its strengths in resource recovery, recycling, and value regeneration [2]. At the same time, the concept of the "Lean Economy," originally rooted in manufacturing, provides a fresh theoretical lens and a practical pathway for addressing persistent problems in current energy supply chains—such as efficiency losses, resource mismatches, and excessive inventories — by adhering to its core philosophy of eliminating waste and maximizing value with minimal resource input [3].

Despite their promise, effectively embedding these advanced concepts into complex energy systems remains highly challenging. In practice, energy supply chain planning and optimization often struggle to reconcile economic feasibility, efficient resource utilization, and increasingly significant social impacts within a single coherent framework. Against this backdrop, this study centers on a fundamental question: under the guidance of lean economy principles, how should a closed-loop integrated energy supply chain network be designed to simultaneously enhance resource efficiency while fully accounting for social adaptability? This question goes beyond technical optimization and speaks directly to whether the energy transition can unfold in a smooth, inclusive, and equitable manner.

A review of the existing literature shows that substantial progress has been made in areas such as energy supply chain optimization, circular economy modeling, and lean production management. For example, many studies have employed mathematical programming techniques to optimize facility location, inventory decisions, and carbon emissions in hybrid renewable energy supply chains involving solar photovoltaics, wind power, and biomass [4]. Multi-objective optimization has also become a dominant approach in the design of sustainable biomass supply chain networks [5]. In addition, some researchers have begun to explore recovery and recycling networks for end-of-life energy equipment—

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such as photovoltaic modules and power batteries — by adapting circular supply chain frameworks originally developed for plastic products [6], thereby taking initial steps toward circularity in the energy sector.

Nevertheless, several important gaps remain. First, much of the existing research focuses on a single energy type or a single stage of the supply chain. There is a notable lack of studies on closed-loop supply chains for Integrated Energy Systems (IES) in which multiple energy technologies—such as PV, wind, hydrogen, and energy storage—are coupled and coexist, limiting insights into system-wide synergies. Second, optimization objectives are often restricted to economic cost minimization or carbon emission reduction, with insufficient attention paid to comprehensive indicators of resource utilization efficiency and to broader social value dimensions, including employment effects and balanced regional development [7]. Third, although lean principles have been widely applied in manufacturing supply chains, their translation into operational mathematical models suitable for strategic, macro-level energy supply chain network design is still at an early stage [8].

To address these gaps, this study pursues three main objectives. First, it develops a multi-objective optimization model for a closed-loop integrated energy supply chain that is deeply aligned with lean principles. For the first time, this model simultaneously captures the forward and reverse logistics of multiple renewable energy technologies within a unified framework, drawing theoretical support from established closed-loop supply chain remanufacturing models [9]. Second, the study proposes a multi-dimensional performance evaluation system that incorporates indicators such as resource recycling efficiency, energy cascade utilization efficiency, employment creation, and regional development balance. Insights from consumer market research on remanufactured energy products are also considered to enhance the model's practical relevance [10]. Third, through an empirical case study, the research quantitatively reveals the underlying synergistic and trade-off relationships among economic, resource, and social objectives, offering decision-makers a clear roadmap for identifying optimal solutions under different strategic priorities.

To ensure rigor and consistency, the study first clarifies the measurement standards for lean production within supply chains [11] and integrates findings from research on lean initiatives and sustainability in closed-loop supply chain game models [12], thereby strengthening the strategic applicability of the proposed framework. The research focuses on regional-level strategic supply chain network planning and draws on multi-objective optimization methods used in electricity market pricing and system security analysis [13], as well as GIS-based spatial analysis approaches for low-carbon energy infrastructure planning [14]. Social sustainability is guided by the principle of a "just transition" [15], and informed by the energy justice framework [16] and systematic reviews of social sustainability assessment in industrial solar energy systems [17], enabling the construction of a comprehensive social impact evaluation system. The ε-constraint method [18] is employed to solve the multi-objective optimization problem, given its maturity and effectiveness in handling complex trade-offs. The remainder of the paper is organized as follows: Section 2 reviews the relevant literature; Section 3 presents the problem description and mathematical model; Section 4 outlines the case study design; Section 5 reports and analyzes the results; Section 6 discusses the key findings; and Section 7 concludes with final remarks and directions for future research.

II. Literature Review

This section provides a structured and comprehensive review of four key research streams closely related to this study: closed-loop supply chains and the circular economy, the application of lean management in supply chains, optimization approaches for energy supply chains, and the social sustainability of energy systems. Through this review, the academic positioning of the study and its main innovative contributions are clearly identified. Figure 1 presents the publication trends across these four research areas from 2015 to 2025, with data sources drawn from recent studies on renewable energy supply chain configuration and total factor productivity [19].

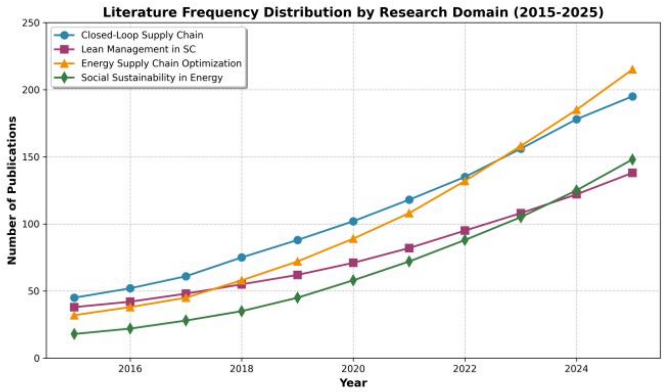

Fig. 1. Literature Frequency Distribution by Research Domain (2015-2025)

Closed-Loop Supply Chains (CLSCs), as a core operational mechanism for implementing the Circular Economy (CE) concept [2], have attracted extensive academic attention alongside the accelerating global low-carbon energy transition [1]. By incorporating reverse logistics, CLSCs enable the recovery, remanufacturing, refurbishment, or recycling of end-of-life products, thereby forming a closed material flow of "resources − products − regenerated resources" [8]. A large body of research has demonstrated that CLSC implementation not only delivers substantial environmental benefits — such as reduced raw material consumption and landfill waste — but also creates new sources of economic value. In particular, mature remanufacturing models developed in manufacturing industries provide a valuable theoretical reference for designing recycling networks for energy equipment [9]. For example, studies in the electronics and automotive sectors have shown that remanufactured products can achieve performance levels comparable to new products at lower costs, offering important insights for the market operation of remanufactured energy equipment [10]. Through well-designed CLSC networks, the "3R" principles of the circular economy — Reduce, Reuse, and Recycle — can be effectively implemented. Moreover, clear definitions and measurement standards for lean production [3,11] can further enhance resource utilization efficiency within CLSCs, while innovation-driven lean initiatives have been shown to significantly improve the sustainability of closed-loop supply chains, laying the groundwork for integrating lean thinking with the circular economy in the energy sector [12]. However, applying CLSCs to energy systems—particularly integrated energy systems involving multiple technologies and complex infrastructures—is far more challenging than in traditional manufacturing. This complexity requires the integration of multi-objective optimization methods for electricity market security [13], spatial analysis techniques for low-carbon energy infrastructure planning [14], and social sustainability principles such as just transition [15] and energy justice [16]. As a result, systematic research in this area remains largely exploratory.

Since its success in the Toyota Production System, lean thinking has been widely adopted in global production and supply chain management, and its core principle of waste elimination offers an important pathway for improving energy supply chain efficiency [3]. Lean management focuses on identifying and removing non-value-adding activities — such as overproduction, excessive inventory, waiting, and unnecessary transportation — to deliver maximum customer value with minimal resource input. The establishment of clear metrics for lean production in supply chains [11] provides a quantitative foundation for applying these principles in the energy sector. At the supply chain level, lean thinking has given rise to management tools such as Just-In-Time production, Kanban systems, Total Quality Management, and continuous improvement (Kaizen), all of which can be adapted to manage forward and reverse logistics in energy supply chains [11]. Genc and De Giovanni (2020), using a game-theoretic framework, demonstrated that innovation-driven lean initiatives can significantly improve the profitability and sustainability of closed-loop supply chains, confirming the relevance of lean management for energy-related CLSC research [12]. In energy supply chain optimization, lean concepts can be combined with multi-objective optimization approaches for electricity market pricing and system security [13], as well as with GIS-based spatial analysis methods [14], to improve both network design and facility layout. Despite its recognized value at the operational level, a major challenge remains in scaling lean thinking from the factory or firm level to the broader industrial ecosystem level and quantitatively embedding lean principles—such as inventory penalties or value-density incentives — into macro-level energy supply chain network optimization models that also account for just transition and social sustainability requirements [15 – 17].

