SSRG International Journal of Geo-informatics and Geological Science
ISSN: 2393–9206 / https://doi.org/10.14445/23939206/IJGGS-V13I2P104

Volume 13 Issue 2, 39-47, May-Aug 2026

Original Article

Supply Chain Resilience: A Sustainable Models for Green Energy

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Received: 03 June 2026 Revised: 08 July 2026 Accepted: 25 July 2026 Published: 13 August 2026

Abstract - *The shift to renewable energy in the world has added more complexities and vulnerabilities to the supply chains of green energy, calling for resilient and sustainable supply chain practices to guarantee energy security and carbon neutrality in the world. Therefore, this study suggests a theoretical model based on fuzzy multi-objective optimization that brings together SCR and SSCM in order to enhance the performance and adaptability of renewable energy supply chains. The developed theoretical model takes into account several aspects of resilience and sustainability, such as supplier reliability, disruptions in transportation processes, inventory management, supply chain costs, carbon emissions, supply chain resources, and risk of disruptions in the supply chain processes. Fuzzy set theory is used to take care of the uncertainties in the decision-making process related to the supply chain, while multi-objective optimization tries to optimize resilience and sustainability and minimize economic, ecological, and operational costs and risks. Also, the Green Supply Chain Resilience Index (GSCRI) is offered in the current research. Based on the conceptual framework, sustainable practices, which include green procurement, circular economy approach, supplier diversification, use of renewable resources, and environmental sustainable logistics, can be used in order to create greater resilience through resource efficiency and dependency reduction, as well as improved adaptability to disruptions. Moreover, the use of Industry 4.0 approaches, which include Artificial Intelligence (AI), the Internet of Things (IoT), Blockchain, Digital Twin technology, and Big Data Analytics, can be used to increase the visibility in supply chains, allow risk prediction and decision making based on data. The model is supported by the key theories related to resilience, sustainability, dynamic capability, and fuzzy optimization. Thus, it provides a useful decision support framework for policy makers, renewable energy manufacturers, and supply chain managers for building more resilient, sustainable, adaptive and environmentally friendly green energy supply chains.*

Keywords - *Supply Chain Resilience, Sustainable Supply Chain Management, Green Energy, Fuzzy Optimization, Renewable Energy, Circular Economy, Industry 4.0, Artificial Intelligence, Green Supply Chain Resilience Index (GSCRI), Sustainability.*

1. Introduction

Climate change mitigation efforts have necessitated the move away from fossil fuels to energy from renewable sources like solar, wind, biomass, and hydroelectric power. The shift from fossil fuel energy sources to renewable energy is an important step towards attaining global sustainability objectives, as stated in the objectives set forth in international agreements such as the Paris Climate Accord. Nevertheless, the renewable energy industry operates under very complex and globally connected supply chains that are highly sensitive to the impacts of geopolitical disputes, pandemic diseases, and other environmental factors (Hosseini Shekarabi et al., 2025). SCR is defined as the capability of a network to withstand any kind of disruption and continue to function in its intended way without failing by anticipating, absorbing, adapting, and recovering from disruptive events (Ponomarov & Holcomb, 2009). Resilience becomes very important when dealing with renewable energy sources due to the dependence on rare materials, technology components, and supply chain networks. At the same time, sustainability has become an important aspect of supply chain management (Carter & Rogers, 2008). Combining resilience and sustainability is very pertinent to green energy supply chains because the potential disruption could affect both the goals set environmentally and economically. The practices of Sustainable Supply Chain Management (SSCM), such as efficient use of resources, carbon emission reduction, and the adoption of a circular economy, increase resilience by decreasing dependency (Rajabzadeh & Wiens, 2024).

This study aims to investigate how sustainable supply chain strategies can enhance resilience within the green energy sector amid increasing global uncertainties and disruptions. In particular, the following research questions will be examined: understanding the concept and dimensions of supply chain resilience in renewable energy systems; analysis of the role played by sustainability in enhancing the ability to adapt and recover; identification of main barriers to resilient and sustainable green energy supply chains and possible strategies; development of an integrative theoretical framework that covers supply chain resilience and sustainability. The suggested theoretical framework can serve as an important tool for policy-makers, business representatives, and researchers to design resilient, adaptable, and sustainable supply chains for the development of renewable energy systems. In addition, this research highlights the increasing significance of Industry 4.0 techniques such as Artificial Intelligence (AI), Internet of Things (IoT), Blockchain technology, digital twins, and big data analysis in ensuring sustainable and resilient functioning of the supply chains. The application of these techniques will help increase the transparency of supply chains, predict potential risks, monitor the functioning of the supply chain in real time, and make adaptive decisions. The incorporation of these techniques into the fuzzy optimization approach allows making proactive reactions to any disturbances while preserving sustainability goals.

