



A Systems-Based Framework for Deep Decarbonization in Closed-Loop Wind Energy Supply Chains

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ABSTRACT

Objective: The transition toward low-carbon energy systems requires supply chains that support deep decarbonization while maintaining economic and operational performance. This study aims to identify and evaluate key deep decarbonization indicators in a sustainable closed-loop supply chain for wind energy logistics and to determine the most suitable supplier/location alternative.

Methods: A hybrid decision-making framework is developed by integrating Critical Systems Heuristics (CSH) with the Combined Compromise Solution (CoCoSo) and Fuzzy CoCoSo methods. CSH is employed to structure the problem context and identify relevant stakeholders and sustainability indicators. Based on expert evaluations from a panel of 16 specialists, the identified criteria are used within the CoCoSo and Fuzzy CoCoSo models to rank potential alternatives. A sensitivity analysis is further conducted to examine the robustness of the obtained rankings.

Results: The results indicate that the selected criteria, covering economic, environmental, and social sustainability as well as reverse logistics considerations, significantly influence supplier selection in a closed-loop wind energy supply chain. The analysis shows that the Isfahan alternative achieves the highest ranking in both the CoCoSo and Fuzzy CoCoSo models. Sensitivity analysis under different weight perturbations confirms the stability and reliability of the ranking outcomes.

Conclusion: This study contributes to the literature by combining systems thinking with multi-criteria decision-making techniques to assess deep decarbonization indicators in a closed-loop wind energy supply chain. The integration of CSH with CoCoSo and Fuzzy CoCoSo offers a novel and comprehensive approach for addressing sustainability challenges in renewable energy logistics.

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1. Introduction

Deep decarbonization, defined as the profound and persistent reduction of greenhouse gas (GHG) emissions across economic sectors, has become a central pathway for confronting climate change (Bataille et al., 2020). It requires lowering emissions to near-zero levels by mid-century (Canales-Bustos et al., 2017, Govindan et al., 2023), an objective that will demand transformative changes in energy systems (Taghipour et al., 2023b, Taghipour et al., 2024), transportation, industry (Taghipour et al., 2023c, Taghipour et al., 2023d), and agriculture. Monitoring the effectiveness and direction of these decarbonization initiatives is essential for assessing global progress and shaping future strategies (Atabaki et al., 2023). In 2021, worldwide GHG emissions reached an unprecedented 36.7 Gt of CO₂-equivalent, with the energy sector alone responsible for nearly 70% of the total (Yang et al., 2022). Without aggressive mitigation, emissions will continue to escalate, amplifying the consequences of climate change. Although renewable energy capacity is expanding, it still represents only about 13% of global electricity production (Ehsanifar et al., 2023, Taghipour et al., 2024). Likewise, electric vehicle adoption is rising but still forms a modest share of the global transport fleet (Roshandel et al., 2023). Particularly challenging are emissions from heavy industrial processes such as cement and steel production, which demand innovative decarbonization pathways (Turki et al., 2017).

More than 120 nations have announced commitments to achieve net-zero emissions, yet many lack the detailed policies or actionable roadmaps required to meet these pledges (Babaeinesami et al., 2022). Carbon pricing mechanisms are expanding worldwide, but their scope and price levels often fall short of what is needed to drive deep decarbonization (Canales-Bustos et al., 2017). Beyond preventing severe climate impacts, including extreme weather events and rising sea levels, deep decarbonization can yield significant economic and societal benefits, such as new employment opportunities, improved air quality, and long-term reductions in energy costs (Govindan et al., 2023). Postponing action will only raise the financial and technological challenges associated with future mitigation efforts (Karlsson et al., 2020). The International Energy Agency (IEA) estimates that achieving global net-zero emissions by 2050 will require annual increases of roughly 7% in clean energy investment up to 2030, while the Intergovernmental Panel on Climate Change (IPCC) stresses that limiting warming to 1.5°C will require swift and far-reaching systemic changes (Xu et al., 2023). This urgency highlights the essential role of deep decarbonization in advancing climate resilience and sustainability objectives. Within this context, sustainable supply chain management (SSCM) has emerged as a crucial lever for reducing emissions and improving environmental performance throughout product lifecycles. SSCM encompasses every phase, from raw material sourcing to manufacturing, distribution, end-of-life treatment, and recycling (Karlsson et al., 2020).