Energy supply chain optimization plays a critical role in ensuring national energy security and supporting efficient economic operation under the dual pressures of climate change and energy transition [1]. Guided by circular economy principles [2] and lean management concepts [3], existing studies have largely relied on mathematical programming approaches, with hybrid renewable systems—such as solar photovoltaic, wind, and biomass—emerging as a key research focus and forming the basis for multi-energy coupling optimization [4]. Multi-objective optimization has become a mainstream method in sustainable biomass supply chain design and can be extended to integrated renewable energy supply chains [5]. Researchers have also adapted circular economy frameworks from plastic supply chains to explore recovery networks for end-of-life energy equipment, initiating the integration of circularity into energy supply chain reverse logistics [6]. Early optimization studies primarily emphasized economic objectives, such as minimizing total investment, operational, and transportation costs, and later incorporated environmental objectives like carbon emission reduction, resulting in dual economic – environmental optimization frameworks [7]. With growing concern for social sustainability, concepts such as just transition [15] and energy justice [16] have been introduced, and recent reviews of social sustainability assessment in industrial solar energy systems have highlighted methodological gaps, driving interest in three-dimensional optimization frameworks that simultaneously consider economic, environmental, and social objectives [17].

In terms of solution techniques, the ε-constraint method has become an increasingly popular and effective tool for solving multi-objective energy supply chain optimization problems [18]. Recent studies have linked renewable energy supply chain configuration with total factor productivity, enriching perspectives on supply chain efficiency evaluation [19], and have empirically examined how green supply chain management and renewable energy consumption influence carbon emissions [20]. Other research has integrated green supply chain management with renewable energy planning and dynamic inventory control, providing a basis for coordinating forward logistics with renewable energy supply [21]. Within the context of China's energy transition, scholars have assessed sustainability progress and system resilience [22], analyzed the social impacts of just energy transitions [23], and examined the interactions between energy transition and socio-economic growth [24]. Technically, multi-energy complementary systems — particularly those integrating renewable energy with hydrogen—have become a key development direction [25], while uncertainty-aware optimization of integrated energy systems, especially under photovoltaic variability, has gained increasing attention [26]. Long-term studies on China's pathway toward net-zero emissions by 2060 [27] and analyses of policy-driven transformations in global solar PV supply chains [28] further underscore the need for holistic, policy-aware energy supply chain optimization.

The energy transition is not only a technological shift but also a profound social transformation [1], making the social sustainability of energy systems an increasingly important research theme. Lean management's emphasis on efficiency [3] must therefore be reconciled with social objectives to achieve truly sustainable energy supply chains. The concept of a just transition emphasizes fair distribution of costs and benefits during decarbonization and the protection of vulnerable workers and communities, providing a normative foundation for defining social objectives in energy supply chain optimization [15]. Based on the energy justice framework, scholars have proposed social impact indicators related to employment, energy accessibility, and regional equity [16]. Systematic reviews of social sustainability assessment for industrial-scale solar projects have further highlighted limitations in current quantitative approaches, pointing to the need for improved evaluation systems [17]. The ε-constraint method [18] enables the integration of social objectives with economic and environmental goals in optimization models, while studies on supply chain configuration and productivity [19] and green supply chain management [20,21] offer opportunities to expand performance evaluation frameworks to include social dimensions. In China, research on energy transition sustainability and resilience [22], social impacts of just transition [23], and socio-economic effects of energy restructuring [24] provides important contextual guidance for defining social sustainability objectives. Emerging multi-energy systems [25,26], long-term net-zero planning [27], and policy-driven supply chain transformations [28] further highlight the need to explicitly consider social impacts in energy supply chain design.

Despite growing consensus on the importance of social dimensions, significant challenges remain in constructing objective functions that can quantitatively capture diverse social values, integrating them with economic and environmental objectives, and analyzing their complex trade-offs — especially within frameworks that also incorporate lean principles and circular economy requirements. Based on a systematic review of the literature [1 – 30], this study identifies several key research gaps. Existing work often focuses on single energy types or forward logistics and lacks unified closed-loop supply chain models that integrate multiple renewable technologies such as photovoltaics, wind, hydrogen, and storage. Lean economy principles have not yet been fully translated into operational mathematical formulations for strategic energy supply chain network design, and social sustainability considerations rooted in just transition and energy justice remain insufficiently embedded in optimization models. Furthermore, current multi-objective approaches rarely combine spatial optimization, uncertainty analysis, and productivity considerations within a closed-loop, lean-oriented framework.

To address these gaps, this study makes a novel attempt to integrate four traditionally separate research domains — lean economy, closed-loop supply chains, integrated energy systems, and social sustainability — within the broader context of global low-carbon transition and circular economy development. By developing a new multi-objective co-optimization model based on the ε-constraint method, the research incorporates China's multi-energy complementary renewable energy characteristics, policy-driven supply chain transformation requirements, and a comprehensive social sustainability evaluation framework grounded in just transition and energy justice. Spatial analysis methods and uncertainty considerations are further embedded to achieve full-chain optimization of closed-loop integrated energy supply chains, encompassing both forward and reverse logistics. Ultimately, this study seeks to identify a feasible pathway for maximizing resource recycling efficiency and enhancing social fairness and adaptability while maintaining economic viability, thereby providing theoretical support and decision-making insights for China's transition toward a net-zero energy system by 2060 and contributing to the realization of a just energy transition.

III. PPROBLEM DESCRIPTION AND MODEL FORMULATION

This chapter is devoted to clearly defining the research problem and developing a mathematical model that can effectively represent the design of a closed-loop integrated energy supply chain network under the framework of a lean economy. The proposed model constitutes the core of this study and provides the analytical foundation for the subsequent case analysis and decision-support results.

A. Problem Description

This research addresses the strategic planning problem of a regional closed-loop integrated energy supply chain system. The objective of the system is to satisfy time-varying energy demand within a given region while simultaneously achieving coordinated optimization across economic performance, resource efficiency, and social objectives. Compared with conventional energy supply systems, the system considered in this study exhibits several distinctive characteristics.

First, the system is based on integrated energy coupling. Rather than relying on a single renewable technology, the network integrates two major intermittent renewable energy sources—photovoltaic (PV) and wind power—and combines them with hydrogen systems (serving as both an energy carrier and a storage medium) as well as battery energy storage. This multi-energy coupling significantly enhances the overall flexibility and reliability of the system in responding to demand fluctuations and renewable energy uncertainty.

Second, the system explicitly incorporates closed-loop material flows. Beyond the forward processes of energy generation, conversion, storage, and distribution, the model emphasizes reverse logistics for key energy equipment, including PV modules, wind turbines, storage batteries, and electrolyzers. After reaching the end of their service life, these components are collected from end users and transported to recycling centers, remanufacturing facilities, or final disposal sites. This bidirectional flow structure forms a closed-loop material system, which is essential for supporting circular economy objectives in the energy sector.

Third, lean economy principles are embedded directly into the model design. The core idea of lean management is reflected through the introduction of inventory holding cost penalty factors, which discourage excessive inventory accumulation and promote the adoption of Just-In-Time supply chain strategies. By reducing capital lock-in and unnecessary space occupation, these lean mechanisms improve value chain efficiency and enhance the overall operational performance of the energy supply chain.

Figure 2 presents a schematic illustration of the closed-loop integrated energy supply chain network structure developed in this study.