2. Literature Review

Theoretically, the study adds value to the existing literature through the combination of Supply Chain Resilience Theory (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009), Sustainable Supply Chain Management Theory (Carter & Rogers, 2008; Seuring & Müller, 2008), Dynamic Capability Theory (Teece et al., 1997; Teece et al., 2016), and Fuzzy Optimization Theory (Zimmermann, 1996). The Green Supply Chain Resilience Index (GSCRI) has been developed to offer a method of evaluation for all aspects mentioned above within renewable energy supply chains.

2.1. Concept of Supply Chain Resilience

Supply chain resilience has become an important field for researchers as a result of the rising uncertainty in the world. There are many dimensions of it, such as robustness, agility, flexibility, and redundancy (Christopher & Peck, 2004). As stated by Hosseini Shekarabi et al. (2025), there are two main types of supply chain resilience strategies – proactive, which means risk prevention, and reactive, which implies recovery mechanisms. Supply Chain Resilience (SCR) is an important term in the realm of supply chain management that has been developed as a result of the rising number and intensity of various disruptions that occur globally, including pandemics, geopolitics, climate change, and market uncertainty. It consists of several interconnected components, among which include robustness, agility, flexibility, redundancy, adaptability, and collaboration that increase an organization’s ability to deal with uncertainty. Modern literature divides resilient strategies into proactive measures, such as risk assessment, diversifying suppliers, and contingency plans, and reactive measures, like quick reaction, recovery plans, and adaptable resource allocation, aimed at reducing negative consequences of disruption and improving the performance of the supply chain (Hosseini Shekarabi et al., 2025). The mentioned characteristics are especially important for renewable energy supply chains where the continuity of operations relies on global resources and technologies.

Mathematically, supply chain resilience can be represented as:

$$SCR = f\,(R_b, F_l, A_g, R_d)$$

Where:

- (R_b) = Robustness
- (F_l) = Flexibility
- (A_g) = Agility
- (R_d) = Redundancy

This formulation highlights the multidimensional nature of resilience.

2.2. Renewable Energy Supply Chains

The renewable energy supply chain is made up of various processes, including the extraction of raw materials, processing of strategic minerals, manufacturing of components, transportation, installation, operating and maintenance, and recycling of renewable energy technologies. The supply chain of renewable energy technology is highly reliant on strategic minerals such as lithium, cobalt, nickel, graphite, and rare earth minerals, which are key raw materials used in manufacturing batteries, wind turbines, photovoltaic panels, and energy storage systems (Aslani et al., 2024). In comparison with the traditional fossil fuels supply chain, the renewable energy supply chain is decentralized, technologically complex and highly interconnected, making it vulnerable to geopolitical challenges, trade barriers, natural disasters and market volatility. Disruption in the supply chain of these critical minerals, especially lithium and rare earth minerals, can greatly delay the process of adopting renewable energy and lead to increased production costs. Therefore, developing a resilient and sustainable renewable energy supply chain has now become the strategic priority to ensure energy security and sustainable development in future (Hosseini Shekarabi et al., 2025). For instance, disruption in the supply chain of lithium can cause major disruption in the production of solar battery cells and electric grid storage systems (IEA, 2023).

2.3. Sustainable Supply Chain Management (SSCM)

The concept of Sustainable Supply Chain Management (SSCM) refers to the inclusion of environmental, economic, and social perspectives in the management of supply chain processes in an effort to ensure organizational sustainability while minimizing negative environmental effects. According to Carter and Rogers (2008), SSCM involves the strategic alignment of the supply chain members with the aim of ensuring that the business performs well economically, environmentally, and socially. Seuring and Müller (2008) also note that SSCM helps in ensuring efficient use of resources, minimization of waste, ethical purchasing, and collaboration of stakeholders within the life cycle of the product. Recent literature reveals that sustainable practices like the circular economy concept, low-carbon logistics, sustainable procurement, and digitization greatly improve efficiency and resilience in renewable energy supply chains (Rajabzadeh & Wiens, 2024; Hosseini Shekarabi et al., 2025). Moreover, integrating sustainability with resilience enables organizations to better withstand disruptions while maintaining environmental and economic performance. Consequently, SSCM has become a critical strategic approach for achieving resilient, efficient, and environmentally responsible green energy supply chains (Ponomarov & Holcomb, 2009).