The sustainable supply chain is a vital component of deep decarbonization strategies as it encompasses the entire lifecycle of a product, from raw material extraction to end-of-life disposal or recycling (Khazaei et al., 2023, Taghipour et al., 2023a). Integrating sustainability considerations into supply chain operations enables organizations to lower their carbon footprint, reinforce environmental responsibility, and enhance long-term competitiveness (Atabaki et al., 2019). Complementing this, the circular economy framework promotes resource efficiency, waste minimization, and material recovery, all of which support decarbonization goals (Atabaki et al., 2020). Circular practices such as reuse, remanufacturing, and recycling help reduce reliance on virgin resources, decrease emissions, and foster a more regenerative industrial system (Foukolaei et al., 2024, Gholian-Jouybari et al., 2024). Achieving deep decarbonization while maintaining sustainable supply chain performance requires an integrated perspective that can address the complex interactions among economic, environmental, social, and circularity-related decisions. Closed-loop supply chains are particularly important in this context because they connect forward logistics with reverse flows, including product return, recycling, reuse, refurbishment, and waste recovery. These activities are central to reducing lifecycle emissions, improving resource efficiency, and supporting circular economy objectives. However, the design and evaluation of such systems remain challenging because decision-makers must consider uncertain demand, changing carbon policies, supplier capabilities, reverse logistics constraints, and stakeholder expectations at the same time.

The present study develops a hybrid systems thinking and multi-criteria decision-making framework for evaluating deep decarbonization indicators in a sustainable closed-loop wind energy supply chain. The proposed framework

integrates Critical Systems Heuristics (CSH), Combined Compromise Solution (CoCoSo), and Fuzzy CoCoSo. CSH is used to structure the problem context, identify relevant stakeholders, and organize the key evaluation criteria. CoCoSo is then applied to rank supplier alternatives using crisp performance data, while Fuzzy CoCoSo is employed to capture uncertainty and ambiguity in expert-based evaluations. A sensitivity analysis is also conducted to examine the robustness of the ranking results under small variations in input data.

Accordingly, the main objectives of this study are: 1) to identify and structure deep decarbonization indicators for sustainable closed-loop wind energy supply chains; 2) to evaluate supplier alternatives by integrating systems thinking with CoCoSo and Fuzzy CoCoSo; 3) to examine the consistency of supplier rankings under crisp and fuzzy decision-making environments; and 4) to assess the robustness of the results through sensitivity analysis. The scope of the study is limited to supplier evaluation in Iran's wind energy sector, with a focus on economic, technical, social, environmental, and circular supply chain criteria.

The contribution of this research is 3-fold. First, it extends the closed-loop supply chain literature by shifting attention from network optimization alone toward a systems-based indicator evaluation framework for deep decarbonization. Second, it contributes methodologically by combining CSH with CoCoSo and Fuzzy CoCoSo, thereby linking qualitative boundary critique with quantitative supplier ranking. Third, it provides practical insights for renewable energy supply chain managers by identifying supplier alternatives that are better aligned with decarbonization, circularity, and sustainability objectives.

The remainder of the paper is organized as follows. Section 2 reviews the literature on deep decarbonization, sustainable supply chain management, circular economy, and wind energy supply chains. Section 3 presents the methodological framework, including the CSH procedure and the CoCoSo and Fuzzy CoCoSo methods. Section 4 describes the case study, input data, criteria, and supplier alternatives. Section 5 reports the results, including the crisp and fuzzy rankings and sensitivity analysis. Section 6 discusses the findings and managerial implications. Finally, Section 7 concludes the study by summarizing the key findings, limitations, and recommendations for future research.

