

Article

Modeling Urban–Rural Energy Mutual Assistance Through Photovoltaic–Carbon Sink Synergy: A System Dynamics Approach

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Abstract

China's dual carbon goals and rural revitalization strategy necessitate innovative models that integrate energy transition with ecological conservation. However, a critical disconnect persists between photovoltaic (PV) promotion and forest carbon sink projects, limiting their collective potential for coordinated urban–rural emission reduction and common prosperity. To bridge this gap, this study pioneers an integrated “cooperation-mutual assistance” framework that synergizes PV and carbon sinks. A system dynamics model encompassing economic, energy, and environmental subsystems is developed to simulate the long-term evolution (2025–2050) of this synergy under multiple policy scenarios. The simulation results demonstrate that this integrated model can achieve substantial co-benefits: It enables a cumulative carbon emission reduction of 17.5 Gt (gigatons of CO₂ equivalent) from 2025 to 2050, boosts regional GDP by 4.8% by 2050 compared to the baseline scenario, and narrows the urban–rural income gap by prioritizing rural resident income growth. The main contribution of this study is the novel integration of PV and carbon sinks into a unified analytical framework, quantitatively verifying its win–win potential. These findings provide a critical scientific basis for crafting integrated policies that combine carbon markets, green finance, and smart grid planning.

Keywords: system dynamics modeling; carbon trading; rural revitalization; policy simulation; integrated development of urban and rural areas

1. Introduction

1.1. Research Background

Global climate change is becoming more severe. China has proposed dual carbon goals and faces challenges in reducing emissions while also managing significant economic and social changes. The international energy situation is complex and unstable. Improving energy security through renewable energy has become crucial for national development.

The urban–rural development gap in China is still significant. Cities are the primary areas for energy consumption and carbon emissions, but the space for renewable energy development is limited. Although large rural areas have ample resources like rooftops and forest land for developing photovoltaic power and carbon sinks, they often lack funding and technology. Their substantial ecological value has not been effectively turned into economic benefits. This mismatch between available resources and demand has hindered overall emission reduction and coordinated development.



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Given this context, creating mechanisms to realize the value of ecological products and to transform the “green mountains and clear waters” of rural areas into “mountains of gold and silver” is essential for ending the urban–rural divide. Finding ways to combine rural ecological resources, like carbon sinks, with energy resources, like photovoltaic power, to create an energy system that supports both urban and rural areas is a pressing issue that needs further study.

1.2. Literature Review

(1) Research on the Benefit evaluation of photovoltaic power generation

Existing studies mainly focus on the technical economy (Yuhang et al., 2024) [1], energy storage configurations (Weijun and Keyi, 2024 [2]; Feng & Han, 2018 [3]), and policies driving (Hanfang L et al., 2020) [4] photovoltaic power generation benefit assessment. At the application level, photovoltaic poverty alleviation projects have been proven to effectively promote rural development (Shengqing et al., 2024 [5]; Yan et al., 2018 [6]; Jing et al., 2023 [7]). However, most of these studies regard photovoltaic systems as an independent energy system and fail to establish a collaborative relationship with ecological projects, such as carbon sinks, which limits their greater value in coordinated emission reduction in urban and rural areas.

(2) Research on carbon sink projects and development

Research on carbon sinks mainly focuses on aspects such as risk management (Yixiong et al., 2025) [8], value realization mechanisms (Tao et al., 2024 [9]; Tang et al. 2023 [10]), and sustainable development paths (Zhengguang et al., 2025 [11]). The development of the carbon financial market (Qing & Lifeng, 2024) [12] and green finance (Shujie S et al., 2023) [13] has provided new value realization channels for carbon sink projects. Song et al. (2025) [14] further quantified the economic value of farmland carbon sinks using a multi-scenario system dynamics model, enriching the methodology for carbon sink asset valuation. However, existing studies generally indicate that carbon sink projects face economic sustainability challenges (Yixiong et al., 2025a) [8], and their synergistic benefits in land use optimization (Xufeng et al., 2025) [15] also need to be further explored.

(3) Research on energy interaction between urban and rural areas

Research on the urban–rural relationship reveals the significant influence of urban–rural interactions on sustainable development (Yanhua et al., 2025 [16]; Tang et al., 2024 [17]) and carbon emissions (Yijia & Yingying, 2025) [18]. Studies have shown that urban–rural economic inequality is closely related to carbon intensity (Ming et al., 2025) [19]. The energy transition (Shuaizhi et al., 2023) [20] and the urbanization process (Mohan et al., 2025) [21] have significant impacts on the energy–carbon performance gap between urban and rural areas (Chong, 2023) [22]. Zhao & Li (2024) [23] highlighted the mediating role of employment structural transformation in narrowing the urban–rural income gap through digital finance, while Muga et al. (2023) [24] evaluated the efficiency of urban–rural integration in the Yangtze River Economic Belt, providing empirical support for regional coordination. Although research on urban–rural functional coupling (Lingyun et al., 2023) [25] provides a theoretical basis for understanding urban–rural relations, existing studies lack quantitative simulations of the flow of energy factors between urban and rural areas, making it difficult to support the formulation of precise energy mutual assistance policies.

(4) Application of system dynamics in the field of energy and environment

The system dynamics method demonstrates unique advantages in the modeling of energy–environment–economic systems. The research fields include the coordination of urban economy–energy–carbon systems (Lu et al., 2024) [26], carbon emission drivers

(Honghua et al., 2021) [27], construction waste management (Zhikun et al., 2018) [28], and the energy–water bond relationship (Hossein, 2024) [29], etc. Evaluations of agrivoltaic systems (Agostini et al., 2021) [30] and analyses of the low-carbon transformation path (Foxon, 2011 [31]; Karamouz et al., 2023 [32]; Linderhof et al., 2020 [33]) further demonstrated the effectiveness of this method in simulating the dynamic behavior of complex systems, providing an important methodological reference for this study.

(5) Review conclusion

To sum up, although existing research has achieved fruitful results in various fields, there are obvious disconnections and deficiencies. Firstly, photovoltaic and carbon sink research falls under the fields of energy and ecology, respectively, lacking an effective collaborative and interactive analysis framework. Secondly, research on the interaction of energy between urban and rural areas mostly remains at the stage of qualitative description and lacks the support of quantitative dynamic models. Therefore, the existing research still lacks a quantitative analysis framework that integrates ‘photovoltaic power generation’, ‘ecological carbon sink’, and ‘urban-rural energy mutual assistance’ through ‘system dynamics dynamic simulation’. This study aims to fill this gap and construct a comprehensive model integrating four elements to systematically simulate and evaluate the comprehensive benefits of the urban–rural energy mutual assistance model from the perspective of photovoltaic–carbon sink synergy.

1.3. Research Content and Technical Route

This research follows the logical main line of ‘theoretical analysis → model construction → simulation → countermeasure proposal’, and the specific technical route is shown in Figure 1. The following are the corresponding research contents.

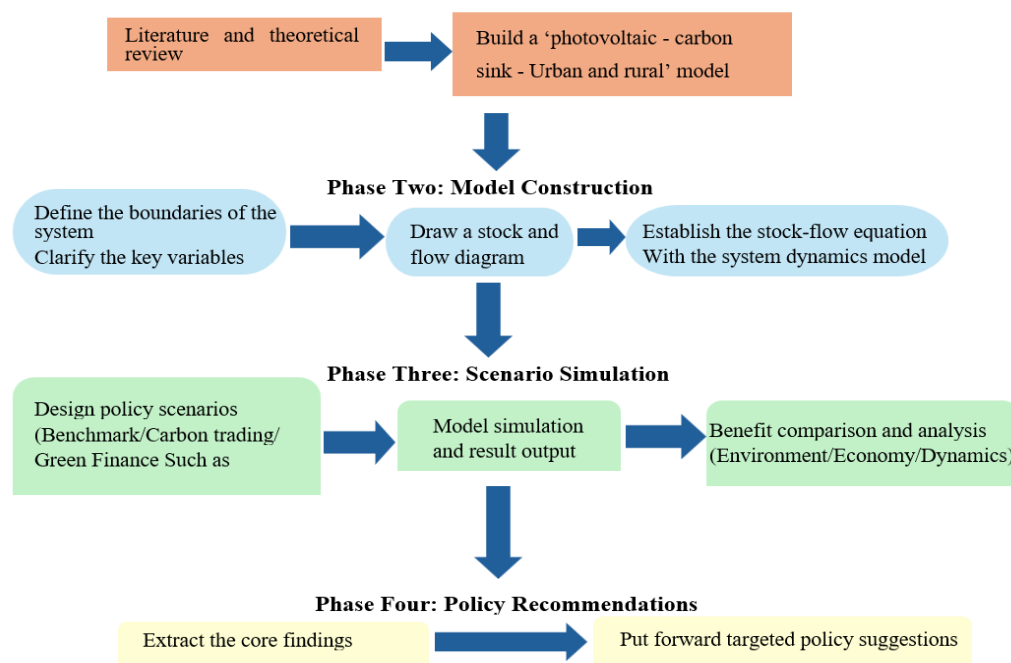


Figure 1. Technical route.