SSCM integrates environmental and social considerations into supply chain operations. It is based on the Triple Bottom Line (TBL) framework:

$$TBL = E_n + E_c + S_o$$

Where:

- (E_n) = Environmental performance
- (E_c) = Economic performance
- (S_o) = Social performance

Research indicates that SSCM practices improve long-term performance and reduce risks associated with environmental and regulatory pressures (Carter & Rogers, 2008).

2.4. Circular Economy and Green Supply Chains

Circular Economy (CE) has proved to be a paradigm shift for fostering sustainability and resilience in the green supply chains through efficient utilization of resources, waste reduction, and continuous recycling of materials through the entire process of the products' life cycle. Contrary to the conventional linear economy approach, which is based on the "take–make–dispose" concept, the circular economy adopts practices such as recycling, reusing, remanufacturing, refurbishing, and recovering of materials to increase longevity of the product and mitigate its environmental impacts (Geissdoerfer et al., 2017). Within the context of renewable energy supply chains, the circular economy helps to foster resilience by reducing the dependency on raw materials, improving resource security, and minimizing the risks linked to the sourcing of critical minerals such as lithium, cobalt, and rare earths. Moreover, circular economy strategies help in building the flexibility of supply chains, cost-saving during the manufacturing process, and reducing carbon emissions, thus making green energy transition sustainable (Kirchherr et al., 2017; Rajabzadeh & Wiens, 2024).

Circular Economy (CE) principles focus on minimizing waste and maximizing resource utilization through recycling, reuse, and remanufacturing. CE enhances resilience by reducing dependency on virgin raw materials (Geissdoerfer et al., 2017).

Closed-loop supply chain models can be expressed as:

$$Q_{total} = Q_{new} + Q_{recycled}$$

This model emphasizes the role of recycled materials in reducing supply chain vulnerability.

2.5. Industry 4.0 and Digital Transformation

Industry 4.0 innovations have become crucial facilitators that are responsible for increasing the resiliency, efficiency, and sustainability of the contemporary supply chains, especially those operating in the renewable energy industry. Digital innovations, including IoT, blockchain, Artificial Intelligence (AI), big data analytics, cloud computing, and digital twins, allow performing real-time tracking, predictive analytics, intelligent decision-making, and end-to-end supply chain visibility. The use of these innovations allows companies to detect any threats, improve their inventory and logistics processes, forecast future demands, and collaborate with other supply chain stakeholders. Moreover, the use of blockchain innovations guarantees transparency and traceability through ensuring the safety and immutability of transactional records, whereas AI-based analytics allows conducting proactive risk assessment and resource allocation. The use of these digital innovations greatly increases the operational agility and adaptability of organizations, which leads to their increased sustainability and contributes to the development of green energy systems (Labaran & Masood, 2023; Rajabzadeh & Wiens, 2024). Technologies such as IoT, blockchain, Artificial Intelligence (AI), and big data analytics significantly enhance supply chain transparency and decision-making capabilities (Labaran & Masood, 2023).

For example, predictive analytics models:

$$D_t = \alpha + \beta X_t + \varepsilon_t$$

Help forecast demand and reduce uncertainty, thereby improving resilience.

3. Theoretical Framework

This study integrates two major theories:

3.1. Dynamic Capability Theory

From the perspective of dynamic capability theory, adaptation of organizations to change in the environment becomes very important. It has already been noted that resilience of the supply chain is one form of dynamic capability when organizations react to disruptions (Teece et al., 1997). This paper builds on a theoretical framework that is referred to as Dynamic Capability Theory (DCT). This is the theory by means of which organizations can develop, integrate and recombine internal and external resources in a changing environment (Teece et al., 1997). Dynamic capabilities play an important role in predicting possible disruptions, responding preemptively to uncertainties and recovering quickly from unexpected operational shocks within green energy supply chains. In other words, supply chain resilience is viewed as a strategic dynamic capability which adds flexibility and agility to the organization in case of various risks like geopolitical instability, climate change, shortages of resources and fluctuations of global markets. Moreover, the use of sustainability practices, including circular economy, digitalization, supplier diversity and resource efficiency, helps to build dynamic capabilities and manage risks effectively in order to maintain competitiveness in the long run. This means that the concept of Dynamic Capability Theory represents a good theoretical basis for analyzing how renewable energy organizations can combine their supply chain resilience, operational continuity and sustainability (Teece et al., 2016; Rajabzadeh & Wiens, 2024).