2. Literature Review

2.1 Deep decarbonization through supply chain

A comprehensive literature review on deep decarbonization in the supply chain can be constructed based on the research findings provided. The literature review highlights the integration and synthesis of the research insights and identify potential future research directions and knowledge gaps. In this regard, Liu et al. (2022) discussed the application of AI-based manufacturing and management techniques to achieve long lifetime batteries, which can contribute to deep decarbonization in the supply chain. Furthermore, Ozkan et al. (2022) emphasized the progress in carbon dioxide capture materials as a significant step towards deep decarbonization. Giri et al. (2022) introduced the Pythagorean fuzzy DEMATEL method for supplier selection in sustainable supply chain management. This method can be potentially applied to select suppliers that align with deep decarbonization goals. Moreover, the study by Al-Awamleh et al. (2022) demonstrated the effect of green supply chain practices on sustainability in the pharmaceutical industry, indicating the importance of sustainable practices for deep decarbonization. Lee et al. (2022) conducted two empirical studies on the impact of digital supply chain and IoT adoption on organizational performance in the manufacturing industry.

Sharma et al. (2022) proposed a conceptual model for the adoption of autonomous robots in the supply chain and logistics industry. This model can be extended to explore the role of autonomous robots in reducing carbon emissions and achieving deep decarbonization. Kurdi et al. (2022) also investigated the effect of blockchain and smart inventory systems on supply chain performance, which can contribute to deep decarbonization efforts. Alshurideh et al. (2022) examined the influence of supply chain partner integration on organizational performance, highlighting the moderating role of trust. This finding suggests the importance of collaborative relationships in achieving deep decarbonization goals. Aityassine et al. (2022) focused on the effect of supply chain resilience on the supply chain performance of chemical industrial companies, which can be extended to explore the resilience needed for deep decarbonization

efforts. Wong et al. (2022) emphasized the use of artificial intelligence-driven risk management for enhancing supply chain agility, which can be an important factor in navigating the complexities of deep decarbonization efforts. Finally, Ivanov and Dolgui (2022) discussed the shortage economy and its implications for supply chain and operations management, highlighting potential challenges that need to be addressed in the context of deep decarbonization.

Recent studies highlight that supply chain decarbonization is a dynamic, multi-dimensional challenge beyond simple emission reduction. Chen et al. (2026) show that achieving both low-carbon and resilient closed-loop supply chains requires additional investment, especially in capacity redundancy. Apata (2025) proposes an adaptive multi-energy planning framework integrating system interactions and stakeholder collaboration. Mubarik et al. (2025) find that supply chain innovation and mapping enhance decarbonization by improving visibility and decision-making. Hao and Khan (2025) note that decarbonization efforts can also create transition-related disruptions if not carefully managed.

2.2 The wind turbine supply chain

The rapid expansion of wind energy has led to significant challenges in managing the end-of-life (EOL) waste from wind turbine blades. Majewski et al. (2022) highlight the urgent need for legislative frameworks to handle the increasing blade waste, which is difficult to recycle due to the composite materials used. Current disposal methods, such as landfilling, incineration, and limited recycling, are insufficient, with only 30% of the fiber-reinforced plastic being reused, mostly in the cement industry. Similarly, Cooperman et al. (2021) project that by 2050, the U.S. will face approximately 2.2 million tons of blade waste, stressing the need for advancements in recycling technologies and policy shifts to foster a circular economy. Lichtenegger et al. (2020) provide a regional forecast for Europe, identifying Germany and the UK as major contributors to onshore and offshore blade waste, respectively, by 2050. They emphasize the importance of local strategies and circular economy pathways to manage the fluctuating waste levels. The dynamics of green supply chain management (GSCM) are crucial in addressing these challenges within the renewable energy sector. Gawusu et al. (2022) discuss how GSCM integrates environmental, economic, and social components to balance performance and meet regulatory pressures, advocating for strategies like eco-efficiency and cleaner production. This is particularly relevant given the reliance on rare-earth elements (REs) for wind turbines, as highlighted by Li et al. (2020), who predict that meeting global wind power targets will require a 11- to 26-fold increase in RE production. They emphasize the need for global cooperation to overcome geopolitical and environmental constraints in the RE supply chain. Shields et al. (2021) explore cost reductions through turbine and plant upsizing, which can decrease the levelized cost of energy by over 23%, further supporting the need for technological innovations and strategic planning. Additionally, Ren et al. (2021) review the state-of-the-art in offshore wind turbine maintenance, identifying areas for optimization and the need to mitigate environmental impacts, which is critical for the sustainability of offshore wind farms.