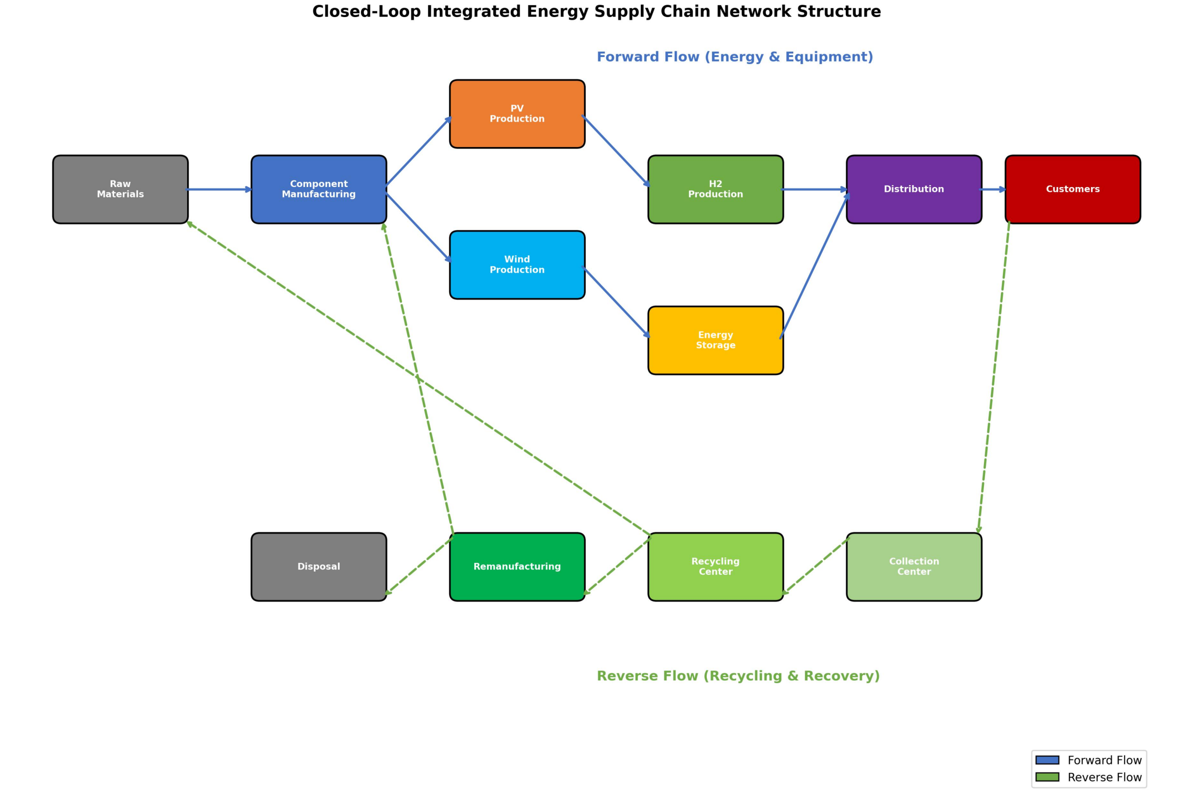

Fig. 2. Closed-Loop Integrated Energy Supply Chain Network Structure

The nodes of the new AD supply chain network are raw material suppliers, equipment manufacturing sector and energy-producing units such as photovoltaic power stations and wind farms. The network also includes central battery energy storage stations, hydrogen centres, which include electrolysis-based hydrogen production and H2-storage sites, similar centers for equipment recycling and remanufacturing, waste disposal sights or several demand nodes (as end users) where experience different types of energy.

Material and energy exchange along the network is both up- and downstream. The flow upstream pushes raw materials, newly manufactured equipment and energy in various ways including electricity and hydrogen towards the lower end of the chain. Conversely, the backward flow retrieves EOL equipment, disposed parts and recyclable materials from demand points/intermediaries to recycling centres, remanufacturing plants or landfills, thus completing the material cycle.

The decisions that we focus on in this paper are of a strategic nature and span a long planning horizon (typically 15-20 years), which is discretized into multiple time periods to account for changing demand patterns and technological development. These choices include those related to facilities locations (e.g., build or not a facility at candidate sites), capacity investments/expan sions that determine the level of some facilities in each planning period, flow patterns that determine the production, transportation, storage and conversion rates among materials/energy carriers over the entire network, and recovery options that define different types of recovery strategies and corresponding recovery rates in EoL energy equipment.

B. Mathematical Model

In order to facilitate a quantitative evaluation of the issue depicture above, we develop an MO-MILP model for this problem. The model is set to reflect the primary structural properties of lean economy system and functional demands on decision-making for closed-loop IE supply chains. The model is systematically described in Table I, which lists the urre.

1) Indices, Parameters, and Decision Variables

TABLE I. KEY MODEL PARAMETER SETTINGS

Parameter Name	Symbol	Unit	Value	Data Source
PV Investment Cost	C_inv_PV	¥/kW	3,500	IRENA 2024
Wind Investment Cost	C_inv_Wind	¥/kW	6,200	IRENA 2024
Hydrogen Investment Cost	C_inv_H2	¥/kW	15,000	IEA 2024
Storage Investment Cost	C_inv_Storage	¥/kWh	1,200	BNEF 2024
PV Operating Cost	C_op_PV	¥/kWh/year	0.05	Industry Report
Wind Operating Cost	C_op_Wind	¥/kWh/year	0.08	Industry Report
Transport Cost	C_trans	¥/ton·km	0.35	Published freight tariff reports / public logistics

				price indices
PV Recycling Rate	α_PV	%	85	Literature
Battery Recycling Rate	α_Battery	%	92	Literature
Energy Conversion Efficiency	β	%	78	Technical Specs
Lean Penalty Factor	Lean_p	-	1.5	Scenario assumption (tested in sensitivity analysis)
Job Creation Rate	Job	jobs/MW	2.8	Statistics Bureau

A number of index sets are used in the model to describe the topology and dynamics of closed-loop integrated energy supply chain network. In particular, the indices i and j indicate the node set of supply chain network which consists of all nodes in upstream, intermediary and downstream facilities. The index k defines types of materials; components or equipment appear in the system and m denotes the set of energy products (electricity, hydrogen). Several discrete periods of time t (e.g., years) are used to index the planning horizon in order to represent long-term system evolution. Geographic variation is indicated by index l, representing distinct sites or regions. Lastly, index s is used to represent the different realisation scenarios which capture demand uncertainty, technology performance uncertainty or other uncertain characteristics of the system across scenarios.

Decision Variables:

- X_ilt (Binary): Decision to invest in building at node i in region l during period t
- Cap_ikt (Continuous): Total capacity of facility type k at node i in period t
- Q_ijkt (Continuous): Quantity of material type k transported from node i to node j in period t
- P_imt (Continuous): Quantity of energy type m produced at node i in period t
- S_ikt (Continuous): Inventory level of material type k at node i at the end of period t

2) Objective Functions

Objective 1: Minimize Total Economic Cost (Z1)

This objective seeks to minimize the total discounted cost of the entire supply chain system over the planning horizon and serves as a key indicator of the system's economic feasibility.

$$\sum_{i,j,k} (C_{trans,ijkt} \cdot Q_{ijkt}) + \sum_{i,k} (C_{stock,ikt} \cdot S_{ikt} \cdot Lean_p)] - \sum_t (ValueofRecoveredMaterials \quad (1)$$

Here, Δ Cap_ikt represents the newly added capacity, and the introduction of Lean_p (>1) increases the penalty for inventory, reflecting the lean principle.

Objective 2: Maximize Overall Resource Efficiency (Z2)

This objective measures the system's level of resource recycling and comprehensive energy utilization at a macro level, composed of two weighted sub-objectives.

$$\max Z2 = w_{rec} \cdot (ResourceRecyclingRate) + w_{eue} \cdot (EnergyUtilizationEfficiency) \quad (2)$$

Where:

- Resource Recycling Rate = Σ (Total amount of material k recovered and reused) / Σ (Total amount of material k discarded)
- Energy Utilization Efficiency = Σ (Total amount of energy m effectively used at the end) / Σ (Total amount of primary energy m input into the system)

Objective 3: Maximize Social Adaptability (Z3)

This objective aims to quantify the positive contributions of the supply chain system to society, with a particular focus on employment and the fairness of regional development, also composed of two weighted sub-objectives.

$$\max Z3 = w_{job} \cdot (TotalNewJobsCreated) + w_{reg} \cdot (RegionalDevelopmentBalance) \quad (3)$$

Where:

- Total New Jobs Created = Σ (Job_ik ・ Δ Cap_ikt)
- Regional Development Balance = 1 - Gini(Σ (Total investment in region l))

Here, the inverse of the Gini coefficient is used to measure the balance of investment distribution among different regions. A smaller Gini coefficient indicates a more balanced distribution, resulting in a larger value for this objective.