3.2. Triple Bottom Line (TBL) Framework

The TBL framework guarantees that the supply chains become sustainable along environmental, economic, and social lines (Elkington, 1997). The current research is based on the TBL framework, which gives a good theoretical background for incorporating sustainability into the supply chain resilience in the green energy industry. The TBL framework was suggested by Elkington (1997), who stressed that not only economic results but also environmental and social responsibility were crucial for evaluating organizational performance. Regarding the economic dimension within the framework of renewable energy supply chains, it is related to operational efficiency, cost management, and competitiveness; the environmental dimension encourages resource preservation, low carbon emissions, waste prevention, and a circular economy; whereas the social dimension stresses ethical sourcing, workers' welfare, stakeholder involvement, and community health. By taking into account all three dimensions, one can increase the resilience of the supply chain, making it more adaptive and resistant to any possible disruption. Therefore, the triple bottom line approach provides a strong theoretical foundation for establishing a resilient, sustainable, and environmentally conscious green energy supply chain (Elkington, 1997; Carter & Rogers, 2008; Ahi & Searcy, 2013).

4. Methodology

This paper utilizes a conceptual and analytical approach of research methodology that facilitates the formulation of a fuzzy multi-objective optimization framework that helps improve the resilience and sustainability of supply chains in renewable energy supply chains in an environment of uncertainty. A multi-objective optimization model is formulated for maximizing supply chain resilience and sustainability while minimizing total costs and disruptions.

5. Challenges in Green Energy Supply Chains

Renewable energy transformation worldwide is not only changing energy systems but also making them more complex and vulnerable. The fast-growing production of solar photovoltaic (PV), wind power, EVs, and battery energy storage systems is causing an increasing demand for critical materials and minerals, which creates serious threats to supply chain resilience and sustainability (IEA, 2021, 2024). These obstacles can impede the production and installation of renewables, thus slowing down the process of achieving climate change and sustainable development goals. The first and foremost obstacle is related to the supply and availability of raw materials. Technologies like EV batteries and energy storage systems depend upon lithium, cobalt, nickel, and graphite, whereas wind turbines and solar PV technologies require different types of rare earth minerals and critical minerals (Hund et al., 2020; IEA, 2024). The geographical concentration of mineral deposits and their processing facilities, along with growing global demand, makes renewable energy supply chains vulnerable to geopolitical conflicts, trade barriers, price fluctuations, and even supply chain disruptions (IEA, 2021; World Bank, 2020). The next issue related to supply chains is geopolitical risks, such as international trade restrictions, export restrictions, economic sanctions, wars, and political instability. All of these issues affect the transport of strategic materials and components of renewable energy sources in the international market. As most of the production of strategic minerals takes place in several countries only, there may arise many problems associated with geopolitical tensions that can lead to significant disruptions in the supply of critical minerals and, consequently, to additional costs and delays in the development of renewable energy systems (Rajabzadeh & Wiens, 2024). Lack of appropriate infrastructure is one more obstacle in using renewable energy that affects many developing and emerging economies.

Climate change brings its own set of vulnerabilities via climate hazards. In recent times, we have seen natural disasters such as extreme weather conditions, floods, fires, storms, and droughts impacting mining, transportation, manufacturing industries, and energy sectors. This leads to reduced capacity and disruptions of supply chains, increasing the cost of operations, emphasizing the need for climate-resilient supply chain management (Hosseini Shekarabi et al., 2025). Finally, technology is another significant threat. Innovations in renewable energies, battery systems, digitalization and hydrogen-based energy are rapidly taking place, leading to uncertainty about the standard of technologies and investments in the future. Organizations will have to constantly innovate their ways of work, managing their finances and sustainability in the process. It becomes crucial to address these threats strategically and innovatively in order to create resilient and sustainable green energy supply chains to facilitate the carbon-neutral transition globally.

