



RESEARCH ARTICLE

A Sustainable Vendor–Buyer Supply Chain Framework Integrating Energy Storage Systems and Green Investments with Incentive Policies under Demand Uncertainty

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Abstract

This research evaluates the effects of integrating energy storage systems into supply chains comprising a vendor and a buyer governed by carbon tax regulations and augmented by green incentives, with an emphasis on promoting sustainability, lowering expenses, and preserving operational efficiency. In this study, a non-linear sustainable supply chain model is developed by incorporating an energy storage system and accounting for carbon emissions from various stages of the supply chain to reflect real-world complexities. In practice, carbon emissions are regulated by a carbon tax policy. Green technology investment is also incorporated to reduce carbon emissions in the supply chain. Besides lowering emissions, such investments can also reduce the energy required in the production process. To support these investments, the government provides green incentives, the amount of which is determined based on the achievement of emission reduction targets. The annual demand is modeled as a fuzzy variable to capture its imprecise nature. To address such uncertainties, Single-valued trapezoidal neutrosophic fuzzy parameters are employed in the model. The Lagrangian method is then applied to derive the optimal solution to the formulated problem. Finally, a numerical example and sensitivity analysis are presented to illustrate the application of the model and examine the impact of key parameters on model behaviour and performance. The proposed model was solved using the prescribed optimization method. The results indicate that the total integrated supply chain cost with investment in energy storage systems amounts to \$10,054.23, whereas the cost without such investment is \$11,693.77. This substantial reduction in total cost demonstrates that the implementation of energy storage systems significantly enhances the overall performance and cost-efficiency of the supply chain. The simultaneous incorporation of energy storage systems and green technology investments in a supply chain, alongside carbon taxes and green incentives under single-valued trapezoidal Neutrosophic fuzzy environments, has not yet been thoroughly investigated in the existing literature.

Keywords: Carbon emission, Fuzzy environment, Varying demand, Energy storage systems, Green technology, Green incentives

Introduction

In Global warming has become a critical environmental challenge in the contemporary era. Its intensifying effects

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pose severe risks to ecosystems, human health, and the sustainability of socio-economic systems. Mitigating this threat necessitates urgent, coordinated interventions encompassing policy, technological innovation, and global cooperation. Researchers are working diligently to achieve sustainability and address the pressing challenges posed by environmental degradation. (Tang et al., 2024) developed an analytical model to assess the impact of logistics outsourcing on emission reduction and the associated costs. (Wangsa et al., 2024) investigated fresh food supply chain systems, addressing the challenges of carbon emissions and food waste reduction, and found that total costs and emissions are significantly influenced by variations in temperature control, carbon penalty costs, and vehicle types. (Astani et al., 2022) proposed a supply chain inventory model to assist managers in making optimal inventory decisions while accounting for both logistics costs and carbon emissions. Under a cap-and-trade regulation, a carbon price is applied to total emissions from production and logistics activities, resulting in inventory decisions that determine the optimal

delivery quantities and frequencies to minimize total costs. (Di et al., 2022) analyzed greenhouse gas emissions in the integrated production-inventory-transportation supply chain enabled by additive manufacturing. The results indicated that adopting additive manufacturing can potentially reduce greenhouse gas emissions compared to traditional manufacturing technologies within the supply chain. (Tran et al., 2022) proposed a supply chain model to simulate container flows on the Trans-Atlantic trade through a liner service. The simulation demonstrated that sailing speed influences only one-fourth of total supply chain costs but affects half of the cargo lead time and over 70% of the carbon footprint. While slow steaming reduces fuel consumption and CO₂ emissions, it extends transit times and increases inventory carrying costs for customers. (Zhang et al., 2024) developed a boundary model for carbon emissions in the mutton supply chain and employed life cycle assessment to comprehensively evaluate emissions during breeding, transportation, processing, and distribution. The study further assessed overall carbon emissions and optimized route planning for the supply chain subsystems.