(1) Theoretical framework construction

Firstly, this study will systematically sort and integrate the energy synergy theory, ecological product value realization theory, and system dynamics theory. On this basis, clearly define the connotations of the two core concepts of “photovoltaic-carbon sink synergy” and “urban and rural energy mutual assistance” and analyze their internal

interaction mechanisms to lay a solid theoretical foundation for the subsequent construction of the model.

(2) System dynamics model development

Based on the above theoretical framework, this study will proceed to construct a system dynamics model. The specific tasks include the following: clearly defining the boundaries of the three subsystems of economy, energy, and environment; identify and determine key variables such as photovoltaic installed capacity, carbon sink volume, power flow between urban and rural areas, and carbon trading revenue; draw a stock and flow diagram of the system to reveal the feedback relationship among various elements; ultimately, a stock-flow equation is established to complete a comprehensive model capable of quantitatively simulating the dynamic behavior of the photovoltaic-carbon sink collaborative system.

(3) Scenario setting and simulation analysis

Based on the model's construction, this study will set up multiple policy scenarios for dynamic simulation, specifically including the benchmark scenario, carbon trading enhancement scenario, green finance support scenario, and smart grid optimization scenario. By simulating the future evolution paths of these scenarios and focusing on comparing and analyzing their impacts on key indicators such as carbon emissions, regional GDP, and the income of urban and rural residents, the optimal system development path can be identified and evaluated.

(4) Policy recommendation summary

Finally, this study will return to real management issues and systematically summarize their management implications based on the core findings and conclusions obtained from scenario simulation. Furthermore, from the two dimensions of effectively promoting the coordinated development of photovoltaic and carbon sinks and improving the energy mutual assistance mechanism between urban and rural areas, a series of targeted and operational policy suggestions have been distilled, with the aim of providing a scientific basis for relevant decisions.

2. Theoretical Framework

This study is grounded in an integrated theoretical framework that synthesizes concepts from complex systems theory, energy systems analysis, and ecological economics. This framework provides the foundational logic for conceptualizing the synergy between photovoltaics (PV) and carbon sinks within an urban-rural energy mutual assistance model. This section first establishes the core theories and then derives the specific conceptual lenses and definitions applied in this research.

2.1. Theoretical Foundations

The analysis is built upon three interconnected theoretical pillars, each providing a distinct yet complementary lens for understanding the proposed integrated system.

2.1.1. System Dynamics Theory: Modeling Complex Feedback Systems

Systems dynamics provides the fundamental methodology for this study. It is a perspective and a set of tools for understanding the behavior of complex systems over time, emphasizing internal feedback loops, time delays, stocks (accumulations), and flows (rates of change). This theory posits that the dynamic behavior of a system is determined by its structure, which refers to the interconnections between its components. The key concepts include reinforcing feedback (which amplifies change) and balancing feedback (which seeks equilibrium). For this research, system dynamics theory offers the essential framework for modeling the nonlinear interactions and time-dependent evolution within

the integrated PV–carbon sink–urban–rural system. It allows us to move beyond static analysis and simulate how capital flows, energy production, carbon sequestration, and policy interventions interact dynamically to produce emergent, long-term outcomes.

2.1.2. Energy Synergy Theory: Principles of Integrated System Optimization

Energy synergy theory focuses on the holistic integration of different energy systems and resources to achieve optimized efficiency, reliability, and value creation that exceeds the sum of individual parts. It transcends the analysis of single technologies, advocating for a system-of-systems approach where complementary attributes are leveraged. This theory provides the core logic for conceptualizing the “synergy” between PV and carbon sinks. It guides the hypothesis that their integration is not merely co-location but a strategic coupling where the limitations of one (e.g., PV’s land use) can be mitigated by the benefits of the other (e.g., carbon sink’s ecological function), and their revenues can be mutually reinforcing, creating a more robust and valuable whole.

2.1.3. Ecological Product Value Realization Theory: From Ecological to Economic Value

This theory addresses the critical gap between the intrinsic ecological value of natural capital and its recognition in socioeconomic systems. It provides a framework for understanding how ecosystem services, such as carbon sequestration, can be quantified, standardized, commodified, and integrated into market or quasi-market mechanisms. The theory encompasses mechanisms like payments for ecosystem services (PESs) and carbon trading markets. For this study, it supplies the crucial “value realization” link. It explains how the environmental service provided by rural carbon sinks can be transformed into a tangible economic asset (carbon credits), thereby creating a new revenue stream. This process is fundamental to enabling the “mutual assistance” between urban and rural areas, as it translates rural ecological advantages into urban market demand, facilitating a two-way exchange of value.

2.2. Conceptual Framework Derived from Theories

Drawing upon the theoretical foundations above, we define the core analytical constructs of this study.

2.2.1. Photovoltaic–Carbon Sink Synergy: An Emergent System Property

Guided by system dynamics theory and energy synergy theory, we define PV–carbon sink synergy not as a simple sum but as an emergent system property arising from the structured interaction and feedback between the two subsystems. It is a self-reinforcing cycle of value creation: PV electricity sales generate revenue that can fund carbon sink expansion and maintenance; the enhanced carbon sinks generate tradable credits, providing additional income that improves the overall financial viability and attracts further investment into both components. This closed-loop interaction, modeled as a reinforcing feedback loop, aims to produce total system output (economic, environmental, and social) greater than the sum of its independent parts. The “emergence” is quantified in this study as the performance gap in key indicators between the comprehensive policy scenario and the best single-policy scenario.

2.2.2. Urban–Rural Energy Mutual Assistance: A Dynamic Rebalancing Process

Informed by system dynamics theory (flows and feedback) and ecological product value realization theory (value exchange), urban–rural energy mutual assistance is defined as a dynamic, feedback-driven process of resource optimization and rebalancing based on comparative advantage. It involves continuous, bidirectional flows: cities provide capital, technology, and market access to rural areas; in return, rural areas provide green electricity

and certified ecological value (carbon sink quotas) to cities. This is not static “complementarity” but a market- and policy-mediated rebalancing act. The process is governed by system dynamics principles where feedback (e.g., rural income growth stimulating local demand) adjusts the flows over time, enhancing the overall efficiency and resilience of the regional socio-ecological energy system.

2.2.3. Distinction from Traditional Energy Cooperation Models

The “urban-rural energy mutual assistance” paradigm represents a significant evolution from traditional models, as summarized in Table 1, and this theoretical framework shifts the perspective from one-way, static, and project-centric “cooperation” to a two-way, dynamic, and systemic “mutual assistance,” aiming to build a resilient system for coordinated economic, energy, and environmental development.

Table 1. Traditional models.

Dimension	Traditional Energy Cooperation Model	Urban–Rural Energy Mutual Assistance Model
Interactive Logic	Unidirectional “supplement” or “poverty alleviation” (e.g., urban-to-rural grid extension).	Bidirectional value co-creation based on comparative advantage (urban capital/tech ↔ rural energy/ecosystem services).
System Attribute	Static complementarity, treating projects (e.g., PV, forestry) as independent entities.	Dynamic collaboration, viewing components as an interconnected system with feedback loops driving self-reinforcement.
Policy Core	Project-based support (e.g., direct subsidies for PV tariffs).	Mechanism construction (e.g., building carbon markets, green finance tools, smart grids) to activate intrinsic market drivers.

3. Methods

3.1. System Conceptual Framework

Based on the theoretical framework, the collaborative system is conceptualized as a dynamic complex system driven by three core flows: energy, capital, and value. The structure and interaction mechanisms of this system are as follows.

3.1.1. System Boundary and Component Analysis

The system’s operation is materialized through three interconnected flows: (1) Cities provide capital and technology to rural areas for constructing PV stations and maintaining carbon sink forests; in return, rural areas supply green electricity and certified carbon sink quotas to cities. (2) Capital flow serves as the economic vein. It follows the energy and carbon sink flows, comprising urban users’ electricity fees, corporate purchases of carbon quotas, government subsidies, and green credit, which are injected into rural areas and transformed into project revenue, resident income, and government taxes. (3) The result represents the comprehensive output, covering the following: (a) environmental value (carbon emission reduction and ecological improvement); (b) economic value (GDP growth, increased urban–rural income, and employment opportunities); (c) social value (fair energy services, narrowed urban–rural development gap, and common prosperity).