3) Main Constraints

The model operation is required to comply with several physical and logical constraints for feasibility and realism. The main constraints include:

Demand Satisfaction Constraint: The energy demand of each zone in all periods should be satisfied..

$$\sum_i P_{imt} \geq Demand_{mt} \quad , \forall m,t \quad (4)$$

Material Balance Constraint:For each node and each material type, the inflow plus the initial inventory and production must equal the outflow plus the ending inventory.

$$\sum_j Q_{ijkt} + S_{ik,t-1} + Production_{ikt} = \sum_j Q_{jikt} + S_{ikt} \quad , \forall i,k,t \quad (5)$$

Capacity Limitation Constraint:The production or processing volume at any node cannot exceed its total capacity for that period.

$$\sum k \quad Processingikt \quad \leq Capikt \quad , \forall i, t \qquad (6)$$

Reverse Logistics Constraint: The generation of end-of-life products is governed by the service life of equipment in the forward supply chain, and the quantity recovered must comply with the minimum recovery rate mandated by policy.

Energy Conversion Constraint: The transformation between different energy forms must satisfy the law of energy conservation and adhere to the specified conversion efficiencies.

Decision Variable Constraints: Ensure that all decision variables are correctly defined in terms of type (binary or continuous) and permissible range (e.g., non-negative values).

C. Solution Method

The model represents a multi-objective optimization problem, meaning that no single solution can simultaneously optimize all objectives. Instead, the solution space consists of a set of Pareto optimal solutions. To ensure practical reproducibility under typical research conditions, this study adopts the Augmented Epsilon-Constraint (AUGMECON) method and formulates the MO-MILP model in a solver-agnostic manner, allowing implementation in widely available open-source modeling platforms and MILP solvers.

The core idea of this approach is to select one objective function—usually the economic cost Z_1—as the primary objective to be optimized, while transforming the remaining objectives (Z_2 and Z_3) into inequality constraints. Its basic form can be expressed as follows:

$$\begin{aligned} \min \quad & Z_1 \\ \text{s.t.} \quad & Z_2 \geq \varepsilon_2, \\ & Z_3 \geq \varepsilon_3, \\ & \text{(All original constraints)} \end{aligned} \qquad (7)$$

By systematically adjusting the constraint thresholds ε_2 and ε_3 within a predefined range and repeatedly solving this single-objective model, a series of efficient solutions distributed on the Pareto frontier can be obtained. Compared to the traditional ε -constraint method, AUGMECON avoids the generation of weakly Pareto optimal solutions and significantly improves solving efficiency by introducing slack variables and their penalty terms for the other objectives into the main objective function, i.e.:

$$\backslash [\min Z_1 - \delta \cdot \left(\frac{slack_{Z_2}}{range_{Z_2}} + \frac{slack_{Z_3}}{range_{Z_3}}\right) \backslash] \qquad (8)$$

This is particularly suitable for handling complex problems with three or more objective functions. The resulting set of Pareto solutions will provide decision-makers with a clear "menu" showing the quantitative trade-offs among the economic, resource, and social objectives under different strategic preferences.

IV. CASE STUDY

To verify the effectiveness and practical applicability of the proposed model, and to generate insights relevant to real-world energy system planning, this study selects Shandong Province, China, as the case study area.

A. Selection of the Study Area

Shandong Province is chosen based on several key considerations. First, it faces enormous energy demand and strong pressure for structural transformation. As one of China ' s most populous and economically developed provinces, Shandong consistently ranks among the highest in total energy consumption nationwide. Its energy mix is still heavily reliant on coal, creating significant challenges for achieving the "dual carbon" transition goals.

Second, Shandong is well endowed with renewable energy resources, particularly solar and wind power. Its long coastline offers favorable conditions for the development of offshore wind energy, providing a solid resource foundation for establishing an integrated energy system.

Third, the province has a strong industrial base and a relatively complete supply chain. Shandong hosts a mature equipment manufacturing sector, including the production of key energy technologies such as photovoltaic modules and wind turbines. In addition, its circular economy sector is gradually taking shape, offering industrial support for the development of a closed-loop energy supply chain.

Finally, Shandong serves as a policy pioneer. As a national comprehensive experimental zone for replacing old growth drivers with new ones, the province benefits from strong policy commitment and institutional advantages in advancing energy restructuring, industrial upgrading, and green development initiatives.

For these reasons, a case study based on Shandong Province is both typical and representative. The findings can provide direct decision-making references for energy transition pathways in Shandong and other provinces with similar characteristics in China.

B. Data Sources

The data used in this study are primarily obtained from publicly available official statistics and open-access industry reports and databases, ensuring that the case study can be replicated without reliance on proprietary surveys.

Energy demand data are sourced from the Shandong Statistical Yearbook and annual energy development reports issued by the Shandong Provincial Energy Bureau. Future electricity and hydrogen demand over the planning horizon (2025 – 2040) is projected by considering regional GDP growth, population trends, and improvements in electrification levels.

Cost and technical parameters — including investment costs, operating costs, conversion efficiencies, equipment lifetimes, and recycling technology parameters for facilities such as photovoltaic plants, wind farms, hydrogen production stations, and recycling plants — are mainly derived from the latest reports of the International Renewable Energy Agency (IRENA), the China Renewable Energy Industries Association, annual financial reports of relevant listed companies, and authoritative academic literature. These parameters are adjusted where necessary to reflect local conditions in Shandong.

Geographical and transportation data are obtained from publicly available GIS datasets, such as administrative boundaries and transport networks. Using open-source tools, Shandong Province is divided into multiple regions (e.g., prefecture-level cities), and transportation distances between candidate facility locations and demand centers are calculated. Transportation costs are based on published freight tariff reports and publicly available logistics price indices.

Socio-economic parameters, including job creation per unit of investment and regional economic development indicators (represented by per capita GDP), are sourced from the Shandong Statistical Yearbook and public data released by the Shandong Provincial Department of Human Resources and Social Security (Table II).

TABLE II. REGIONAL INVESTMENT DISTRIBUTION DATA

Region	GDP ($\times 10^9$ ¥)	BAU Investment ($\times 10^9$ ¥)	Lean Investment ($\times 10^9$ ¥)	Social Priority Investment ($\times 10^9$ ¥)
Jinan	1,200	12.5	10.8	8.5
Qingdao	1,400	18.2	16.5	10.2
Yantai	850	14.5	15.2	10.5
Weifang	680	8.2	7.5	8.8
Linyi	520	4.5	4.2	12.5
Jining	480	3.8	3.5	14.2
Heze	380	2.5	2.2	15.8
Dongying	350	6.8	8.5	8.2

C. Scenario Settings

In order to further examine how different strategic orientations influence the design of the supply chain system, this study develops three representative development scenarios.

1) Business as Usual (BAU) Scenario:

The BAU scenario assumes a continuation of current technological development trends and policy intensity, and it serves as a benchmark for comparison. Under this scenario, the optimization model mainly focuses on minimizing economic costs, while requirements related to resource efficiency and social adaptability are kept at the minimum levels mandated by existing policies.

2) Lean Economy (LE) Scenario:

The LE scenario highlights the comprehensive application of lean principles. In the model, this is reflected by a substantially higher penalty factor for inventory costs (Lean_p), along with stricter targets for equipment utilization and energy conversion efficiency. The objective is to identify a supply chain network configuration that maximizes overall resource efficiency.

3) Social Priority (SP) Scenario:

The SP scenario places social adaptability at the center of strategic decision-making. During model solution, greater weight is assigned to the social adaptability objective (Z3) in order to evaluate the trade-offs in economic performance and resource efficiency required to achieve higher employment creation and more balanced regional development.