Recent studies also show that renewable energy supply chains must be examined through broader sustainability, logistics, and resource-recovery perspectives. Chen et al. (2025) analyzed carbon dioxide emissions and mitigation strategies in China's hydrogen energy supply chain and emphasized the importance of renewable energy integration, green supplier selection, and policy support in reducing lifecycle emissions. In the wind energy context, Zupok et al. (2025) reviewed the U.S. wind energy market and identified policy uncertainty, grid limitations, infrastructure constraints, and supply chain disruptions as key barriers to further wind power development. Kosek et al. (2025) focused on offshore wind farm supply chains in the Central Baltic Region and highlighted the strategic role of ports, logistics infrastructure, and local supply chain participation in supporting offshore wind deployment. Furthermore, Cristiu et al. (2025) developed an optimization model for critical raw materials recycling in renewable energy technologies, including neodymium magnets from wind turbines, and showed that recycling infrastructure and facility location decisions are essential for resilient and sustainable renewable energy supply chains.

2.3 Gaps and contributions

The literature review on deep decarbonization in supply chains uncovers critical gaps and novelties, emphasizing the complex challenge of integrating deep decarbonization strategies with circular economy principles. It points out the absence of a cohesive framework for incorporating circular economy principles into supply chain strategies to achieve deep decarbonization. Furthermore, it highlights the lack of comprehensive indicators for measuring progress towards deep decarbonization, suggesting the need for a mixed systems thinking approach to develop these indicators, considering the intricate interdependencies within supply chains. The review also identifies a shortfall in applying systems thinking to implement deep decarbonization indicators, as well as a gap in research on the systematic application to support decarbonization efforts. Additionally, it notes the underexplored areas of supply chain collaboration and trust in driving decarbonization initiatives and the necessity of addressing supply chain resilience in the context of decarbonization. These gaps underscore the need for innovative research and approaches that leverage systems thinking and embrace the principles of the circular economy to advance deep decarbonization in supply chains effectively.

3. Methods and Materials

The methodology for this study involves a systematic approach to develop and structure deep decarbonization indicators within a sustainable supply chain context. The process begins with a comprehensive literature review to establish a theoretical foundation, followed by the formation of an expert panel to provide diverse insights. CSH is then employed to uncover underlying assumptions and values. Next, key quantitative and qualitative indicators are developed and evaluated using the CoCoSo and Fuzzy CoCoSo methods. A case study of Iran's wind energy sector is conducted to apply these indicators in a real-world context. Sensitivity analysis is performed to assess the robustness of the findings, followed by detailed results analysis and interpretation (Figure 1).

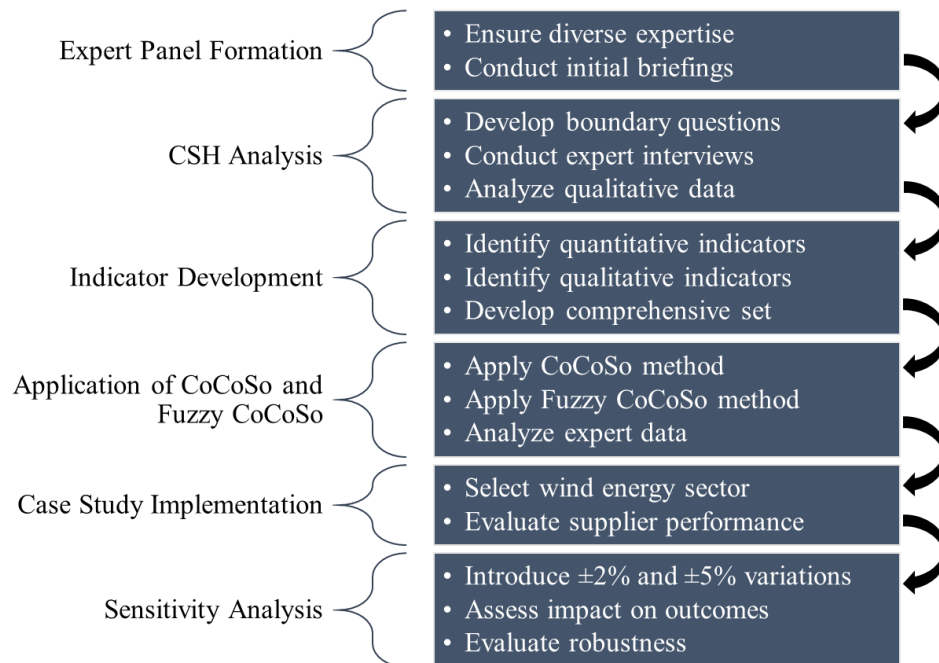


Figure 1. Schematic process of proposed methodology.