3.1.2. Analysis of Collaborative Mutual Assistance Mechanisms

The ‘1 + 1 > 2’ synergy is achieved through the following core mechanisms: (1) PV’s Promoting Mechanism for Carbon Sinks: (a) Financial Support: Stable revenue from PV electricity sales provides a sustainable funding source for the afforestation and management of carbon sink forests, alleviating their financing constraints; (b) Land Use Optimization: Models like ‘agrivoltaics’ allow for the construction of PV facilities without sacrificing

significant ecological or agricultural space, creating a broader spatial carrier for carbon sink projects. (2) Carbon Sinks' Value-Added Mechanism for PV: (a) Revenue Superposition: In a mature carbon market, the income from trading certified carbon sink quotas generates additional cash flow. This, superimposed on PV electricity sales revenue, significantly enhances the overall investment return rate and financial feasibility of the integrated project, attracting more social capital. (3) Urban–Rural Mutual Assistance as the Realization Path: This interaction outlines the comparative advantages: rural areas act as 'resource providers' and 'product producers', while urban areas serve as 'suppliers of capital and technology' and 'market consumers'. 'Using urban resources to solve rural difficulties, and using rural greenery to meet urban needs' enables both parties to form a sustainable development community with complementary functions and shared benefits.

3.2. Model Development

3.2.1. Photovoltaic Development Subsystem

Based on the aforementioned conceptual framework, the system dynamics model constructed in this study is shown in Figure 2. This subsystem simulates the dynamic accumulation process of photovoltaic power generation capacity. The core stock variable is the installed capacity of photovoltaic power. The increase in this stock is driven by the annual investment in photovoltaic power, and the investment amount is jointly determined by investment attractiveness, policy support, and available funds. Unit investment cost and operation and maintenance cost are the key negative factors affecting the economic viability of a project. The installed capacity determines annual power generation. Power generation, combined with the on-grid electricity price, generates electricity sales revenue, which in turn feeds back and affects the economic subsystem. The output of this subsystem is the supply of clean electricity, which serves as the basis for the emission reduction calculation in the environmental benefit subsystem.

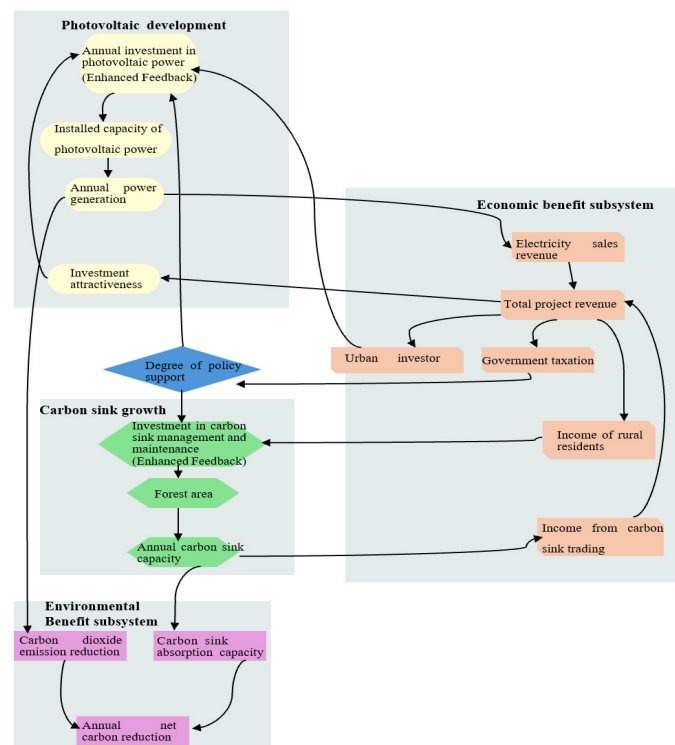


Figure 2. Dynamic flow diagram of the photovoltaic–carbon sink synergistic system. Note: The system integrates photovoltaic development, carbon sink growth, economic benefits, and environmental outcomes through multiple reinforcing and balancing feedback loops. Variables are grouped by subsystem to enhance visual clarity.

3.2.2. Carbon Sink Growth Subsystem

This subsystem depicts the cultivation and growth of the forest's carbon sink capacity. Its core stock variable is the forest area. The variation in this stock is influenced by afforestation and management activities, while the annual management investment of carbon sinks is the main driving force, and its level depends on the economic benefits of carbon sink projects. The carbon sink volume per unit area and the carbon sink price jointly determine the income from carbon sink trading. The core output of this subsystem is the annual carbon sink absorption volume, which directly contributes to environmental benefits and forms a closed-loop connection with the economic subsystem through carbon sink trading income.

3.2.3. Economic Benefit Subsystem

This subsystem is the core module that integrates the benefits of photovoltaic power and carbon sinks and quantifies their macroeconomic benefits. The quantitative correlation between photovoltaic power generation, carbon sink income, and regional GDP is established in the model through the following series conduction mechanism and feedback loop.

(1) Direct income convergence

Photovoltaic power generation revenue = Annual photovoltaic power generation $\times$ feed-in tariff

Carbon sink income = annual carbon sink volume $\times$ carbon sink price

The total project revenue = photovoltaic power generation revenue + carbon sink revenue

(2) Income Distribution and Contribution to Primary GDP

The total project revenue is allocated in the model according to the preset proportion as follows:

Government Taxation: The "net production tax" directly included in GDP.

Investor Returns: A part is used for reinvestment (forming fixed assets), and another part is used as corporate surplus.

Rural Residents' Income: Including land rent, maintenance wages, etc., directly increasing the disposable income of rural residents.

(3) Indirect Economic Impact and Feedback Loop

The growth of rural residents' income mentioned above will further stimulate the local service industry and related industries through the variables of "rural consumption" and "local investment", generating a multiplier effect and indirectly boosting GDP.

The expected returns of investors and the total revenue of the project will significantly affect the key variable "investment attractiveness" in the model, thereby determining the scale of new photovoltaic and carbon sink investments in the next period, forming an enhanced feedback loop that drives the continuous growth of the system. An increase in government tax revenue can be reflected in a higher "policy support intensity", thereby reducing project costs or enhancing income stability. Therefore, regional GDP in the model is a comprehensive reflection of all directly added values and indirectly induced values and dynamic feedback results mentioned above. Its quantitative relationship is not a simple linear superposition but is embedded in a dynamic cycle that encompasses investment, consumption, taxation, and reinvestment.

3.2.4. Environmental Benefit Subsystem

This subsystem assesses the environmental value of the collaborative mode. The calculation is based on two core variables: one is the carbon dioxide reduction converted

from photovoltaic power generation (achieved by replacing fossil energy power generation), and the other is the carbon sink absorption output by the carbon sink growth subsystem. The sum of the two is the annual net carbon reduction brought about by this model. This indicator is a direct reflection of the contribution of the measurement model to achieving the 'dual carbon' goals.

3.3. Parameter Setting

3.3.1. Main Equations

(1) Core stock-flow equation

Photovoltaic installed capacity = INTEG (annual newly added photovoltaic installed capacity – retired photovoltaic capacity, initial installed capacity)

Forest carbon sink area = INTEG (annual newly added afforestation area – annual degraded forest land area, initial forest area)

(2) Key auxiliary variable equation

The annual newly installed capacity of photovoltaic power = the annual investment in photovoltaic power / the unit investment cost

The annual investment in photovoltaic power = the initial investment base value × investment attractiveness × the multiplier of policy support

Investment attractiveness = (Electricity sales revenue + carbon sink trading revenue) / (Initial investment cost + annual operation and maintenance cost)

Electricity sales revenue = Annual photovoltaic power generation × feed-in tariff

Carbon sink trading income = Annual carbon sink volume × Carbon sink price

Annual net carbon reduction = photovoltaic reduction + carbon sink absorption

The total project revenue = photovoltaic power generation revenue + carbon sink revenue

Investment attractiveness = (Total project revenue) / (Investment cost + Operation and maintenance Cost)

The growth of rural residents' income = Total project income × income distribution ratio (rural)

Regional GDP contribution (direct + partial indirect) = government tax revenue + fixed asset formation (from investment) + induced value of rural residents' consumption

3.3.2. Parameter Setting

The parameters for the system dynamics model were derived from a combination of authoritative statistical sources, peer-reviewed literature, and expert judgment to ensure empirical grounding and relevance to the Chinese context. They are categorized below based on their primary source.

(1) Data Sources and parameter classification

Historical Statistical Parameters: Sourced from official yearbooks and guidelines (e.g., China Electric Power Statistical Yearbook 2023 [34], China Forestry Statistical Yearbook 2023 [35]) to reflect baseline conditions and trends.

Literature-Based Parameters: Obtained from recent, high-impact research to align with current technological and economic benchmarks (e.g., PV cost from IRENA reports, carbon sink factors from relevant studies).

Expert-Elicited Parameters: Determined via a structured Delphi method involving domain experts for parameters not directly available from public data (e.g., policy multiplier).

Sensitivity Parameters: Identified as key variables with high future uncertainty (e.g., carbon price, technological progress rate); baseline values and ranges are set for subsequent sensitivity analysis.

(2) Key parameter values and justifications

The core parameters for the baseline scenario are summarized in Table 2, with their justifications and sources.

Table 2. Key model parameters for the baseline scenario.