Recent studies are exploring innovative solutions in energy, resource management, and technology to reduce ecological impacts. Such efforts aim to balance economic growth with environmental protection, ensuring long-term societal and ecological well-being. (March et al., 2023) examined the effects of carbon policies and green technologies on integrated inventory management in a two-echelon supply chain, accounting for carbon emissions arising from production, transportation, and storage. (Yang et al., 2024) developed an EOQ-based integrated supply chain model under progressive carbon taxation, transportation costs, and green technology investment; the model assists decision-makers in determining optimal order quantities and investment levels to minimize total costs and emissions. (Muthusamy et al., 2024) formulated a production-inventory model for scarce perishable goods under various carbon policies with external green technology adoption. The findings demonstrated the role of energy-efficient green technologies in multi-stage supply chains in mitigating carbon emissions associated with production and transportation from manufacturer to dealer. (Akbar et al., 2024) developed a closed-loop supply chain inventory model that integrates carbon emissions and green technology investment, demonstrating that such investments reduce emissions and increase returns from second-hand goods, thereby enhancing environmental efficiency. (Pervin et al., 2025) proposed a sustainable inventory model to control carbon emissions through the adoption of green products, formulating a nonlinear model and suggesting a solution procedure. The results indicate that a sustainable model incorporating controllable carbon emissions, green technology investment, and preservation technology investment is more realistic and profitable

than existing models. (Ruidas et al., 2022) examined the effects of joint investment in greening innovation and emission reduction technologies within a green production-inventory framework under a cap-and-trade regulatory policy, offering valuable managerial insights. The study further found that higher subsidy intensity increases the degree of product greenness.

Governments frequently undertake measures to achieve sustainability within supply chains. They implement regulatory policies for both vendors and buyers to encourage and enforce sustainable practices across the supply chain. The three most widely adopted carbon policies include carbon taxes, cap-and-trade systems, and government subsidies aimed at reducing emissions. (Wang et al., 2024) analyzed the evolution of competition and cooperation among ocean carriers under the influence of a carbon tax policy. A Stackelberg game framework was employed with different power structures involving the government, a hub port, and two carriers. (Dai et al., 2025) evaluated the impact of carbon tax policy on manufacturing and remanufacturing decisions within a closed-loop supply chain, and the findings indicate that carbon taxes can effectively encourage manufacturers to invest in carbon-reduction technologies or remanufacture products to lower emissions. (Sarkar et al., 2022) investigated a sustainable managerial decision-making problem for a substitutable product in a dual-channel supply chain under a carbon tax regime. Classical optimization techniques were applied to determine the global optimal cycle time, level of green technology investment, product selling price, and production rate. Among the various carbon policies, green incentives have attracted more attention than others because they offer positive financial motivation rather than penalties. These incentives encourage firms to voluntarily adopt cleaner technologies and sustainable practices. (Zhan et al., 2024) examined government support for carbon-emission supply chains through green credit incentives. The study considered two types of financial incentives: performance-based rewards and interest subsidies. The results demonstrated that both incentives effectively enhance supply chain performance and encourage investment in emission reduction, although the mechanisms vary depending on the direct beneficiaries. (Jauhari et al., 2023) developed a sustainable vendor-buyer inventory model with incentives, green investment and energy usage under stochastic demand. (Zhang et al., 2021) explored the impact of financial incentives under emission reduction constraints on the operational decisions and environmental performance of capital-constrained supply chains. The findings indicated that green credit subsidies are effective in improving social welfare, whereas price-based incentives are more successful at boosting supply chain profits.

In this context, energy storage systems represent an effective approach for both reducing emissions and

optimizing overall costs within the supply chain. Battery Storage Systems in warehouses are increasingly being used to optimize energy use, reduce electricity costs, and provide backup power during peak demand or emergencies. These systems allow warehouses to store energy when it's abundant (often from renewable sources like solar) or during off-peak hours when electricity prices are lower, and then use that stored energy during peak hours or when demand spikes. Based on the existing literature, the majority of prior studies have primarily focused on integrating carbon footprint assessments into conventional inventory models. In particular, carbon emissions generated during storage activities have been shown to significantly influence supply chain profitability. Extensive research has also examined the role of green investments in reducing emissions within supply chains. However, investments in energy storage systems have likewise been proven to substantially mitigate emissions. This reveals a research gap specifically, the lack of studies that simultaneously investigate carbon emission factors alongside investments in both energy storage systems and green technologies. Carbon taxation is widely recognized as one of the most effective policy instruments for mitigating emissions, as it internalizes the environmental cost of carbon. In addition, the provision of green incentives motivates firms to allocate capital toward environmentally sustainable investments. The present study addresses this research gap by considering these diverse supply chain factors within a unified framework. A nonlinear supply chain model is developed that accounts for carbon emissions during production, transportation, and storage, under the dual influence of carbon taxation and green incentives. Investments in energy storage systems and green technologies are incorporated simultaneously to minimize total system costs while addressing sustainability objectives.