By comparing the optimal solutions obtained under these three scenarios, the behavioral patterns of the system and the performance differences arising from alternative strategic choices can be clearly identified.

V. RESULTS AND ANALYSIS

Through the application of the AUGMECON method to solve the model, a set of Pareto optimal solutions is obtained, forming a three-dimensional frontier surface that illustrates the trade-off relationships among economic, resource, and social objectives. This chapter subsequently presents and interprets the key results from four perspectives: Pareto frontier analysis, optimal network structure, scenario comparison, and sensitivity analysis.

A. Pareto Frontier Analysis

Figure 3 depicts the Pareto frontier surface among the three primary objectives. The results reveal pronounced non-linear trade-off relationships between them.

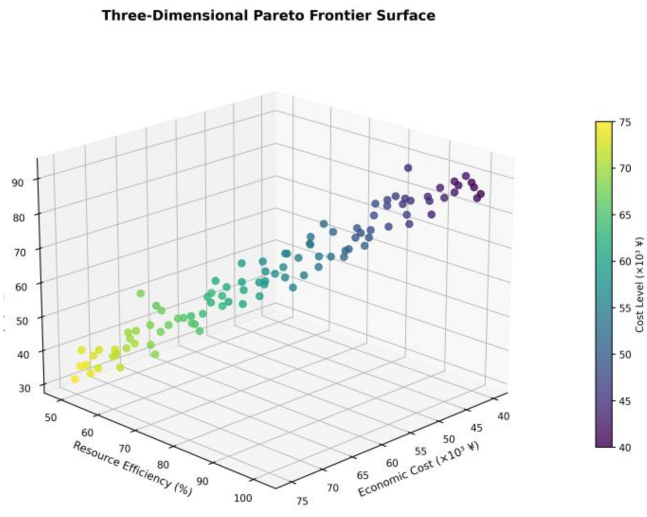

Fig. 3. Three-Dimensional Pareto Frontier Surface

First, economic cost (Z1) and resource efficiency (Z2) exhibit a certain degree of synergy. Optimizing the network layout and reducing waste in intermediate processes can simultaneously lower costs and improve resource utilization. However, once resource efficiency requirements exceed a critical threshold — such as mandating extremely high recycling rates — substantial investments in advanced and high-cost recycling technologies and facilities become necessary. This leads to a rapid increase in economic costs, causing the two objectives to shift from synergy to conflict.

Second, the trade-off between economic cost (Z1) and social adaptability (Z3) is more direct. Achieving higher employment levels or redirecting investment toward less developed regions often requires constructing facilities that are not economically optimal, thereby increasing the overall system cost. This highlights the economic price that must be paid to realize a “just transition.”

Finally, the relationship between resource efficiency (Z2) and social adaptability (Z3) is more nuanced. In certain situations, the development of labor-intensive recycling and remanufacturing industries can improve both objectives simultaneously, indicating a synergistic effect.

B. Scenario Comparison Analysis

Figure 4 shows the comparison of key performance indicators across the three scenarios.

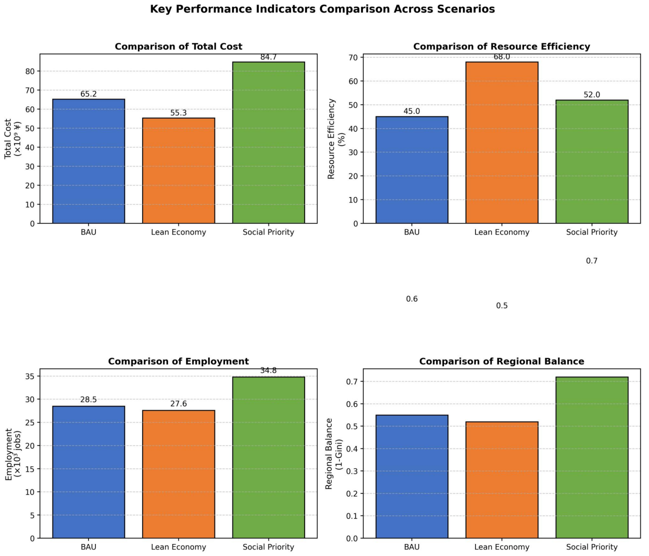

Fig. 4. Comparative Analysis of Key Performance Indicators Across Scenarios

TABLE III. COMPARISON OF KEY PERFORMANCE INDICATORS ACROSS THREE SCENARIOS

Indicator	BAU	Lean Economy	Social Priority
Total Cost (×10⁹ ¥)	65.2	55.3	84.7
Investment Cost (×10⁹ ¥)	25.0	22.0	35.0
Operating Cost (×10⁹ ¥)	18.0	15.0	22.0
Transport Cost (×10⁹ ¥)	12.0	10.0	15.0
Inventory Cost (×10⁹ ¥)	8.0	4.0	10.0
Recovery Value (×10⁹ ¥)	-5.0	-8.0	-4.0
Resource Efficiency (%)	45.0	68.0	52.0
Energy Utilization (%)	72.0	82.0	75.0
Recycling Rate (%)	48.0	65.0	55.0
Total Employment (×10³)	28.5	27.6	34.8
Regional Gini Coefficient	0.45	0.42	0.28
Social Index	68.0	72.0	92.0

A quantitative comparison of the key performance indicators across the three scenarios shows that, relative to the BAU scenario, the Lean Economy scenario reduces total supply chain costs by approximately 15.3%, increases the overall resource recycling rate from 45% to 68%, and improves comprehensive energy utilization efficiency by about 8 percentage points. However, the total number of jobs declines slightly (by around 3%), mainly because automation and efficiency improvements replace some low-skilled positions.

In contrast, the Social Priority scenario produces markedly different outcomes. Total employment is about 22% higher than in the BAU scenario, and the Gini coefficient of regional investment decreases from 0.45 to 0.28, indicating a significant improvement in social equity. These social gains, however, come at the expense of economic performance, as the total system cost increases by nearly 30% (Table III).

Figure 5 shows the breakdown of the cost structure.

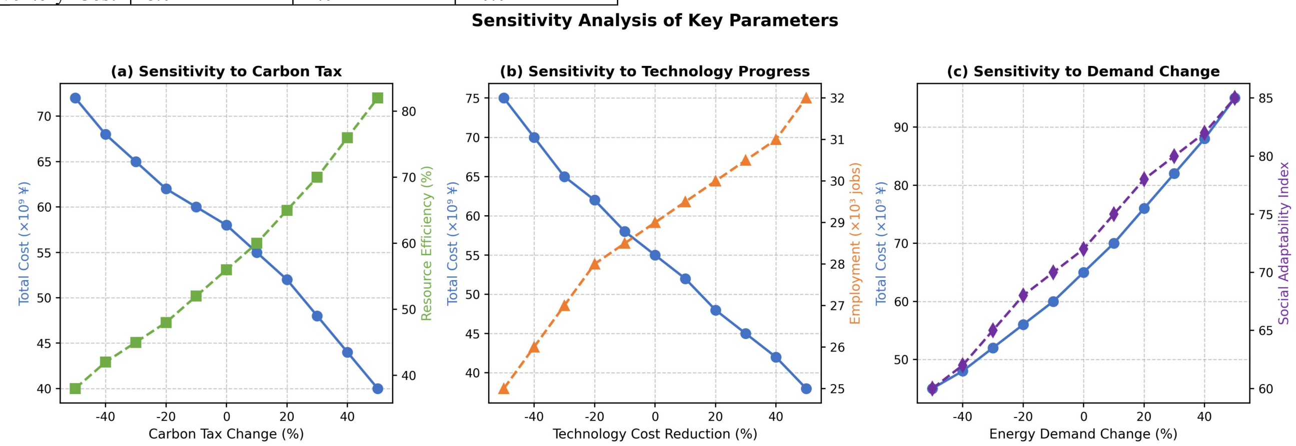

Fig. 5. Cost Structure Breakdown by Scenario

C. Optimal Network Structure Analysis

Figure 6 shows the optimal spatial layout of the supply chain network under different scenarios.