Parameter	Symbol	Value	Justification and Source
PV Unit Investment Cost (2023)	C_pv_inv	3.2 CNY/W	Reflects current industry scale and maturity. Source: IRENA (2024) [36].
PV O&M Cost Ratio	f_pv_om	1.8% (of initial investment)	Median value from operational studies of typical Chinese PV plants. Source: Yuhang et al. (2024) [1].
Carbon Sink Factor (Fir Forest)	CS_f	5.0 t/(ha·a) of CO ₂	Median carbon sequestration capacity for fir forests in Southern China. Source: Yixiong et al. (2025) [8].
Baseline Carbon Price	P_c	70 CNY/t CO ₂	Approximates the average transaction price of China's Certified Emission Reductions (CCER) in 2023.
Policy Support Multiplier	M_policy	1.2	Derived from a two-round Delphi expert survey (n = 8). Represents the estimated enhancement in project attractiveness due to integrated policy incentives.
Social Discount Rate	r	8%	Set in accordance with the Economic Evaluation Methods and Parameters for Construction Projects issued by China's National Development and Reform Commission.
PV Technical Progress Rate	g_tech_pv	3–3.3% in 2025, increasing to approximately 4% by 2030, and declining thereafter.declining there after	Based on industry learning curve projections from IRENA(2024) [36] and the literature, driving long-term cost reduction.
Model Simulation Start Year	T_start	2025	Start of the policy simulation period.
Model Simulation End Year	T_end	2050	Horizon for assessing long-term system behavior.

Note on Expert Elicitation: The policy support multiplier (M_policy) was determined through an anonymous, iterative Delphi process involving eight experts specializing in energy policy, forestry carbon sinks, green finance, and system dynamics. The final value represents the consensus estimate of the investment attractiveness boost for integrated PV–carbon sink projects under typical policy incentives. The detailed model parameters and historical verification data used in this study are provided in Appendix A.

3.3.3. History Test

The period from 2018 to 2023 was selected as the historical test period, with 2018 as the base year, and the simulated values of the model were compared with the actual statistical values. The comparison for the year 2023 is summarized in Table 3.

As shown in Table 3, the relative errors between the simulated values and the actual values of the main variables are all controlled within 5%, proving that the model can reproduce the historical behavior of the system quite well.

Table 3. Historical test results (2023).

Test Variable	Simulated Value	Actual Value	Relative Error
Installed capacity of photovoltaic power	5.8 GW	6.0 GW	−3.3%
Forest coverage rate	24.1%	24.02%	+0.3%
Annual power generation	690 TW h	710 TW h	−2.8%

Note: Simulated values are from this study's system dynamics model. Actual values for installed PV capacity and annual power generation are from the China Electric Power Statistical Yearbook 2023 [34]. The actual forest coverage rate is from the China Forestry Statistical Yearbook 2023 [35].

The selected validation period (2018–2023) aligns with the availability of consistent national data on PV deployment and forest coverage following China's policy acceleration in these domains. While a longer historical window would be desirable, data prior to 2018 are less standardized for integrated PV–carbon sink analysis. The model demonstrates good short-term behavioral validity, though we acknowledge that long-term socio-ecological cycles extend beyond this five-year window. In subsequent research, we aim to extend the calibration period as more integrated data become available.

3.3.4. Description of Model Verification Methods

To comprehensively evaluate the structural validity and behavioral reliability of the model, the following three types of validation tests were implemented in this study:

Historical Test: The period from 2018 to 2023 is selected as the test period, with 2018 as the base year. The simulated values of the model are compared with the actual statistical values. As shown in Table 1, the relative errors of the main variables are all controlled within 5%, indicating that the model can reproduce the historical behavior of the system quite well.

Extreme Condition Test: By setting extreme parameter values (such as policy support being 0, carbon price doubling, investment cost surging, etc.), it examines whether the model's behavior conforms to theoretical expectations. All test results are consistent with common sense or theoretical inferences, proving that the model has good structural robustness.

Dimensional Consistency Test: Conduct dimensional checks on all equations to ensure that the physical meanings of the mathematical expressions are consistent. All equations passed this test.

3.3.5. Extreme Condition Testing

Zero Policy Support: When the policy support level is set to 0, the growth rate of photovoltaic installed capacity is negative, which is in line with expectations.

The carbon sink price has doubled: The carbon sink price has risen from 70 CNY/t for CO₂ to 140 CNY/t for CO₂, and the annual growth rate of forest area has increased by 42%.

Investment costs have soared: Unit investment costs have increased by 50%, while new photovoltaic installations have dropped by 35%.

All extreme test results were in line with theoretical expectations, proving that the model has good structural robustness. Through the above tests, it can be considered that the dynamic model of this system is effective and reliable and can be used for subsequent policy scenario simulation and analysis.

3.4. Simulation Design, Validation, and Testing

This study uses the system dynamics method for simulation, aiming to simulate the long-term dynamic behavior of the “photovoltaic-carbon sink” cooperative system. The system dynamics model was developed using Vensim DSS (version 9.x) developed by

Ventana Systems, Inc. (Harvard, MA, USA), and the core is the difference equation system established based on the stock flow graph (Figure 2).

Simulation Algorithm and Execution: The model adopts the Euler integral method for period-by-period calculation, with the simulation step size set at 0.25 years, ensuring stable results while also taking into account computational efficiency. The simulation time span is from 2025 to 2050. Before each run, the model undergoes comprehensive dimensional consistency checks and extreme condition tests to ensure the rigor of its mathematical foundation. Policy scenario analysis is achieved through batch operation, where only specific policy parameters (such as carbon price and financing cost) are changed each time to isolate and compare the driving effects of different policies.

Endogenous Processing of Technological Evolution: The model regards technological progress as an endogenous and continuous process, which is reflected through the following mechanisms:

- (1) **Cost Learning Curve:** The unit investment cost of photovoltaic power is set as a function of the cumulative installed capacity, following the “learning curve” effect: That is, as the global and regional deployment scale expands, the cost continues to decline. This relationship has been verified through historical data and extrapolated to the future.
- (2) **Efficiency Improvement Path:** The model assumes that the efficiency of photovoltaic modules gradually increases with technological iterations, which is directly reflected in the interannual growth of power generation per unit area. Parameters are set based on the industry’s technical roadmap.
- (3) **Consideration of “Breakthrough Technologies”:** Although the model does not preset specific new technology nodes (such as the commercialization of perovskite cells), by setting the “rate of technological progress” as a key sensitive parameter and applying a wide range of fluctuations (such as $\pm 30\%$ to $\pm 50\%$) for scenario analysis, it substantially covers the accelerating impact that technological breakthroughs may bring. This enables us to assess the system’s performance under different technical prospects, ranging from incremental improvement to leapfrog development.

In conclusion, this simulation not only reproduces the basic feedback structure of the system but also incorporates the uncertainty of technological evolution into the analysis framework through the endogenous learning mechanism and external scenario design, enhancing the rationality and inspiration of long-term simulation.

The simulation was implemented in Vensim DSS (Version 11.3) using Euler integration with a time step of 0.25 years. Model validation followed a three-stage process:

- (1) **Historical Test (2018–2023):** Comparing simulated outputs with actual statistical data.
- (2) **Extreme Condition Test:** Testing model behavior under zero policy support, doubled carbon price, and surging investment costs.
- (3) **Dimensional Consistency Test:** Ensuring all equations are dimensionally sound.

Sensitivity analyses were conducted on key parameters (carbon price, discount rate, and technical progress rate) by varying them by $\pm 30\%$ to assess output robustness.

4. Scenario Design and Simulation Analysis

To scientifically assess the long-term impacts of different policy interventions under the ‘photovoltaic-carbon sink synergy’ model, this section designs multiple policy scenarios for simulation based on the verified system dynamics model. By comparing the dynamic responses of the system in various scenarios, the aim is to identify effective policy levers and provide a quantitative basis for decision-making.

4.1. Scenario Design

This study sets up one baseline scenario, three independent policy scenarios, and one comprehensive scenario, with a simulation period from 2025 to 2050.

4.1.1. Benchmark Scenario

This scenario assumes that the current policy framework continues, and no break-through incentives are introduced. The specific parameter settings include the following: maintaining the carbon sink price at the current medium to low level (~70 CNY/t of CO₂), keeping the financing cost of photovoltaic and carbon sink projects at the benchmark interest rate level, and gradually increasing the consumption capacity of rural power grids in accordance with the existing plan. This scenario serves as a 'control baseline' for evaluating the effectiveness of other policies, and it is used to identify the inertial path of system development and potential problems without strong intervention.

4.1.2. Policy Scenarios

To examine the precise effects of specific policies, the following three single-policy scenarios have been designed:

Scenario A: Deepening of the Carbon Market Scenario: This scenario simulates the driving effect of the deepening development of the national carbon market on the system. The core parameters are set as follows: The carbon sink price will rise to 150 CNY/t of CO₂ by 2030 and remain stable at this level. Meanwhile, the access conditions for forestry carbon sink projects to enter the national carbon market have been significantly relaxed, and the upper limit of the offset ratio has been raised.