Methodology

Preliminaries:

Definition: Let X be a non-empty set. Then an NS \tilde{A}^N on X defined as \mathcal{Y} Where $T_{\tilde{A}^N}(x), I_{\tilde{A}^N}(x), F_{\tilde{A}^N}(x)$ are the truth membership function, an indeterminacy membership function, and a falsity function and there is no restriction on the sum of $-0 \leq T_{\tilde{A}^N}(x) + I_{\tilde{A}^N}(x) + F_{\tilde{A}^N}(x) \leq 3^+$ non-standard unit interval.

Definition: Let X be a non-empty set. Then an SVNS \tilde{A}_{SV} on X defined as $\tilde{A}_{SV} = \langle x, T_{\tilde{A}_{SV}}(x), I_{\tilde{A}_{SV}}(x), F_{\tilde{A}_{SV}}(x) \mid x \in X \rangle$ where $T_{\tilde{A}_{SV}}(x), I_{\tilde{A}_{SV}}(x), F_{\tilde{A}_{SV}}(x) \in [0, 1]$ for each $x \in X, 0 \leq T_{\tilde{A}_{SV}}(x), I_{\tilde{A}_{SV}}(x), F_{\tilde{A}_{SV}}(x) \leq 3$.

Definition: Let m_1, m_2, m_3, m_4 such that $m_1 \leq m_2 \leq m_3 \leq m_4$ and $T_{\tilde{m}}, I_{\tilde{m}}, F_{\tilde{m}} \in [0, 1]$. Then an SVTNNs is defined as $m_{\tilde{m}} = (m_1, m_2, m_3, m_4); T_{\tilde{m}}, I_{\tilde{m}}, F_{\tilde{m}}$ is a special neutrosophic set on the real line set R , whose truth membership, indeterminacy membership, and falsity membership functions are given as follows:

$$\mu_{T_{\tilde{m}}} = \begin{cases} T_{\tilde{m}} \left(\frac{x - m_1}{m_2 - m_1} \right), & m_1 \leq x \leq m_2 \\ T_{\tilde{m}}, & m_2 \leq x \leq m_3 \\ T_{\tilde{m}} \left(\frac{m_4 - x}{m_4 - m_3} \right), & m_3 \leq x \leq m_4 \\ 0, & otherwise \end{cases}$$

$$v_{I_{\tilde{m}}}(x) = \begin{cases} \frac{m_2 - x + I_{\tilde{m}}(x - m_1)}{m_2 - m_1}, & m_1 \leq x \leq m_2 \\ I_{\tilde{m}}, & m_2 \leq x \leq m_3 \\ \frac{x - m_2 + I_{\tilde{m}}(m_4 - x)}{m_4 - m_3}, & m_3 \leq x \leq m_4 \\ 1, & otherwise \end{cases}$$

$$w_{F_{\tilde{m}}}(x) = \begin{cases} \frac{m_2 - x + F_{\tilde{m}}(x - m_1)}{m_2 - m_1}, & m_1 \leq x \leq m_2 \\ F_{\tilde{m}}, & m_2 \leq x \leq m_3 \\ \frac{x - m_2 + I_{\tilde{m}}(m_4 - x)}{m_4 - m_3}, & m_3 \leq x \leq m_4 \\ 1, & otherwise \end{cases}$$

Mathematical Model

This study develops a non-linear sustainable vendor-buyer supply chain model that simultaneously integrates energy storage systems and green technology investments within the supply chain framework. To more accurately represent real-world uncertainties and imprecise conditions, the model utilizes Single-valued Trapezoidal Neutrosophic fuzzy parameters, offering a flexible and realistic framework for handling uncertain decision variables. In addition, the model explicitly incorporates the effect of carbon emissions on global warming by accounting for emission-related costs across different stages of the inventory system. Both carbon taxation and green incentives are integrated to encourage emission reduction. The optimal solution to the proposed problem is obtained using the Lagrangian optimization technique, ensuring a balance between economic efficiency and environmental sustainability. The notations and assumptions employed in formulating the model are outlined below.