3.1 Critical Systems Heuristics

In the pursuit of embedding deep decarbonization indicators within sustainable supply chains, conducting a CSH approach (Mirhosseini et al., 2021, Nayeri et al., 2022, Ramezani et al., 2021) offers a robust framework for exploring the systemic complexities and decision-making boundaries. The methodology employed involved assembling a panel of 16 experts, each with distinct insights into various facets of sustainability, supply chain management, and decarbonization. The panel comprised individuals from diverse backgrounds, including academia, industry, and non-governmental organizations, to ensure a comprehensive and balanced perspective. Appendix A provides an overview of the interviewees' fields of expertise, organizational types, educational qualifications, and other relevant demographics while preserving confidentiality (Ulrich and Reynolds, 2020). The core of the CSH approach centered on deep, semi-structured interviews guided by boundary questions, designed to identify assumptions, values, and perspectives that shape decision-making processes. These boundary questions were meticulously crafted to probe four critical domains: sources of motivation, sources of power, sources of knowledge, and sources of legitimacy (Khazaei et al., 2021a). By dissecting these domains, the research aimed to illuminate the hidden constraints and opportunities within the current systems, and to uncover innovative pathways towards integrating deep decarbonization indicators into sustainable supply chain practices (Khazaei et al., 2021b).

The same panel of 16 experts participated in the CSH interviews, BWM-based criteria weighting, and CoCoSo/Fuzzy CoCoSo performance scoring. To reduce the risk of circularity and bias, these stages were conducted sequentially and with distinct purposes: CSH was used to identify and structure the decision context and criteria, BWM was used to elicit criteria weights, and CoCoSo/Fuzzy CoCoSo scoring was used to evaluate supplier alternatives. The experts were asked to reassess each stage independently, and the aggregated results were reviewed for consistency before being used in the final analysis. Each interview was conducted as a deep dive into the expert's understanding and vision for a decarbonized future, focusing on the systemic challenges and opportunities for embedding sustainability into supply chains. The discussions were designed to be open-ended yet structured enough to ensure comprehensive exploration of the boundary conditions that define the operational, strategic, and ethical limits and potentials of sustainable supply chain management.

The qualitative CSH findings were operationalized into the quantitative evaluation framework through a traceability process. First, the boundary critique discussions were coded into recurring themes related to economic feasibility, operational capability, environmental performance, social responsibility, and circular supply chain readiness. These themes were then translated into the 10 evaluation criteria used in the CoCoSo and Fuzzy CoCoSo models. For example, stakeholder concerns about affordability and supply continuity were reflected in Cost (C1) and Capacity (C2), while concerns about emission reduction, renewable energy use, labor conditions, waste handling, recycling, and reverse logistics were reflected in C3 to C10. The BWM procedure was then used to assign weights to these criteria based on expert judgments.

The analysis of these interviews relied on qualitative data analysis techniques to synthesize the insights into a coherent framework. This framework aimed to identify common themes, divergences in perspectives, and to distill actionable strategies for incorporating deep decarbonization indicators. The findings from this research underscored the importance of adopting a holistic, systems-oriented approach to sustainability, highlighting the interdependencies between environmental, social, and economic dimensions. Ultimately, the application of critical systems heuristics illuminated the multifaceted challenges and opportunities inherent in driving deep decarbonization within supply chains. By engaging directly with a diverse panel of experts and leveraging their insights through deep interviews guided by boundary questions, this research contributes valuable perspectives to the ongoing discourse on sustainable supply chain management and the integration of decarbonization efforts. The outcomes not only provide a roadmap for businesses and policymakers but also offer a methodological blueprint for future research in the realm of sustainable and resilient supply chain design.