Scenario B: Green Finance Support Scenario: This scenario aims to assess the promoting effect of financial instruments on the initial development of the project. The set parameters are as follows: The special low-interest loan interest rate for photovoltaic and forestry carbon sink projects will be reduced by 30% from the benchmark level. At the same time, a certain proportion of fiscal interest subsidies will be provided for the initial investment of the projects, effectively reducing the financing costs and financial pressure of the projects.

Scenario C: Interactive Scenario of a powerful power grid. This scenario focuses on the optimization of system operation through infrastructure improvement. The core setting is to increase investment in rural smart grids and ultra-high voltage transmission channels, raise the green electricity consumption rate in rural areas from the current 85% to over 95%, and significantly reduce transmission and distribution losses, thereby enhancing the actual returns and stability of photovoltaic power generation.

On this basis, to examine the synergy effect of the policy mix, Scenario D is established: the comprehensive policy scenario, where all policies in Scenarios A, B, and C are implemented simultaneously. This scenario aims to explore the optimal effect that can be achieved through the combined efforts of policies.

4.1.3. Rationale for Policy Scenario Combination

The designed policy scenarios (A–D) are structured to examine both isolated and synergistic effects. Scenario A (carbon market deepening) provides a long-term price signal essential for carbon sink valuation. Scenario B (green finance support) addresses initial financing barriers, crucial for early-stage PV deployment. Scenario C (smart grid optimization) ensures the physical integration and utilization of renewable electricity, transforming capacity into tangible benefits. Scenario D (comprehensive policy) integrates all three levers to explore whether their combined implementation yields multiplicative

rather than additive benefits. This structure allows us to identify not only the most effective single policy but also the synergistic potential of a coordinated policy mix.

4.2. Result Analysis

4.2.1. Economic Benefit Comparison

The simulation results show that each policy scenario has a significant impact on economic indicators. Figure 3 demonstrates that the comprehensive policy scenario (D) unequivocally outperforms all singular policy approaches, achieving a 4.8% higher GDP, a 5.2% increase in rural income, and a 4.5-percentage-point improvement in investment return rate by 2050. This dominance underscores a critical finding: The coordinated implementation of multiple policy instruments yields substantially greater benefits than any single policy acting alone. While the present model does not explicitly decompose the marginal contributions of each policy or test for strict super-additivity (i.e., $D > A + B + C$), the results clearly indicate that policy combination effects amplify system performance beyond the best individual intervention. This suggests a strong coordination advantage among carbon markets, green finance, and grid optimization rather than a simple linear accumulation of isolated policy effects. The green finance scenario (B) is particularly effective in stimulating investment returns in the short term, while the carbon market scenario (A) plays a more substantial role in boosting rural income, likely through direct carbon revenue channels. The superior performance of Scenario D confirms that addressing financial barriers, market incentives, and infrastructure simultaneously creates a virtuous cycle that amplifies overall economic benefits. Scenario C is not shown in Figure 4 because its impact on the urban–rural income ratio is marginal and largely overlaps with the benchmark trajectory.

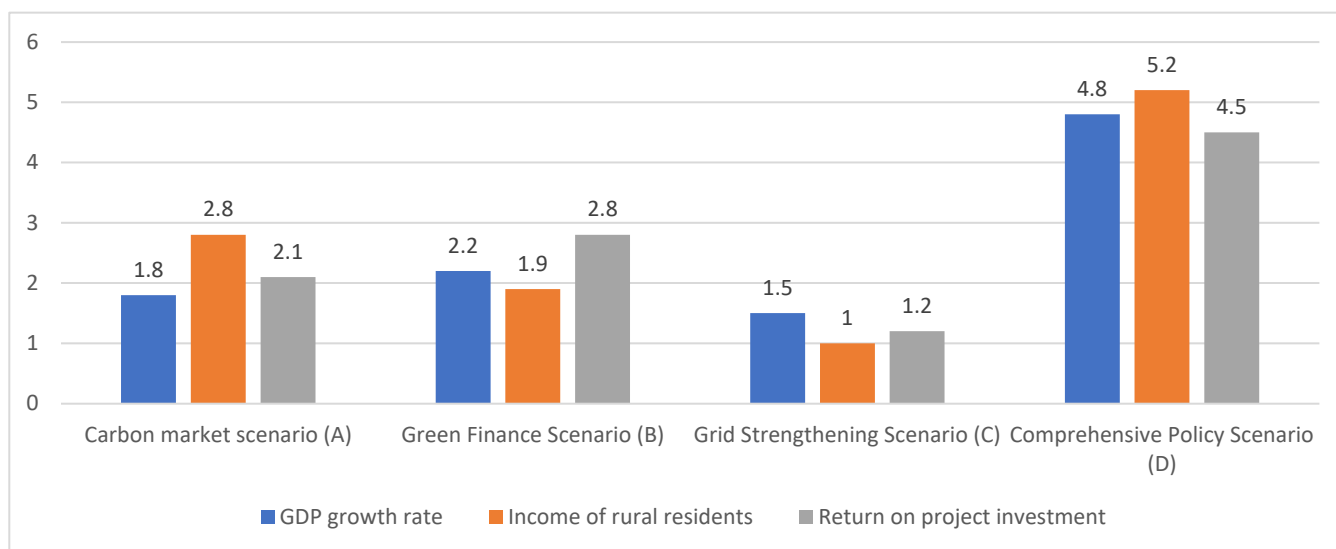


Figure 3. The change rate of key economic indicators in 2050 under each scenario compared to the benchmark scenario. Note: This chart compares the impacts of four policy scenarios (A: deepening of the carbon market; B: support from green finance; C: optimization of the smart grid; D: comprehensive policies) on regional GDP, rural residents' income, and project return on investment in 2050. The comprehensive policy scenario (D) performs the best in all economic indicators, revealing the multiplier effect of policy synergy. The data is derived from the simulation output of the system dynamics model in this study.

The model's impact on social equity is captured by the evolution of the urban–rural income ratio (Figure 4). While all policy scenarios contribute to narrowing the income gap compared to BAU, the trajectory and pace of convergence differ markedly. The

comprehensive scenario (D) demonstrates the most rapid and sustained decline, reducing the ratio from 2.35 to 2.08 by 2050. Notably, the carbon market scenario (A) initiates a steeper early decline than the green finance scenario (B), suggesting that creating a new revenue stream (carbon credits) for rural areas has a more immediate impact on income distribution than solely lowering investment costs. The convergence of these trends in Scenario D highlights that combining asset-building (via carbon markets) with opportunity-building (via green finance) is the most effective pathway to common prosperity.

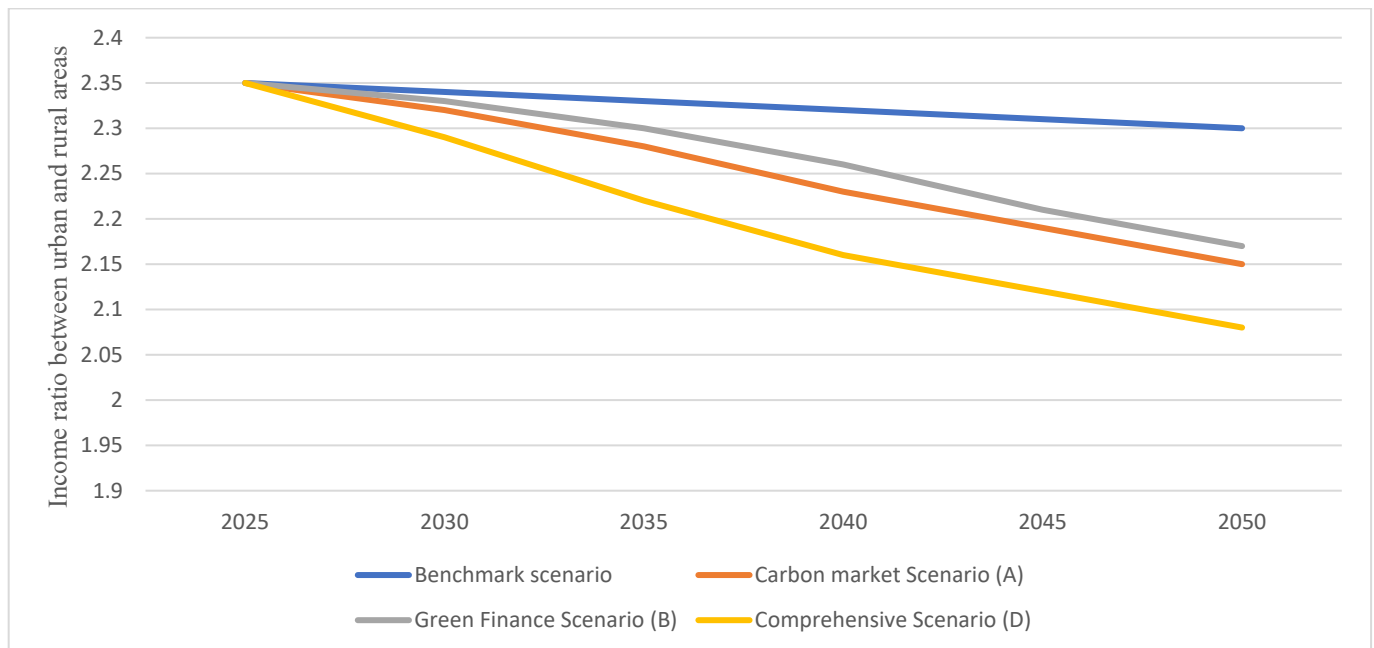


Figure 4. The changing trends of the urban–rural income ratio in various scenarios. Note: Dynamic changes in the urban–rural income ratio (per capita income of urban residents/per capita income of rural residents). Under the baseline scenario (BAU), this ratio remains high, while all policy scenarios can prompt its convergence. Comprehensive scenario (D) shows the fastest and most significant downward trend, indicating the outstanding potential of the collaborative model in promoting urban–rural equity.