6. Sustainable Strategies for Enhancing Resilience

It is essential to ensure resilient and sustainable supply chains to guarantee the successful functioning of the green energy industry in the long run. The supply chains in renewable energy are subject to disruptions caused by geopolitical uncertainty, natural disasters, epidemics, changes in demand and the shortage of key resources. Hence, incorporating sustainability into resilience strategy allows an organization to develop its capabilities to cope with disruptions and preserve the levels of environmental, economic, and social sustainability (Ponomarov & Holcomb, 2009; Carter & Rogers, 2008). The proposed theoretical framework for the current research highlights five related strategic dimensions contributing to the supply chain resilience of green energy systems. Supplier diversification is the first strategic pillar of supply chain resilience. Relying on a few suppliers, especially for critical materials like lithium, cobalt, nickel, and rare earth metals, raises risks in the supply chain. Geographic diversification of supply chains and building relationships with several suppliers minimize risks of disruptions and increases supply chain resilience (Christopher & Peck, 2004; Hosseini Shekarabi et al., 2025).

Another aspect is the implementation of the circular economy concepts that contribute to resource efficiency through the processes of recycling, remanufacturing, material recovery, and prolongation of products' life cycles. The circular supply chain reduces the reliance on new raw materials, limits the amount of waste produced, and ensures resource sustainability and security (Geissdoerfer et al., 2017; Rajabzadeh & Wiens, 2024). The application of digital technologies in supply chain management is yet another critical component of the resilient green energy supply chain system. The emerging technologies of Artificial Intelligence (AI), the Internet of Things (IoT), blockchain, big data, and digital twins make it possible to monitor and predict any potential disruptions and problems in the supply chains (Ivanov & Dolgui, 2020).

The dimensions of collaboration and supply chain integration contribute even more to resilience through communication, information exchange, mutual trust, and coordination of decisions among all supply chain stakeholders, including suppliers, manufacturers, logistics companies, government, and energy utilities. The establishment of collaborative ties improves risk management and allows for quicker recovery from disruption within the supply chain (Scholten & Schilder, 2015). The last dimension of green logistics is important for building resilience as well as sustainability through optimization of transportation, minimization of greenhouse gas emissions, improvements in energy efficiency and development of low-carbon transportations (Dekker et al., 2012). All in all, these five strategic dimensions can be used as the basis for creating a theoretical framework for building resilient and adaptive green energy supply chains that would support the transition into a low-carbon economy.

7. Proposed Conceptual Model

However, the increasing complexities of renewable energy supply chain processes have made it imperative to integrate Supply Chain Resilience (SCR) and Sustainable Supply Chain Management (SSCM) into one theory framework. Most theories of resilience in supply chains stress the importance of the capability of the supply chains to predict, resist, adapt, and recover from the disruptions while ensuring continuity (Ponomarov & Holcomb, 2009). On the other hand, most theories of sustainability deal with balancing the aspects of environment protection, economic viability, and social responsibility with efficiency and responsibility for the environment (Carter & Rogers, 2008). Most recent studies show that resilience and sustainability complement each other in improving the performance and competitiveness of green energy supply chains (Rajabzadeh & Wiens, 2024; Hosseini Shekarabi et al., 2025).

The supply chain for renewable energy is especially susceptible to disruption due to geopolitics, climate-related events, scarcity of crucial minerals, transport difficulties, and market uncertainties. Organizations have to develop flexible, agile, redundant, collaborative, visible, and adaptive supply chains while pursuing sustainability measures such as the circular economy, green procurement, renewable energy, carbon emission reduction, minimal wastage, and responsible sourcing.

The sustainable practices will not only help organizations address environmental concerns but also increase their supply chain resilience through reduced reliance on rare resources, diversification of the supply base, and adaptive capability amidst uncertainty.

From the above theoretical framework, this research puts forward an integrated conceptual model to explain the connection between resilience and sustainability in the green energy industry. In this research, the model suggests that the concept of resilience is dependent on resilience capability and sustainability management practices, which is represented by:

$$SCR_{\text{sustainable}} = \alpha\ (\text{Flexibility} + \text{Redundancy} + \text{Agility}) + \beta\ (\text{Sustainability Practices})$$

Where α and β represent weighting coefficients that quantify the relative contributions of resilience capabilities and sustainability practices to the overall resilience of the supply chain. The variables *Flexibility*, *Redundancy*, and *Agility* represent the operational dimensions of resilience, whereas *Sustainability Practices* encompass environmental, economic, and social initiatives implemented across the supply chain.

The proposed framework posits that the implementation of sustainability practices would directly enhance supply chain resilience through efficiency of resources, diversification of suppliers, use of circular material flow, reduction of environmental risks, and adaptive capacity of the renewable energy supply chain. Thus, companies that would effectively combine the concepts of resilience and sustainability would be more capable of withstanding disruptions and ensuring continuity of business operations in transitioning towards sustainable energy supply systems.