3.2 CoCoSo and Fuzzy CoCoSo

CSH, CoCoSo, and Fuzzy CoCoSo were selected because they provide complementary methodological advantages for this study. CSH was used because the identification of deep decarbonization indicators requires stakeholder-based problem structuring and boundary critique rather than only numerical weighting. CoCoSo was selected because it combines multiple aggregation strategies and provides a compromise-based ranking, making it suitable for evaluating suppliers across conflicting economic, environmental, social, and circularity criteria. Compared with methods such as TOPSIS or VIKOR, CoCoSo considers both additive and multiplicative aggregation logic, which improves the balance between overall performance and relative compromise. Fuzzy CoCoSo was added to address uncertainty and ambiguity in expert judgments, which are common in sustainability and decarbonization evaluations.

To assess deep decarbonization indicators within a sustainable supply chain context, a comparative study employing both the CoCoSo (Yazdani et al., 2019) method and its Fuzzy counterpart (Fuzzy CoCoSo) was conducted (Ecer and Pamucar, 2020). This investigation sought to leverage the expertise of 16 experts in fields spanning environmental science, supply chain management, and sustainability assessment, aiming to achieve a nuanced evaluation of relevant indicators. The CoCoSo method, recognized for its effectiveness in multi-criteria decision-making (MCDM) (Khazaei et al., 2023), was chosen to facilitate an objective evaluation of decarbonization indicators. This method computes a composite score for each indicator based on predetermined criteria, weighting, and the performance of each indicator. To begin, the experts were asked to identify and define the most crucial indicators for deep decarbonization within the supply chain. Subsequently, they provided weights for each criterion based on their significance towards achieving sustainability and decarbonization objectives.

In parallel, the Fuzzy CoCoSo method (Pamucar and Görçün, 2022) was deployed to address the inherent uncertainties and subjective judgments often encountered in expert evaluations. This approach extends the conventional CoCoSo by incorporating fuzzy logic, allowing experts to express their assessments and preferences in more flexible terms, such as linguistic variables, which are then converted into fuzzy numbers. The process involved two main stages: firstly, the experts assessed the indicators using both the CoCoSo and Fuzzy CoCoSo methods independently. For CoCoSo, they provided precise numerical values for each criterion's weight and the performance of each indicator. In contrast, for Fuzzy CoCoSo, their assessments were expressed in terms of linguistic terms (e.g., high, medium, low), which were subsequently translated into fuzzy numbers.

Following the data collection, the assessments were processed using the respective algorithms of each method. The CoCoSo method aggregated the weighted performance scores of each indicator to identify the most effective decarbonization strategies. Meanwhile, the Fuzzy CoCoSo method utilized fuzzy arithmetic and defuzzification processes to achieve a similar goal, but with the added benefit of accommodating the vagueness and ambiguity inherent in expert judgments. Comparing the results from both methods can provide insightful contrasts and corroborations. The comparison highlights the robustness of certain indicators across both methodologies, underscoring their critical role in deep decarbonization efforts. It also illuminates areas where expert opinions diverged, particularly in scenarios where the flexibility of fuzzy logic captured nuances that traditional numerical assessments could not. This comparative study of CoCoSo and Fuzzy CoCoSo methods, enriched by the deep expertise of the panel, offers a comprehensive framework for evaluating deep decarbonization indicators in sustainable supply chains. By elucidating the strengths and limitations of each method, the research contributes to the refinement of decision-making tools in sustainability assessments, offering a nuanced approach to navigating the complexities of deep decarbonization.

4. Results

Iran's wind energy sector is experiencing a period of significant growth and development, marking its position as a notable player in the renewable energy landscape of the Middle East. With a total installed capacity that has reached impressive figures in recent years, the country is on a steadfast path toward harnessing the potential of wind as a sustainable and eco-friendly source of power (Ghaedi et al., 2024). The Iranian government, recognizing the immense benefits and the necessity of diversifying energy resources, has set ambitious targets aiming for a substantial increase

in installed wind energy capacity within the coming years. These goals are supported by detailed plans and strategies, outlined by entities such as the Iranian Ministry of Energy and also the Iranian Renewable Energy Organization (SUNA), which emphasize the country's commitment to expanding its renewable energy footprint, particularly in wind power generation.