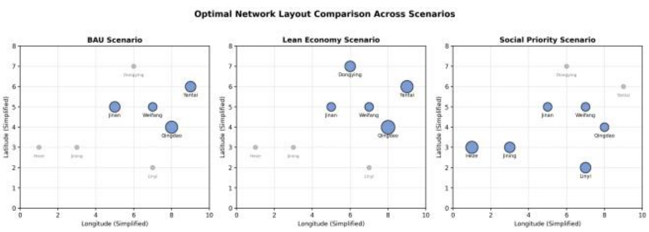

Fig. 6. Optimal Supply Chain Network Layout Across Scenarios

The optimal spatial configuration of the supply chain network differs markedly across the scenarios. In the BAU scenario, facility locations are highly concentrated in areas with strong resource endowments—such as coastal regions with abundant wind energy and northwestern Shandong with high solar radiation—and in proximity to major load centers, in order to minimize transportation costs.

Under the Lean Economy scenario, the network becomes more integrated, with shorter logistics paths. Energy storage and hydrogen facilities, acting as key flexibility resources, are more widely distributed and flexibly sited to better accommodate the variability of intermittent renewable power, thereby reducing wind and solar curtailment. The reverse logistics network is also more perfect, with recycling centers generally located near urban clusters to lower collection and transportation costs.

In the Social Priority scenario, investment patterns shift noticeably toward the relatively less developed western and southern regions of Shandong Province. Although this spatial arrangement is not economically optimal, it effectively promotes more balanced regional development.

D. Energy Flow and Recycling Analysis

Figure 7 shows the energy flow distribution matrix within the system.

Figure 8 shows the projected trend of recycling rates for different types of equipment.

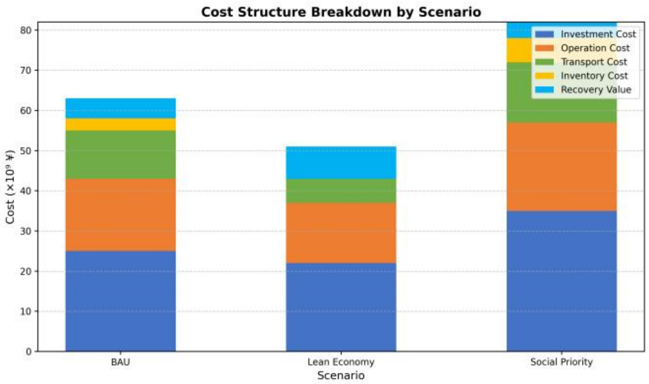

Fig. 7. Energy Flow Distribution Matrix (Lean Economy Scenario)

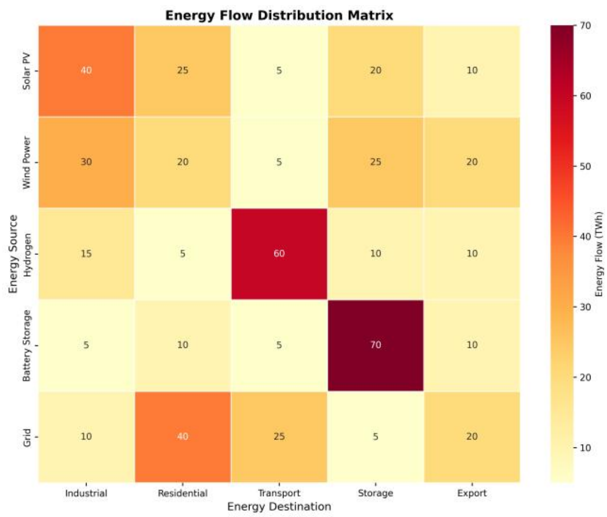

Fig. 8. Projected Recycling Rate Trends by Equipment Type (2025-2040)

E. .Sensitivity Analysis

We conducted a sensitivity analysis （Table IV) on several key external parameters, the results of which are shown in Figure 9.

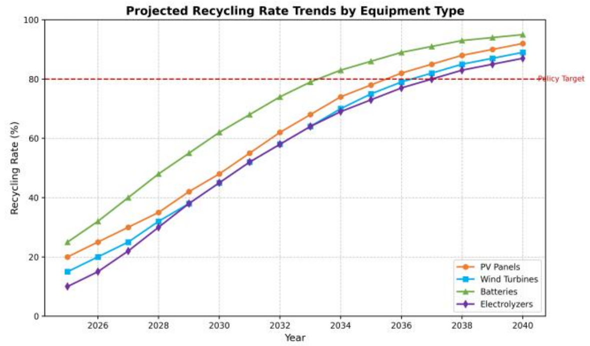

Fig. 9. Sensitivity Analysis of Key Model Parameters

TABLE IV. SENSITIVITY ANALYSIS RESULTS

Parameter	Variation (%)	Total Cost (×10⁹ ¥)	Resource Efficiency (%)	Employment (×10³)
Carbon Tax	-30	68.5	52.0	26.5
Carbon Tax	0	55.3	68.0	27.6
Carbon Tax	+30	48.2	78.0	29.2
Technology Cost	-30	62.1	62.0	26.0
Technology Cost	0	55.3	68.0	27.6
Technology Cost	+30	48.5	75.0	30.5
Demand Growth	-30	48.2	65.0	25.0
Demand Growth	0	55.3	68.0	27.6
Demand Growth	+30	72.8	70.0	32.0

The results indicate that the model is highly sensitive to variations in the carbon tax level. As the carbon tax increases, system investments rapidly shift toward zero-carbon hydrogen and renewable energy technologies, while the economic attractiveness of the closed-loop recycling network is also strengthened.

Moreover, the pace of technological progress — particularly reductions in energy storage costs and improvements in recycling technology efficiency—emerges as a critical driver shaping the system ’ s long-term evolution. The analysis further suggests that if energy storage costs decline faster than anticipated in the future, renewable energy consumption will be significantly boosted, leading to a substantial reduction in the overall system cost.

F. Employment Impact and Regional Balance Analysis

Figure 10 shows the results of the employment impact analysis under different scenarios.

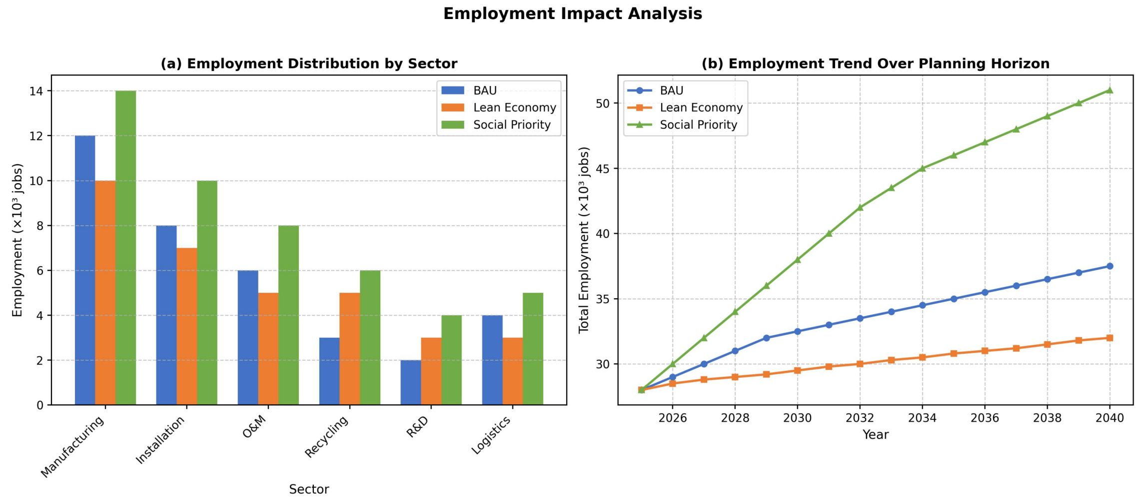

Fig. 10. Employment Impact Assessment Across Scenarios

Figure 11 shows the analysis results of regional balanced development, including the Lorenz curve and a comparison of investment distribution.