4.2.2. Comparative Analysis of Environmental Benefits

Figure 5 delineates a clear functional divergence between policies. The carbon market scenario (A) drives the vast majority of carbon sink accumulation, increasing it by 43.8% over BAU. In contrast, the green finance scenario (B) is the primary driver of cumulative emission reductions, contributing an additional 35 billion tons. This stark contrast reveals the specialized roles of each instrument: Green finance accelerates the deployment of clean energy substitution (PV), while the carbon market incentivizes the enhancement of natural carbon sinks. The comprehensive scenario (D), by harnessing both pathways, achieves the highest total environmental benefit. These results indicate that a coordinated dual strategy addressing both emission reduction and carbon sequestration achieves more comprehensive mitigation outcomes than any single-policy pathway. Although the model does not explicitly quantify super-additive effects, the comprehensive scenario consistently delivers the highest cumulative environmental benefits, highlighting the practical advantage of integrated policy design.

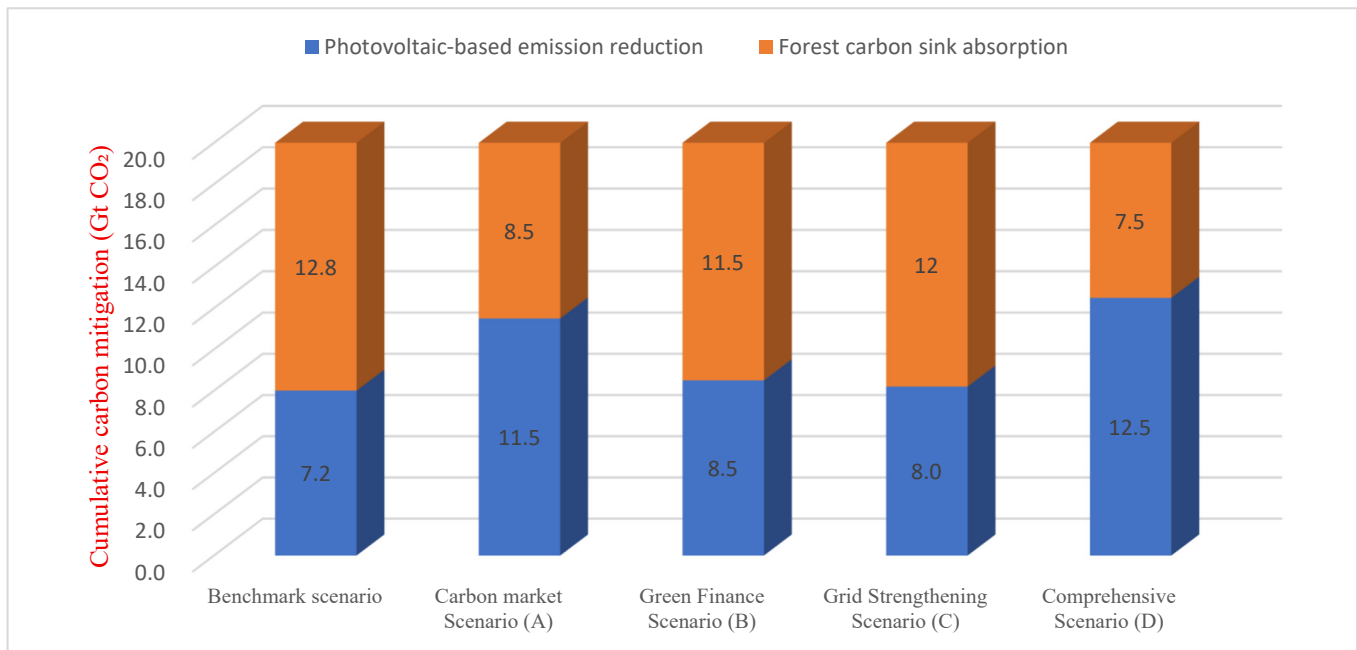


Figure 5. Note: Carbon mitigation is measured in gigatons of CO₂ (Gt CO₂), representing the total mass of emissions reduced or absorbed during the simulation period. Blue indicates photovoltaic-based emission reduction, while orange represents forest carbon sink absorption.

4.2.3. Dynamic Trend Analysis

The temporal dynamics of photovoltaic installed capacity (Figure 6) reveal a critical sequencing effect. The green finance scenario (B) triggers the most rapid initial expansion, confirming its role as a powerful catalyst for overcoming initial investment hurdles. However, its growth trajectory plateaus earlier than the comprehensive scenario (D). Scenario D, while slightly slower in the very first years, exhibits stronger and more resilient growth in the medium to long term. This indicates that financial subsidies alone cannot sustain growth; they require the long-term price signal of a carbon market to maintain investment attractiveness and profitability, ensuring that the system does not lose momentum after the initial push.

The evolution of carbon sink revenue (Figure 7) provides the clearest evidence of the system's transition to a mature, synergistic phase. Under Scenario D, carbon income does not just grow; it accelerates post-2030, eventually surpassing CNY 200 billion by 2050. This exponential growth pattern signifies a fundamental shift: The model evolves from a "PV-led" system to a balanced "PV-Carbon Sink Co-Driver" system. This emerging revenue stream diversifies the project's income base, enhances its resilience to market fluctuations in electricity prices, and fundamentally alters its long-term economic viability. The carbon market (Scenario A) alone also shows strong growth, but Scenario D's even higher trajectory suggests that lower financing costs (from green finance) enable faster and larger-scale development of carbon sink projects, which are then monetized at a higher price.

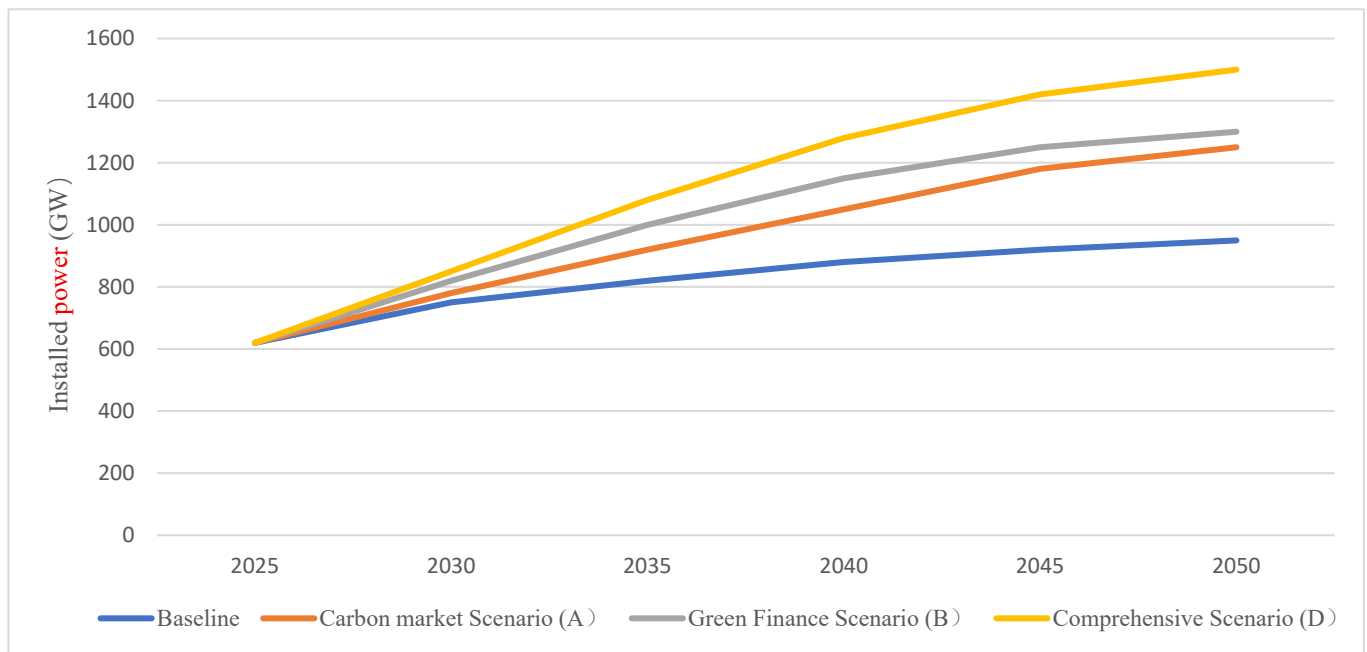


Figure 6. The growth trend of photovoltaic installed capacity under various scenarios. Note: The growth path of photovoltaic installed capacity during the simulation period. Green finance scenario (B) demonstrates the strongest growth initiation effect in the initial stage, but its medium- and long-term growth momentum relies on continuous policy input. In the comprehensive scenario (D), under the combined effect of long-term price signals in the carbon market and grid security, a more sustainable and stable growth trajectory is presented, demonstrating the stable support role of the “policy mix” for energy transition.