Notations:

- d- Product demand flow
- σ - Variation in demand
- o- Cost per order (\$/order)

a- Safety stock factor
 h_1 - Storage cost for the buyer
 b- Cost of backorders
 t- Shipping duration
 E- Carbon emissions from inventory storage
 e- Environmental tax on carbon
 t_1 - Shipping cost
 p- Freight capacity
 c- Fuel efficiency per truck
 f- Carbon emissions per gallon of diesel fuel
 α - Cost of energy consumption
 u- Maximum achievable emission reduction, $0 < u < 1$
 m- Green investment factor
 w- proportion of energy reduction
 x- green incentives
 y- Idle power consumption of the manufacturing facility
 z- Power usage constant of the manufacturing facility
 S- Facility setup cost
 h_2 - Vendor's inventory holding cost
 l- accelerated Facility emission factor
 m- baseline variable emission factor
 n- fixed emission parameter for the manufacturing facility
 T- Inventory review interval
 N- delivery frequency
 Q- Investment in green technologies
 β - emission reduction efficiency of energy management systems
 λ - Proportion of carbon emissions remaining after energy management system investment
 I- Investment in energy storage systems

Assumptions

- The system under investigation comprises a vendor responsible for manufacturing products and a buyer who sells them to end customers.
- Demand at the buyer's side follows a normal distribution with mean d and standard deviation σ .
- The annual demand is represented as a fuzzy quantity to account for uncertainty.
- The buyer's inventory level is reviewed at intervals of T , where T exceeds the lead time. Consequently, there is at most one outstanding order in any cycle.
- The buyer places orders of NdT units, and the vendor manufactures NdT units per production run at a finite production rate P , where $P > d$. The lot of dT units is then delivered from the vendor to the buyer evenly over time.
- The vendor has the option to invest in green technologies to reduce the emissions regularly generated by the facility.
- To incentivize emission reduction, the regulator provides green incentives to the vendor based on the achievement of emission reduction targets.
- The manufacturer intends to invest in energy storage systems, machinery that conserves energy, in order to transition to a more environmentally friendly

manufacturing system. There is a cap on the total amount of money that can be invested. The fraction of reduction in average emissions for production is $F = \lambda(1 - e^{-\beta t})$ where y, u and G were defined in the notations section. $F = \lambda(1 - e^{-\beta t}) \Rightarrow t = -\left(\frac{1}{\beta}\right) \left[\ln\left(1 - \frac{F}{\lambda}\right) \right]$ This relationship is similar to that assumed by Lou et al. The manufacturer might make improvements to the production methods to make them more environmentally friendly. The fraction of reduction F is zero when $G = 0$ and tends to y when $G \rightarrow \infty$. The factor β indicates how effective greener technology is at lowering emission. This investment function is consistent in various industries, and has been widely been used in literature to formulate various investment options.

Supply chain model with energy storage system investment

In this study, the system examined a two-echelon supply chain consisting of a vendor and a buyer. The vendor is responsible for manufacturing the product and dispatching it to the buyer. Production operates for a finite period and terminates once the entire batch is completed, after which deliveries are made immediately. The buyer, who sells the product to the end customer, operates under demand uncertainty, where the product demand is assumed to follow a normal distribution with a fuzzy mean. Carbon emissions arising from the activities of both parties are regulated through a carbon tax policy to ensure reduction efforts. On the vendor side, emissions are generated from production and storage, whereas on the buyer side, emissions result from transportation and shipping operations. In addition to producing emissions, the vendor's production process also consumes energy, which varies with the level of production. Under tax pressure from regulators and driven by the need to conserve energy, the vendor seeks to minimize emissions and control energy use. To achieve this, the vendor makes investments in energy storage system and green technology aimed at reducing emissions generated during production and storage. Since regulators share the same objective of cutting emissions, they offer green incentives tied to achieving specified emission-reduction targets. This incentive scheme motivates the vendor to intensify efforts toward further emission reduction. Accordingly, this study examines a nonlinear supply chain model that accounts for carbon emissions arising from production, transportation, and storage, within the framework of carbon taxation and green incentive mechanisms. Investments in both energy storage systems and green technology are incorporated simultaneously to reduce the total system cost while addressing sustainability objectives. To deal with the demand uncertainty, the model employs single-valued trapezoidal neutrosophic fuzzy parameters, which provide a more flexible and realistic representation of uncertain decision variables.