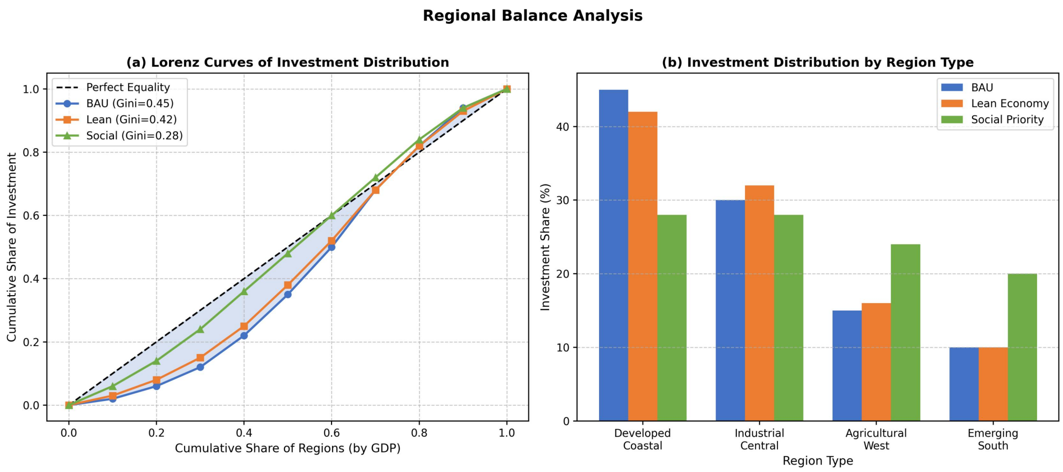

Fig. 11. Regional Development Balance Analysis

G. Model Validation

To validate the effectiveness of the model, we compared the model's prediction results with publicly available historical statistics, as shown in Figure 12.

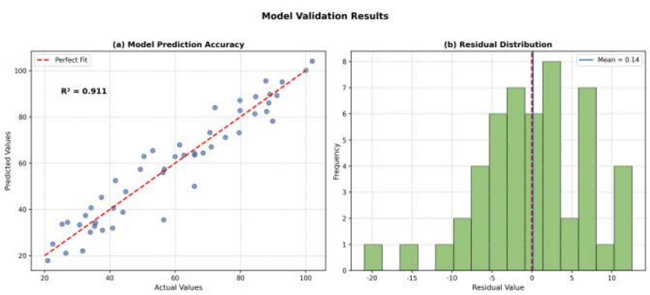

Fig. 12. Model Validation Results

The comparison in Figure 12 indicates a close alignment between the model's outputs and the historical benchmarks, and standard goodness-of-fit diagnostics (e.g., R^2 and residual checks) support the model's adequacy for planning-level decision analysis.

VI. Discussion

This chapter provides a deeper interpretation of the preceding results and explores their theoretical contributions, practical implications, and research limitations.

A. Interpretation of Results and Managerial Implications

The findings clearly highlight the inherent tension between "efficiency" and "equity" in the transition of energy systems. The success of the Lean Economy scenario demonstrates that extending lean thinking from the micro level of firm operations to the macro level of supply chain strategy can effectively deliver a "win–win" outcome in terms of both economic and environmental performance. This success stems from value stream reconfiguration through system-level optimization, which reduces multiple forms of waste related to inventory, transportation, and energy conversion.

At the same time, the observed "job reduction" in the Lean Economy scenario confirms the phenomenon of "creative destruction" driven by technological progress and efficiency gains. This finding serves as an important warning for managers and policymakers: while promoting lean and automated transformation, it is essential to implement forward-looking workforce transition strategies—such as skills retraining and the cultivation of new service-oriented business models—to mitigate potential social impacts.

In contrast, the Social Priority scenario quantifies the economic cost of achieving a "just transition." The results show that social objectives are not achieved at zero cost but require a trade-off with economic efficiency. For policymakers, this implies that regional development and subsidy policies must be carefully designed with explicit cost–benefit evaluations in order to strike an appropriate balance between maximizing social welfare and maintaining acceptable economic costs.

B. Theoretical Contributions

The theoretical contributions of this study are reflected in three main aspects. First, it achieves cross-disciplinary integration by bringing together lean economy theory, closed-loop supply chain management, integrated energy systems, and social sustainability within a unified analytical framework. This integration broadens the application scope of each theory and offers a new interdisciplinary paradigm for analyzing complex socio-technical systems.

Second, the study advances the macro-level quantification of lean principles. By incorporating parameters such as inventory penalty factors and value stream efficiency into a multi-objective optimization model, it provides a practical and operational approach for applying lean thinking at the strategic level, addressing a gap in the literature that has largely focused on qualitative discussions or micro-level case studies.

Third, the study contributes to the modeling of social sustainability by constructing a composite social adaptability objective that captures both employment effects and regional balance, quantified using measures such as the Gini coefficient. This approach offers new insights into how the social dimension can be more comprehensively integrated into supply chain optimization models.

C. Practical Implications

The results offer clear guidance for both governments and enterprises.

For governments, a coherent top-level design is needed to encourage and guide firms toward building cross-regional, multi-energy integrated closed-loop energy supply chains. Fiscal and taxation policies should play a more directive role—for example, through differentiated carbon or environmental taxes and targeted subsidies for firms adopting advanced recycling and remanufacturing technologies—thereby internalizing environmental and social externalities. Moreover, the concept of a "just transition" must be translated into practice by establishing transition funds, strengthening regional cooperation mechanisms, and investing in vocational education, ensuring that energy transition policies do not disproportionately harm specific groups.

For enterprises, energy companies should move beyond traditional decision-making frameworks and adopt a full life-cycle and supply-chain-system perspective. Investment decisions should account not only for upfront construction costs but also for long-term operational efficiency, the value of resource recovery, and associated social and environmental risks. In addition, firms should actively embrace digital and intelligent technologies, leveraging big data and the Internet of Things to enhance supply chain transparency and coordination, thereby supporting the effective implementation of lean management.

D. Research Limitations

Despite its contributions, this study has several limitations. First, certain model parameters—such as future technology costs and demand growth—are subject to uncertainty. Although scenario and sensitivity analyses partially address this issue, future research could enhance robustness through transparent interval assumptions and broader sensitivity ranges that remain easy to replicate. Second, the model adopts a system-planning perspective and does not explicitly capture strategic interactions among heterogeneous stakeholders; future work could incorporate simple, data-driven behavioral rules or alternative scenarios without relying on complex and hard-to-reproduce agent-based simulations. Finally, challenges remain in data availability and indicator quantification. Future studies should prioritize fully traceable public datasets and clearly documented parameter elicitation procedures to further improve replicability.

VII. Conclusion

This study, centered on the theme of "Designing Closed-Loop Energy Supply Chains under a Lean Economy," develops a multi-objective mixed-integer linear programming model to achieve the coordinated optimization of economic cost, resource efficiency, and social adaptability. Based on a case study of Shandong Province, China, several key conclusions can be drawn.

First, the strategic design of energy supply chains involves complex and non-linear trade-offs among economic, resource, and social objectives. There is no universal "optimal solution," and decision-makers must select appropriate solutions in line with their strategic priorities.

Second, incorporating lean economy principles into the design of macro-level supply chain networks is both feasible and effective, yielding substantial economic and resource-related benefits. This approach represents a critical pathway for improving the overall quality and efficiency of energy systems. The results indicate that lean strategies can reduce total supply chain costs by approximately 15% while increasing resource recycling rates by more than 20 percentage points.

Third, the social impacts of the energy transition cannot be overlooked. Social adaptability indicators—such as employment creation and regional equity—need to be explicitly embedded in decision-making models to quantify the costs and benefits of a "just transition" and to prevent potential social conflicts arising from an overly "efficiency-first" perspective.

Building on these findings, this study offers a new analytical framework and decision-support tool for exploring sustainable energy transition pathways. Future research can further extend this work in both depth and scope. For instance, more advanced methods for handling uncertainty, such as stochastic programming and robust optimization, could be introduced to address dynamic market and technological changes. The model could also be scaled from the regional level to national or even global contexts to examine cross-border energy trade and supply chain security. In addition, the assessment of social impacts could be expanded to include factors such as public acceptance and health effects, thereby making the decision-support system more comprehensive and human-centered.