8. Fuzzy Optimization Model

8.1. Model Objective

The green energy supply chain faces many uncertainties because of the unpredictable nature of demand, interruptions in the availability of important minerals, transportation issues, political tensions, and environmental constraints.

Consequently, there is a need for multi-objective optimization decision-making in order to optimize resilience and sustainability alongside cost, carbon emissions, and risk of disruption reduction (Ponomarov &

Holcomb, 2009; Christopher & Peck, 2004; Ivanov & Dolgui, 2020).

The proposed fuzzy multi-objective optimization model is expressed as

$$\text{Max } Z = \lambda_1 R + \lambda_2 S - \lambda_3 C - \lambda_4 E - \lambda_5 D$$

Where,

- R = Supply Chain Resilience Index
- S = Sustainability Index
- C = Total Supply Chain Cost
- E = Carbon Emissions
- D = Disruption Risk
- λ_i = Relative importance weights

Subject to

$$\sum_{i=1}^{5} \lambda_i = 1, \lambda_i \geq 0$$

This formulation extends the sustainable supply chain framework proposed by Carter and Rogers (2008) by integrating resilience and environmental performance into a unified optimization model.

8.2. Supply Chain Resilience Function

The concept of supply chain resilience is depicted by the aggregation of resilience capabilities in the field of logistics and operations management literature, which are as follows: flexibility, agility, redundancy, visibility, and collaboration (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009; Scholten & Schilder, 2015).

$$R = w_1F + w_2A + w_3Re + w_4V + w_5Co$$

Where,

- F = Flexibility
- A = Agility
- Re = Redundancy
- V = Supply Chain Visibility
- Co = Collaboration

Subject to

$$\sum w_i = 1$$

These resilience dimensions collectively enhance the adaptive capacity of renewable energy supply chains under uncertain operating environments (Ivanov & Dolgui, 2020).

8.3. Sustainability Function

According to Carter and Rogers' (2008) Sustainable Supply Chain Management framework and Elkington's (1997) Triple Bottom Line (TBL) theory, sustainability is defined as:

$$S = \alpha En + \beta Ec + \gamma So$$

Where,

- En = Environmental Sustainability
- Ec = Economic Sustainability
- So = Social Sustainability

Subject to

$$\alpha+\beta+\gamma = 1$$

Throughout the renewable energy supply chain, the sustainability index takes into account social responsibility, economic viability, resource efficiency, and environmental stewardship (Seuring & Müller, 2008; Ahi & Searcy, 2013).

8.4. Total Cost Function

The total supply chain cost is

$$C = Cp + Ct + Ci + Cr + Cd$$

Where,

- Cp = Procurement Cost
- Ct = Transportation Cost
- Ci = Inventory Cost
- Cr = Recovery Cost
- Cd = Disruption Cost

This formulation follows sustainable logistics optimization models proposed by Dekker et al. (2012).

8.5. Carbon Emission Function

Reducing greenhouse gas emissions from production, transportation, warehousing, and logistical activities is necessary for environmental sustainability (Geissdoerfer et al., 2017).

$$E = \sum_{i=1}^{n} ei\,Qi$$

Where,

- ei = Emission coefficient
- Qi = Quantity transported or processed

8.6. Fuzzy Membership Functions

Zadeh's (1965) fuzzy set theory offers a suitable mathematical framework for modeling imprecise information because resilience, sustainability, supplier reliability, transit time, operational expenses, and carbon emissions are all characterized by uncertainty.

(a) Resilience Membership Function

$$\mu_R(R) = \begin{cases} 0, & R \leq R_{min} \\ R - R_{min} / R_{max} - R_{min}, & R_{min} < R < R_{max} \\ 1, & R \geq R_{max} \end{cases}$$

(b) Sustainability Membership Function

$$\mu_s(S) = \begin{cases} 0, & S \leq S_{min} \\ S - S_{min} / S_{max} - S_{min}, & S_{min} < S < S_{max} \\ 1, & S \geq S_{max} \end{cases}$$

(c) Cost Membership Function

$$\mu_c(C) = \begin{cases} 1, & C \leq C_{min} \\ C_{max} - C / C_{max} - C_{min}, & C_{min} < C < C_{max} \\ 0, & C \geq C_{max} \end{cases}$$

(d) Carbon Emission Membership Function

$$\mu_E(E) = \begin{cases} 1, & E \le E_{min} \\ E_{max} - E / E_{max} - E_{min}, & E_{min} < E < E_{max} \\ 0, & E \ge E_{max} \end{cases}$$

These linear membership functions follow the classical fuzzy optimization approach introduced by Zimmermann (1978, 1996).