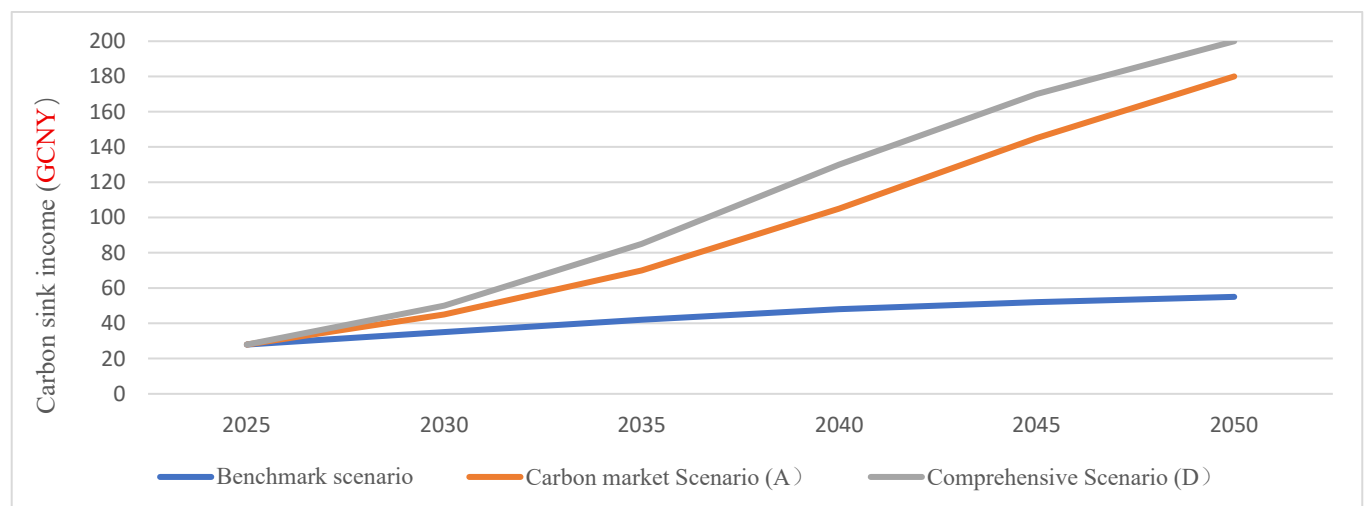


Figure 7. The growth trend of carbon sink income under various scenarios. Note: Carbon sink income refers to the cash flow obtained through trading verified carbon sink quotas. Under the carbon market scenario (A) and the combined scenario (D), this income shows an exponential growth feature, especially with a significant increase after 2030. This reflects that as carbon prices rise and the scale of carbon sink projects expands, the mechanism for realizing ecological value has gradually become an important economic pillar for the projects, enhancing the overall financial resilience.

5. Discussion

This section aims to elucidate the core implications of the simulation results and interpret them within a broader policy and academic context. Through a systematic analysis of the policy coordination mechanism, model robustness, theoretical contributions,

and research limitations, this discussion offers an in-depth interpretation of the findings and provides guidance for future research and policy development.

5.1. Policy Combination Amplification and Coordinated Implementation Pathway

The superior performance of the comprehensive policy scenario (Scenario D) demonstrates a policy-combination amplification effect among the carbon market, green finance, and power grid optimization. This synergy arises from the following mechanisms: Green finance reduces financing costs, thereby accelerating the short-term expansion of photovoltaic production capacity (as illustrated in Figure 6). The carbon market establishes long-term, stable expectations for carbon sink revenues, enhancing the economic sustainability of projects and driving exponential growth in such revenues (as shown in Figure 7). Meanwhile, smart grid development provides essential physical infrastructure that ensures efficient integration and utilization of renewable electricity, transforming installed capacity into tangible economic benefits. This integrated framework suggests that an effective policy mix should follow a dynamic implementation pathway: During the initial phase, financial instruments should be prioritized to overcome investment barriers; during the expansion phase, infrastructure support—particularly in power grids—should be strengthened concurrently; ultimately, a mature carbon market must serve as the cornerstone for long-term value anchoring and systemic self-sustaining momentum.

5.2. Sensitivity of Key Parameters and Policy Implications

Sensitivity analysis reveals that model outputs are most responsive to variations in “carbon price” and “discount rate.” A $\pm 30\%$ deviation from the benchmark carbon price (150 CNY/t) results in a projected change in cumulative carbon sink revenue by 2050 ranging from -25% to $+28\%$, underscoring the critical role of robust carbon pricing in guiding ecological investments. Similarly, a ± 2 percentage point fluctuation in the discount rate—reflecting changes in financing costs—leads to approximately $\pm 15\%$ variations in the predicted photovoltaic installed capacity by 2050, confirming the pivotal importance of fiscal and financial support during the early stages of project development. While parameter variability influences the quantitative magnitude of outcomes, the qualitative conclusion—that the integrated policy approach yields optimal results—remains consistently robust across all scenarios, thereby reinforcing the reliability of the study’s central findings.

5.3. Theoretical Engagement with Existing Literature

This study contributes to and extends existing scholarly discourse in several ways. First, it reaffirms the positive impacts of photovoltaic poverty alleviation and carbon sink initiatives on rural development. However, by constructing an integrative policy model, it demonstrates that the combined benefits significantly exceed the sum of individual project effects, thus addressing a key limitation in the current literature that often examines these domains in isolation. Second, through system dynamics modeling, this research translates abstract theoretical concepts—such as urban–rural energy interaction and functional coupling—into quantifiable, time-dependent trajectories, advancing theoretical discussions toward actionable, predictive policy analysis. Finally, the findings align closely with the established view that sustainable low-carbon transitions require coordinated policy interventions. By contextualizing this framework within China’s unique socio-economic setting, this study enhances its explanatory power and practical applicability.

5.4. Research Limitations and Future Directions

Several limitations of this study also present opportunities for future research. First, the model treats carbon sinks as homogeneous entities, without accounting for variations in sequestration capacity across tree species, forest age classes, or geographical regions—

potentially limiting the precision of micro-level policy recommendations. Second, the model does not fully incorporate the physical risks posed by extreme climate events (e.g., droughts, wildfires) on both forest carbon sinks and photovoltaic generation efficiency. Third, the assumption of perfect policy implementation overlooks real-world institutional challenges, including policy friction and inter-agency coordination costs.

To address these constraints, future studies may pursue three key directions: (1) develop a climate risk disruption module to assess the impact of extreme events on system resilience; (2) construct a regionally differentiated model integrated with geographic information systems (GIS) to reflect spatial heterogeneity in natural resources and enable localized policy planning; and (3) leverage longitudinal data from pilot projects to empirically calibrate and iteratively refine the model, thereby strengthening its utility as a decision-support tool.

Furthermore, the model operates at a high level of aggregation and does not capture regional heterogeneities in solar potential, forest types, or local grid constraints. It also does not incorporate climate-related physical risks such as wildfires, droughts, or pests, which could affect both forest carbon sinks and PV performance. These simplifications were necessary for a national-scale simulation but imply that the model is more suited for macro-level policy assessment than for localized planning. Future iterations will integrate GIS-based spatial analysis and climate risk modules to address these limitations.

6. Conclusions and Policy Recommendations

6.1. Main Conclusions

This study, by constructing a system dynamics model of photovoltaic–carbon sink synergy and conducting simulations on multiple policy scenarios, draws the following three core conclusions.

First, the coordinated development model of photovoltaic and carbon sinks can create significant economic and environmental ‘win-win’ benefits. The simulation results show that this model, while achieving the carbon reduction target (approximately 15% reduction in emissions by 2050 compared to the baseline), can effectively promote regional GDP growth (approximately 4.8% increase by 2050) and become an effective path to narrow the income gap between urban and rural areas and promote common prosperity.