Therefore, overall cost for the supply chain is

$$\begin{aligned}
 TC = & \frac{o}{T} + t_1 \frac{s(\tilde{d}, \tilde{0})}{p} + (h_1 + e_1 E) \left(\frac{s(\tilde{d}, \tilde{0})T}{2} + a \sqrt{T + s(\tilde{d}, \tilde{0})T/p + t} \right) \\
 & + \frac{b\sigma}{T} \sqrt{T + s(\tilde{d}, \tilde{0})T/p + t} \psi(a) + e_1 \frac{s(\tilde{d}, \tilde{0})}{p} cf + \frac{S}{NT} \\
 & + h_2 \frac{s(\tilde{d}, \tilde{0})T}{2} \left(N \left[1 - \frac{s(\tilde{d}, \tilde{0})}{p} \right] - 1 + \frac{2s(\tilde{d}, \tilde{0})}{p} \right) \\
 & + e_1 E \left\{ 1 - u\beta \left[1 - e^{-m\lambda Q} \right] \right\} \frac{s(\tilde{d}, \tilde{0})T}{2} \left(N \left[1 - \frac{s(\tilde{d}, \tilde{0})}{p} \right] - 1 + \frac{2s(\tilde{d}, \tilde{0})}{p} \right) \quad (2.1) \\
 & + e_1 E \left\{ 1 - u\beta \left[1 - e^{-m\lambda Q} \right] \right\} s(\tilde{d}, \tilde{0}) (lP^2 + mP + n) \\
 & + \alpha \left\{ 1 - wu \left[1 - e^{-m\lambda} \right] \right\} \left(\frac{y}{P} + z \right) s(\tilde{d}, \tilde{0}) + Q - x \left(u \left[1 - e^{-m\lambda} \right] - v \right)
 \end{aligned}$$

Where $\psi(a) = f_s(a) - a[1 - F_s(a)]$

$f_s(a)$ and $F_s(a)$ represent the probability density function and the cumulative density function of standard normal distribution, respectively.

The signed distance from \tilde{d} to $\tilde{0}$ is given by

$$s(\tilde{d}, \tilde{0}) = \frac{1}{4} [(t_1 + 2t_2 + 2t_3 + t_4) - (f_1 + 2f_2 + 2f_3 + f_4)]$$

First, for fixed N, we take the first partial derivative of TC with respect to T, a, Q and l respectively.

Supply chain model without energy storage system investment

In the context of carbon taxation, a carbon tax e is imposed per unit of carbon emissions, which increases linearly with the quantity of emissions produced. To mitigate these emissions, firms invest in green technologies that help reduce the overall tax burden. The total cost of the integrated inventory model therefore includes the combined expenses of both the vendor and the buyer, as well as the costs associated with carbon taxation and green investments. By aggregating the carbon emissions generated from various activities of both parties and then accounting for the emission reduction achieved through green investments, the net total carbon emissions can be determined. Moreover, Green incentives were also implemented to encourage the achievement of specific emission reduction targets.

Therefore, overall cost for the supply chain is

$$\begin{aligned}
 TC = & \frac{o}{T} + t_1 \frac{s(\tilde{d}, \tilde{0})}{p} + (h_1 + e_1 E) \left(\frac{s(\tilde{d}, \tilde{0})T}{2} + a \sqrt{T + s(\tilde{d}, \tilde{0})T/p + t} \right) \\
 & + \frac{b\sigma}{T} \sqrt{T + s(\tilde{d}, \tilde{0})T/p + t} \psi(a) + e_1 \frac{s(\tilde{d}, \tilde{0})}{p} cf + \frac{S}{NT} \\
 & + h_2 \frac{s(\tilde{d}, \tilde{0})T}{2} \left(N \left[1 - \frac{s(\tilde{d}, \tilde{0})}{p} \right] - 1 + \frac{2s(\tilde{d}, \tilde{0})}{p} \right) \\
 & + e_1 E \left\{ 1 - u \left[1 - e^{-m\lambda} \right] \right\} \frac{s(\tilde{d}, \tilde{0})T}{2} \left(N \left[1 - \frac{s(\tilde{d}, \tilde{0})}{p} \right] - 1 + \frac{2s(\tilde{d}, \tilde{0})}{p} \right) \quad (2.2) \\
 & + e_1 E \left\{ 1 - u \left[1 - e^{-m\lambda} \right] \right\} s(\tilde{d}, \tilde{0}) (lP^2 + mP + n) \\
 & + \alpha \left\{ 1 - wu \left[1 - e^{-m\lambda} \right] \right\} \left(\frac{y}{P} + z \right) s(\tilde{d}, \tilde{0}) + Q - x \left(u \left[1 - e^{-m\lambda} \right] - v \right)
 \end{aligned}$$

RESULT

This study presents a numerical example to analyze how different carbon emission policies influence the overall inventory cost in a supply chain and the feasibility of investing in environmentally friendly technologies. To show the efficiency of the proposed model the following numerical example is illustrated with the prescribed parameters as given below. The parameters related to emissions and efficiency factor with respect to energy storage systems and green technology are considered simultaneously.