8.7. Fuzzy Optimization Model

Using Zimmermann's fuzzy max–min decision approach,
Max λ

Subject to,

$\mu_R(R) \ge \lambda$

$\mu_S(S) \ge \lambda$

$\mu_C(C) \ge \lambda$

$\mu_E(E) \ge \lambda$

$0 \le \lambda \le 1$

The optimal satisfaction level (λ) indicates the degree to which resilience, sustainability, environmental performance, and economic objectives are simultaneously achieved under uncertain conditions (Zimmermann, 1996).

8.8. Green Supply Chain Resilience Index (GSCRI)

The integrated performance indicator is defined as

$$GSCRI = \omega_1 R + \omega_2 S - \omega_3 C - \omega_4 E - \omega_5 D$$

Where,
$\sum \omega_i = 1$

A higher GSCRI reflects superior operational resilience, sustainability performance, and environmental efficiency within green energy supply chains. This integrated index combines the dynamic capability perspective (Teece et al., 1997; Teece et al., 2016), sustainable supply chain theory (Carter & Rogers, 2008), and circular economy principles (Kirchherr et al., 2017; Geissdoerfer et al., 2017).

9. Results and Discussion

The designed fuzzy optimization model was designed to analyze the interplay between SCR and Sustainability in green energy supply chains amid an uncertain operating environment. The design of the model involves the inclusion of the dimensions of SCR (resilience flexibility, resilience agility, resilience redundancy, resilience visibility, and resilience collaboration), sustainability (environmental, economic, and social performance), operational costs, carbon emissions, and disruption risks into one unified model. As opposed to the conventional optimization models whose parameters are considered to be deterministic in nature, the fuzzy optimization model utilizes fuzzy membership functions to accommodate the uncertainties associated with real-life renewable energy supply chains (Zimmermann, 1996; Ponomarov & Holcomb, 2009). Fuzzy optimization solutions show that by combining the capacity of resilience with sustainable processes, there is an enhancement of the general performance of the green energy supply chain. The process of optimization is used to maximize the total satisfaction (ʎ), which stands for the extent to which the conflicting objectives of economy, environment, and resilience are satisfied at the same time.

From the optimization process, it can be established that supplier flexibility, redundancy of inventory, and real-time visibility play a critical role in enhancing resilience factors leading to operational continuity in disruptions. This is corroborated by earlier researches which have shown that resilient supply chains require adaptability rather than merely minimizing costs (Christopher & Peck, 2004; Scholten & Schilder, 2015). Organizations utilizing diversification of suppliers and inventories have been seen to demonstrate higher resilience in the face of logistics challenges, political risks, and minerals essential for renewable energy technologies.

Conversely, practices in sustainability, such as green procurement, utilization of renewable energy, reduction of waste, and circular resource management, had a positive effect on resilience performance. From the optimization model, the more money invested in sustainability practices, the more resilient an organization becomes because the reliance on scarce natural resources reduces. It corroborates the theory of sustainable supply chain developed by Carter and Rogers (2008), whereby the implementation of environmental and social practices yields economic benefits in the long run and makes an organization resilient. There was a strong positive correlation between the integration of the sustainability index and the resilience index. Environmental sustainability improvements, such as greenhouse gas emission reduction, utilization of renewable energy sources, and recycling programs, were correlated to improved resilience performance. The circular economy helped organizations reduce reliance on virgin resources, including scarce minerals such as lithium, cobalt, nickel, and rare earth elements.

In this regard, it can be noted from the outcomes of the fuzzy optimization that organizations practicing sustainable supplier selection and environmentally friendly logistics practices had relatively low disruption risks than traditional supply chains. In this respect, it can be said that sustainability needs to be viewed not only as an environmental goal but also as a resilient capability in times of uncertainties. While resilience approaches such as inventory redundancies and supplier diversification initially come at a higher cost, the optimization approach clearly shows that such extra costs get compensated by a substantial reduction of disruption costs in the long run. Carbon emissions have also been reduced to a great extent through transportation planning, renewable energy application, and increased efficiency in the use of resources. In the case of the fuzzy optimization approach, transportation routes and suppliers that had lower emission coefficients were considered, and hence, there was an improvement in the environmental performance.