Second, although a single-policy tool is effective, a comprehensive policy system can produce significant synergy effects. The carbon market, green finance, and power grid policies play key roles in different fields (market creation, financial support, and infrastructure), but any single policy has its limitations. The comprehensive policy scenario that combines the three has a 15–30% increase in benefits compared to the best single policy, which provides strong quantitative evidence that a coordinated, multi-instrument policy framework outperforms isolated policy interventions, thereby supporting the necessity of integrated policy design.

Thirdly, there are obvious differences in the timing and path of the role of policy levers. Reducing financing costs has a more significant leverage effect in promoting the short-term growth of photovoltaic installations. The upward carbon price plays a more fundamental role in stimulating long-term carbon sink investment and enhancing the comprehensive return rate of projects. This suggests that policy-making should take into account both short-term effectiveness and long-term sustainability.

6.2. Potential Obstacles to Policy Implementation

Although the comprehensive policy plan demonstrates synergistic benefits in simulations, its real-world implementation may encounter two primary obstacles. First, institutional barriers arise from complex departmental coordination and benefit distribution,

as photovoltaic and carbon sink projects involve multiple management bodies (e.g., energy, forestry, ecology). The absence of an efficient coordination mechanism often leads to cumbersome approval processes and inconsistent standards, while unclear distribution mechanisms for urban–rural land rights and project benefits could trigger social resistance. Second, budgetary constraints pose a significant challenge, characterized by substantial upfront investments and insufficient long-term financing. Green finance support and grid modernization require heavy initial funding, the sustainability of which is uncertain under local fiscal pressures. Moreover, early-stage carbon sink value remains difficult to monetize, creating overreliance on traditional credit or government investment and a lack of effective financial instruments to attract private capital.

To realize the synergistic benefits identified by quantitative models, it is essential to address real-world “implementation friction” through deliberate qualitative governance design, with its core being the establishment of practical institutional safeguards. First, a substantive cross-departmental coordination body, such as a “Photovoltaic-Carbon Sink Coordinated Development Office,” should be set up in key project areas and vested with integrated resource allocation and approval authority. This office would synthesize policies from departments like development and reform, energy, forestry and grassland, ecology, and finance, offering one-stop services to dismantle “policy silos” at the source. Second, standardized processes and data sharing must be advanced through the formulation of “Project Development and Operation Guidelines” to clarify departmental responsibilities and linkages, alongside building a cross-departmental ecological-energy big data platform. This platform would integrate data on project identification, ownership, resources, grid operations, and carbon sink monitoring, thereby reducing coordination and financial risks through digitization. Third, a contractual and participatory benefit-sharing mechanism needs to be instituted, structured around a complete chain of “pre-contract, in-process participation, and post-audit.” This involves legally defining income distribution methods and responsibilities for all parties beforehand; establishing an oversight committee with community representation during operations to ensure transparency and supervision; and introducing third-party independent audits afterward to guarantee equitable distribution and link outcomes to future policy support. In conclusion, by marrying the rigidity of quantitative targets with the flexibility of governance design—through tangible institutions, standardized processes, and binding contractual ties—practical friction can be mitigated, thereby effectively unlocking the model’s synergistic potential.

6.3. The Guiding Significance of the “Win-Win” Paradigm for Policy-Making

The “win-win” paradigm of this study provides a clear framework for integrated policy-making, and its guiding significance is mainly reflected in the following four aspects.

- (1) Promote the policy design to shift from “goal weighing” to “goal coordination”: Research has demonstrated that by systematically integrating photovoltaic (energy transition) systems with carbon sinks (ecological protection), multiple goals such as emission reduction, growth, and equity can be achieved simultaneously. This suggests that policy-making should adopt multi-dimensional collaborative designs, such as embedding ecological restoration requirements in energy planning or integrating the benefits of green energy into ecological compensation, to resolve potential conflicts among policy goals from the source.
- (2) Clarify the differentiated roles and the sequence of their functions of policy tools to enhance the efficiency of resource allocation: The model shows that green finance, carbon markets, and grid investment play different roles at different stages of the project. This provides a “policy roadmap” for decision-making: During the start-up period, financial tools should be prioritized to lower the threshold; during the

expansion period, infrastructure guarantees should be strengthened simultaneously. The mature stage relies on the carbon market to ensure long-term value. By arranging policy priorities and resource inputs based on this, resource misallocation can be avoided, and the leverage effect can be maximized.

- (3) Define the roles of multiple subjects and build a governance framework of “co-construction and sharing of interests”: “Win-win” depends on transforming urban and rural entities into a “community of development”. Policies need to clearly define and motivate the roles of all parties: The central government mainly focuses on the market and standards, local authorities are responsible for project integration and coordination, the power grid ensures physical connectivity, and communities become the beneficiaries through property rights, employment, and dividend mechanisms. Relevant policies should focus on building such incentivized, compatible governance structures and transforming national strategies into internal driving forces.
- (4) Guide policy assessment to shift from “project economy” to “system resilience”: This paradigm emphasizes the synergy and long-term robustness of the system. Therefore, the policy evaluation criteria should go beyond the rate of return of a single project and establish a comprehensive indicator covering economic gains, emission reduction contributions, ecological value, income convergence, and the system’s risk resistance capacity. From this, high-quality projects that truly generate overall positive externalities can be screened out, guiding the optimal allocation of resources.

In conclusion, this paradigm provides a solid theoretical basis and operational logic for formulating integrated policies that are synergistic, precise in timing, clear in subject, and stable in system.

6.4. Policy Recommendations

Based on the above conclusions, this paper puts forward the following operational policy suggestions for decision-making and implementation entities at different levels.

For the central government, efforts should be focused on top-level design and innovation in market mechanisms. The top priority is to improve the national carbon market, raise the carbon price to a level that better reflects its environmental value at an appropriate time (such as moving towards the range of 150 CNY/t by 2030), and actively promote the inclusion of forestry carbon sinks and other projects in the offset mechanism to achieve value linkage between energy emission reduction projects and ecological carbon sequestration projects. Create a stable market return expectation for the ‘photovoltaic-carbon sink’ collaborative model.

For local governments, the core role lies in project implementation and resource integration. It is suggested to design and promote a bundled bidding project of ‘photovoltaic + carbon sink’, integrating land space, light resources, and ecological restoration goals to attract comprehensive developers. At the same time, local green financial products should be innovated. Special loans and interest subsidy funds should be established in cooperation with financial institutions, or financing models such as carbon sink income rights pledge should be explored to effectively lower the initial financing threshold for projects.

For power grid enterprises, their key responsibility lies in providing a stable and reliable technical platform. It is necessary to strengthen the planning and construction of smart grids in rural areas in a forward-looking manner, with a focus on enhancing the access capacity and consumption level of distributed photovoltaic power. Through technological upgrades, we should ensure that green electricity can be ‘generated, transmitted and utilized’ and transform high-quality resource endowments into tangible economic outputs.

For urban and rural communities, the core of success lies in establishing a fair interest connection mechanism. A clear benefit-sharing mechanism must be established at the early stage of project planning. Through various means such as land rent, equity dividends, and employment opportunities, it is necessary to ensure that farmers can share the value-added benefits brought by energy transformation and ecological value conversion in a long-term and stable manner, thereby stimulating their intrinsic motivation as key participants and owners.

In conclusion, promoting the coordinated development of photovoltaic and carbon sinks is a systematic project that requires the joint governance of the central government, local governments, market entities, and community residents. Only through policy coordination, resource integration, and benefit sharing can the substantial potential of this model be transformed into solid achievements in achieving the ‘dual carbon’ goals and the rural revitalization strategy.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Model parameters and input data.

Data Name	Numerical Value	Source
Unit investment cost of photovoltaic (2018)	4.5 CNY/W	IRENA (2024) [36]
Unit investment cost of photovoltaic power (2023)	3.2 CNY/W	IRENA (2024) [36]
Proportion of PV operation and maintenance costs	1.5–2% (Initial investment)	Yuhang W et al. (2024a) [1]
Carbon sink per unit area (for fir forests)	4.5–5.5 CO ₂ t/h · a	Yixiong H et al. (2025a) [8]
The current price range of carbon sinks	CNY 60–80 per ton CO ₂	Description of sensitivity parameters
Policy support degree multiplier (benchmark value)	1.2	Expert consultation (Delphi method)
Investment decision delay time	One year	Expert consultation
The historical verification base year	In 2018	Model setting

Table A2. Model checking and historical data.

Data Name	Simulated Value (2023)	Actual Value (2023)	Relative Error	Source
Installed capacity of photovoltaic power	5.8 GW	6.0 GW	Billion −3.3%	China Electric Power Statistical Yearbook 2023
Forest coverage rate	24.1%	24.02%	+0.3%	China Forestry Statistical Yearbook 2023
Annual photovoltaic power generation	690 TW h	710 TW h	Billion −2.8%	China Electric Power Statistical Yearbook 2023

Note: This type of data is used to verify the validity of the model by comparing the model simulation results with historical actual data.

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