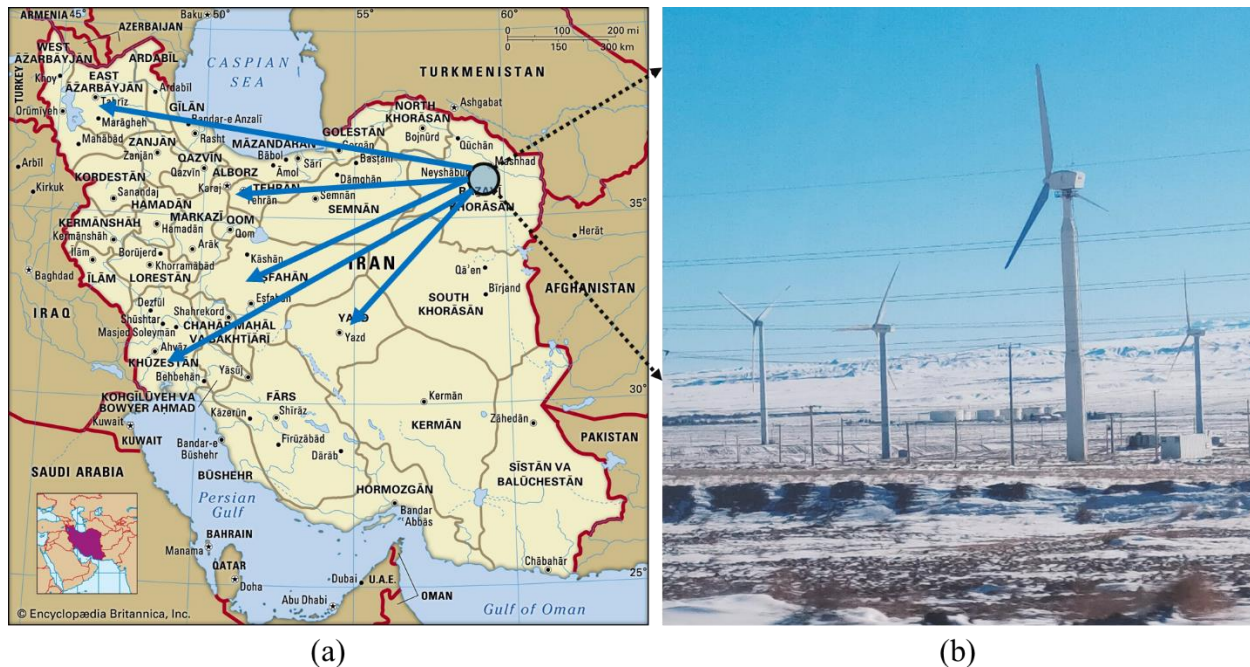


Figure 2. (a) The locations of the parts suppliers and (b) the wind site of Razavi Khorasan (Source: Encyclopedia Britannica).

Despite the promising advancements in wind energy production, Iran faces significant challenges in the areas of wind turbine recycling, repair, and refurbishment. The composite materials used in wind turbine blades, known for their durability and strength, pose a considerable challenge when it comes to recycling, echoing a global issue within the wind energy sector. This predicament highlights the need for Iran to explore and invest in sustainable methods and technologies for wind turbine recycling, ensuring that the environmental footprint of wind energy remains minimal. Moreover, the importance of establishing a skilled workforce and facilities dedicated to the regular maintenance, repair, and refurbishment of wind turbines cannot be overstated. Such initiatives are essential for maximizing the efficiency and operational lifespan of wind turbines, thereby enhancing the overall sustainability of Iran's wind energy sector. The Figure 2 shows a map of Iran with arrows indicating the supply routes from various regions (such as Isfahan and Yazd) to Razavi Khorasan, along with an image of wind turbines located at a wind site in Razavi Khorasan, highlighting the area's focus on wind energy production.