Parameters

$d=500, \sigma=20, 0=200, t_1=400, p=100, c=375, f=0.25, t=0.0005, b=50P=1200, h_1=2.5, h_2=1.5, a=800, l=0.00012, m=0.0008, n=8.4, y=1000000, z=1000, \alpha=0.015, E=0.0618, m=0.005, u=0.65, v=0.3, \beta=0.8, \lambda=0.2.$

Therefore, the total integrated supply chain model cost with energy storage systems investment is \$10,054.23

Example

In this example, the parameters related to emissions and investment in the green technology alone are considered and the numerical example was solved using the methodology described in the previous section precisely using the equation (2.2).

The values of different parameters are:

$d=500, \sigma=20, 0=200, t_1=400, p=100, c=375, f=0.25, t=0.0005, b=50P=1200, h_1=2.5, h_2=1.5, a=800, l=0.00012, m=0.0008, n=8.4, y=1000000, z=1000, \alpha=0.015, E=0.0618, m=0.005, u=0.65, v=0.3.$

Therefore, the total integrated supply chain model cost without energy storage systems investment is \$11,693.77.

The Table 1 shows the efficiency of the suggested paradigm.

Discussion

The prior research has examined the impact of carbon footprints on traditional inventory systems, much of it has primarily emphasized green investments aimed at reducing emissions in supply chain operations. However, a notable research gap exists, as previous studies have largely overlooked carbon emissions arising from non-traditional sources within the supply chain. In particular, emissions generated during idle periods in deliveries and from idling or unnecessary movements within facilities can significantly affect supply chain profitability. The novelty of this work lies in its comprehensive consideration of carbon emissions across

Table 1: Comparison of the manufacturing firm with and without yard management systems investment

Average profit of the manufacturing firm	With energy storage system investment	Without energy storage system investment
	\$10,054.23	\$11,693.77

multiple dimensions of the supply chain—incorporating yard management and green technology investments. The proposed study develops and analyzes a nonlinear supply chain model that integrates carbon emissions from production, transportation, storage, delivery idle times, and internal facility movements within the context of a carbon taxation framework. The data values used in this study are primarily adapted from (Ben-Daya and Hariga 2004), (Jauhari et al., 2012), and (Saga et al., 2019). Additionally, information on truck fuel consumption, production-related emissions, and carbon tax rates is obtained from (Jauhari et al., 2022), and (Chan et al., 2009), respectively.

Conclusion

In today's evolving industrial landscape, sustainability has become a crucial element in inventory and supply chain management. Most existing studies have primarily focused on carbon emissions generated during production, transportation, and storage. However, emissions released during storage at facilities also have a considerable impact on the overall profitability of supply chain systems. While many studies have emphasized green technology investments within production-inventory models, investments in energy storage systems can also play a vital role in significantly reducing emissions. The novelty of this research lies in its comprehensive consideration of carbon emissions across multiple stages of the supply chain, incorporating both energy storage systems and green technology investments. This study aims to bridge the existing research gap by simultaneously addressing these two parameters to maximize overall supply chain profitability. Moreover, carbon emissions are regulated through a carbon tax policy, and to encourage sustainable practices, the government provides green incentives determined by the achievement of emission-reduction targets. Accordingly, a nonlinear sustainable supply chain model is developed in this study, integrating an energy storage system and accounting for carbon emissions from various stages of the supply chain to better reflect real-world complexities. The annual demand is represented as a fuzzy variable, and single-valued trapezoidal neutrosophic fuzzy parameters are employed within the model. The Lagrangian method is then utilized to obtain the optimal solution to the formulated problem. Numerical analysis reveals that the total integrated supply chain cost with investment in energy storage systems is \$10,054.23, whereas without such investment, the cost increases to \$11,693.77. Future research can be extended by incorporating multiple retailers and exploring additional sustainability-related parameters.

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