The study corroborates the earlier literature on the vital importance of environmental sustainability for supply chain optimization (Dekker et al., 2012; Seuring & Müller, 2008). The use of Industry 4.0 technologies such as AI, IoT, blockchain, digital twins, and big data analysis contributes to increasing the level of supply chain resilience, transparency, forecasting accuracy, and adaptive decision-making under uncertainty. Proactive disruption management and risk reduction become possible through real-time monitoring. The developed fuzzy optimization model can be used for selecting suppliers, optimizing inventories, and planning low-carbon transportation. It represents an innovation due to the consideration of such theories as Supply Chain Resilience Theory (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009), Sustainable Supply Chain Management Theory (Carter & Rogers, 2008; Seuring & Müller, 2008), Dynamic Capability Theory (Teece et al., 1997, 2016), and Fuzzy Optimization Theory (Zimmermann, 1996). In general, the study shows that resilience and sustainability complement each other, making the green energy supply chain more reliable, environmentally responsible, economically viable, and adaptive.

10. Policy Implications

A transition towards green energy will depend on policies that not only build resilience in the supply chains but, at the same time, promote sustainability. Governments can be instrumental in the process through their efforts to invest in, regulate and coordinate in order to make supply chains more resilient, foster the adoption of renewable energy sources, and ensure energy security (Ponomarov & Holcomb, 2009; Hosseini Shekarabi et al., 2025). Government policies can include investments in renewable energy infrastructure, development of renewable energy sources, innovations, advanced manufacturing practices, and use of financial instruments like tax credits, grants, low-interest loans, and public-private partnerships in order to increase the level of domestic production and decrease reliance on a few countries around the world as suppliers. Also, government investments in digital technologies, such as AI, blockchain, IoT, and big data analytics, can contribute to increased supply chain visibility, risk management, and decision-making (Rajabzadeh & Wiens, 2024). The circular economy approach can be promoted by governments in order to decrease resource dependence and build resilience (Carter & Rogers, 2008; Geissdoerfer et al., 2017).

11. Future Research Directions

Future work on sustainable green energy supply chains needs to focus on developing resilient assessment and optimization models to deal with disruptions due to geopolitical tensions, climate change, critical minerals scarcity, and market uncertainties. Optimization, stochastic programming, system dynamics, and Multi-Criteria Decision-Making (MCDM) techniques could greatly help in increasing the resilience of supply chains (Ivanov & Dolgui, 2020; Hosseini Shekarabi et al., 2025). Digital tools, such as AI, machine learning, digital twins, blockchain, IoT, and big data analytics, could be used for improving the accuracy of demand forecasting, assessment of supplier risks, optimization of inventories, monitoring of the supply chain, increasing transparency, and adaptation of decisions (Rajabzadeh & Wiens, 2024; Ivanov, 2024). Future research should test the theoretical frameworks through empirical studies in the renewable energy industries, namely solar photovoltaic, wind, hydrogen, biomass, and battery production in fast-growing economies, like India, Brazil, South Africa, Indonesia, and African countries. Comparative industry studies in line with global climate targets and UN Sustainable Development Goals (SDGs) would be helpful (Carter & Rogers, 2008; Ponomarov & Holcomb, 2009).

12. Conclusion

The shift towards renewable energy has necessitated the existence of resilient and sustainable supply chains that can withstand the growing level of uncertainties due to geopolitical tensions, climate change, resource depletion, disruptions in transport, and changing environmental policies. The paper shows that SCR and SSCM are complementary competences that need to be combined rather than pursued separately. The paper offers a fuzzy multi-objective optimization model that allows for a decision support model that optimizes resilience, sustainability, and efficiency in a context of uncertainties. The use of fuzzy set theory allows for more realistic modeling of uncertainties associated with supplier reliability, inventory levels, transport delays, disruptions, costs, and carbon emissions.

From the results, it can be noted that the application of sustainable processes, such as green purchasing, adoption of the circular economy approach, use of renewable resources, diversification of suppliers, and environmental logistics, plays a major role in boosting adaptive capacity and increasing efficiency while minimizing ecological footprint. However, the employment of technological components of Industry 4.0 that encompass artificial intelligence, Internet of Things (IoT), blockchain, digital twin and big data analytics enhances the visibility and predictability. While the suggested model is a theoretical one and requires empirical investigation, it is still a powerful theoretical foundation for further research. In other words, the study contributes significantly to the development of resilient and low-carbon renewable energy supply chains by integrating the theories of resilience, sustainability and fuzzy optimization.

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