REFERENCES

[1] Bashmakov, I. A., Nilsson, L. J., Acquaye, A., Bataille, C., Cullen, J. M., Fischedick, M., … Tanaka, K. (2022). Climate change 2022: Mitigation of climate change. In Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Chapter 11). https://doi.org/10.1017/9781009157926.013

[2] Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? Journal of Cleaner Production, 143, 757 – 768. https://doi.org/10.1016/j.jclepro.2016.12.048

[3] Womack, J. P., & Jones, D. T. (1997). Lean thinking—banish waste and create wealth in your corporation. Journal of the Operational Research Society, 48(11), 1148. https://doi.org/10.1057/palgrave.jors.2600499

[4] Patil, A., Arora, R., Arora, R., & Sridhara, S. N. (2025). Comprehensive review on hybrid solar photovoltaic-wind-biomass smart sustainable renewable energy system. International Journal of Power and Energy Conversion. https://doi.org/10.1504/IJPEC.2025.149308

[5] Durmaz, Y. G., & Bilgen, B. (2020). Multi-objective optimization of sustainable biomass supply chain network design. Applied Energy, 272, 115259. https://doi.org/10.1016/j.apenergy.2020.115259

[6] Chaudhari, U. S., Lin, Y., Thompson, V. S., Handler, R. M., Pearce, J. M., Caneba, G., … Shonnard, D. R. (2021). Systems analysis approach to polyethylene terephthalate and olefin plastics supply chains in the circular economy: A review of data sets and models. ACS Sustainable Chemistry & Engineering, 9(22), 7403 – 7421. https://doi.org/10.1021/acssuschemeng.0c08622

[7] Carley, S., & Konisky, D. M. (2020). The justice and equity implications of the clean energy transition. Nature Energy, 5(8), 569–577. https://doi.org/10.1038/s41560-020-0641-6

[8] Guide Jr., V. D. R., & Van Wassenhove, L. N. (2009). OR forum—The evolution of closed-loop supply chain research. Operations Research, 57(1), 10–18. https://doi.org/10.1287/opre.1080.0628

[9] Savaskan, R. C., Bhattacharya, S., & Van Wassenhove, L. N. (2004). Closed-loop supply chain models with product remanufacturing. Management Science, 50(2), 239 – 252. https://doi.org/10.1287/mnsc.1030.0186

[10] Abbey, J. D., Meloy, M. G., Blackburn, J., & Guide Jr., V. D. R. (2015). Consumer markets for remanufactured and refurbished products. California Management Review, 57(4), 26 – 42. https://doi.org/10.1525/cmr.2015.57.4.26

[11] Shah, R., & Ward, P. T. (2007). Defining and developing measures of lean production. Journal of Operations Management, 25(4), 785–805. https://doi.org/10.1016/j.jom.2007.01.019

[12] Genc, T. S., & De Giovanni, P. (2020). Closed-loop supply chain games with innovation-led lean programs and sustainability. International Journal of Production Economics, 219, 440 – 456. https://doi.org/10.1016/j.ijpe.2018.05.026

[13] Milano, F., Cañizares, C. A., & Invernizzi, M. (2003). Multiobjective optimization for pricing system security in electricity markets. IEEE Transactions on Power Systems, 18(2), 596 – 604. https://doi.org/10.1109/TPWRS.2003.810897

[14] Strachan, N., Balta-Ozkan, N., Joffe, D., McGeevor, K., & Hughes, N. (2009). Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system. International Journal of Hydrogen Energy, 34(2), 642–657. https://doi.org/10.1016/j.ijhydene.2008.10.083

[15] Heffron, R. J. (2022). What is the "just transition"? In Achieving a just transition to a low-carbon economy (pp. 9 – 19). Springer International Publishing. https://doi.org/10.1007/978-3-030-89460-3_2

[16] Jenkins, K., McCauley, D., Heffron, R., Stephan, H., & Rehner, R. (2016). Energy justice: A conceptual review. Energy Research & Social Science, 11, 174 – 182. https://doi.org/10.1016/j.erss.2015.10.004

[17] Zafar, I., Stojceska, V., & Tassou, S. (2024). Social sustainability assessments of industrial level solar energy: A systematic review. Renewable and Sustainable Energy Reviews, 189, 113962. https://doi.org/10.1016/j.rser.2023.113962

[18] Mavrotas, G. (2009). Effective implementation of the ε -constraint method in multi-objective mathematical programming problems. Applied Mathematics and Computation, 213(2), 455 – 465. https://doi.org/10.1016/j.amc.2009.03.037

[19] Lin, B., & Zhu, Y. (2025). Supply chain configuration and total factor productivity of renewable energy. Renewable and Sustainable Energy Reviews, 209, 115140. https://doi.org/10.1016/j.rser.2024.115140

[20] Wen, C., Xing, Y., Wang, T., Liao, S., & Gao, K. (2025). How do green supply chain management and renewable energy consumption influence carbon emissions in China and India? A comparative analysis. Energy Economics, 143, 108186. https://doi.org/10.1016/j.eneco.2025.108186

[21] Huang, J., Xie, D., Qiu, Y., Wang, J., & Song, J. (2024). Green supply chain management: A renewable energy planning and dynamic inventory operations for perishable products. International Journal of Production Research, 62(24), 8924 – 8951. https://doi.org/10.1080/00207543.2023.2220047

[22] Gatto, A., Drago, C., Panarello, D., & Aldieri, L. (2023). Energy transition in China: Assessing progress in sustainable development and resilience directions. International Economics, 176, 100450. https://doi.org/10.1016/j.inteco.2023.08.001

[23] Sun, Z., Zhang, F., Wang, Y., & Shao, Z. (2023). Literature review and analysis of the social impact of a just energy transition. Frontiers in Sustainable Food Systems, 7, 1119877. https://doi.org/10.3389/fsufs.2023.1119877

[24] Liu, P., Zhao, R., & Han, X. (2023). Assessing the influence of energy transition on economic-social growth: The case of China. Environmental Science and Pollution Research, 1 – 25. https://doi.org/10.1007/s11356-023-29009-3

[25] Li, Z., Zhang, W., Zhang, R., & Sun, H. (2020). Development of renewable energy multi-energy complementary hydrogen energy system (a case study in China): A review. Energy Exploration & Exploitation, 38(6), 2099 – 2127. https://doi.org/10.1177/0144598720953512

[26] Zhai, J., Wu, X., Zhu, S., Yang, B., & Liu, H. (2020). Optimization of integrated energy system considering photovoltaic uncertainty and multi-energy network. IEEE Access, 8, 141558 – 141568. https://doi.org/10.1109/ACCESS.2020.3013396

[27] Ma, Y., Liu, Y., Zhang, Q., Li, Y., & Huang, G. (2025). Full-chain optimization of China's net-zero emissions energy system toward 2060. Resources, Conservation and Recycling, 222, 108485. https://doi.org/10.1016/j.resconrec.2025.108485

[28] Cui, C., Lonergan, K. E., & Sansavini, G. (2025). Policy-driven transformation of global solar PV supply chains and resulting impacts. Nature Communications, 16(1), 6742. https://doi.org/10.1038/s41467-025-61979-5

[29] Dong, B., Zhang, Z., & Zhou, C. (2025). Towards a just Chinese energy transition: Socioeconomic considerations in China's carbon neutrality policies. Energy Research & Social Science, 119, 103855. https://doi.org/10.1016/j.erss.2024.103855

[30] Qiu, S., Liu, S., Lu, G., Zhang, K., Teng, Y., & Chen, Z. (2025). Energy optimization model of multi-energy system considering distributed photovoltaic coordinated carbon reduction. Scientific Reports, 15(1), 21016. https://doi.org/10.1038/s41598-025-06870-5

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AVAILABILITY OF DATA

Not applicable.

AUTHOR CONTRIBUTIONS

Tiankeng He (T.H.) and Yuanting Chen (Y.C.) contributed to the study design, performed the experiments, and collected and analyzed the data. Tiankeng He (T.H.) drafted the initial manuscript. Dandan Tang (D.T.) provided overall supervision and guidance, reviewed the data interpretation, and critically revised the manuscript. All authors discussed the results, contributed to manuscript revision, and approved the final version for publication.

COMPETING INTERESTS

The authors declare no competing interests.