4.1 CSH findings

In this analysis, the application of CSH to the realm of manufacturing and supply chain operations unveils a comprehensive understanding of the intricate balance between cost efficiency, supplier and production capacity, alongside sustainability and recycling efforts. By systematically dissecting the criteria groups into specific factors, this study aims to shed light on the multifaceted challenges and opportunities present in achieving sustainable operational excellence.

The criteria presented in Table 1 provide a comprehensive framework for evaluating suppliers, encompassing economic, technical, social, environmental, and circular supply chain dimensions. Economic and technical criteria include "Cost (C1)" and "Capacity (C2)," which are crucial for assessing the financial viability and scalability of suppliers. These criteria ensure that suppliers can meet demand efficiently without compromising on cost-effectiveness. Additionally, "Carbon Emissions Per Unit (C3)" and "Renewable Energy Utilization (C4)" are essential for evaluating the environmental impact of suppliers, focusing on reducing carbon footprints and increasing the use of sustainable energy sources in production processes. These metrics are vital for promoting eco-friendly practices and aligning with deep decarbonization goals.

The social and environmental criteria further enhance the framework by addressing ethical and sustainability concerns. "Workplace Safety (C5)" and "Job Security (C6)" are included to ensure that suppliers provide safe and stable working environments, reflecting a commitment to social responsibility. Environmental criteria such as "Waste Management (C7)" and "Material Recycling Rate (C8)" evaluate suppliers' effectiveness in minimizing waste and promoting recycling, supporting the principles of the circular economy. Moreover, the "Circular Supply Chain" criteria, including "Recycling and Reuse Facilities (C9)" and "Product Return Ease (C10)," emphasize the importance of resource sustainability and the ease of returning products for recycling or reuse. This multifaceted approach not only measures supplier performance and reliability but also their adherence to sustainability and ethical standards, fostering a holistic view of supply chain management.

Table 1. Criteria groups, criteria, and descriptions.

Categories	Criteria	Description	References
Economic and Technical	Cost (C1)	Evaluates the cost of the supplier in delivering products or services, ensuring economic viability without compromising quality.	(Taghipour et al., 2023a, Turki et al., 2017, Zhu et al., 2022)
	Capacity (C2)	Assesses the supplier's ability to meet demand volumes, considering their production capacity and scalability to respond to market changes.	(Atabaki et al., 2020, Foukolaei et al., 2024)
Social and Environmental	Carbon Emissions Per Unit (C3)	Measures the amount of carbon emissions produced per unit of product manufactured, aiming for lower emissions to support decarbonization efforts.	(Keshavarz-Ghorbani and Pasandideh, 2022, Yang et al., 2022)
	Renewable Energy Utilization (C4)	Examines the proportion of renewable energy used in the supplier's production processes, promoting the shift towards cleaner energy sources.	(Tsiliyannis and Tsiliyannis, 2019)
Circular Supply Chain	Workplace Safety (C5)	Focuses on the safety conditions within the supplier's operations, including accident rates, ergonomic practices, and overall health and safety standards.	(Salehi-Amiri et al., 2022, Soleimani et al., 2022, Song et al., 2023)
	Job Security (C6)	Considers the stability of employment offered by the supplier, including contractual adherence, insurance benefits, and fairness in labor practices.	(Fathollahi-Fard et al., 2018, Salehi-Amiri et al., 2022, Zhu et al., 2022)
	Waste Management (C7)	Evaluates the effectiveness of the supplier's practices in safely disposing of waste to prevent environmental pollution.	(de Souza et al., 2016, Ehsanifar et al., 2023, Ramezani et al., 2024, Gholian-Jouybari et al., 2024)
	Material Recycling Rate (C8)	Assesses the percentage of materials that can be recycled from the supplier's products, promoting material recovery and reuse in new products.	
	Recycling and Reuse Facilities (C9)	Looks at the availability and sophistication of facilities for recycling and reusing materials within the supplier's operations.	(Govindan et al., 2017, Song et al., 2023)
	Product Return Ease (C10)	Examines the ease with which products or materials can be returned to the supplier or collected for reuse or recycling, enhancing the circularity of resources.	(Dulman and Gupta, 2018)

4.2 Input data

Appendix A details the input data for CoCoSo, presenting a structured approach to evaluate suppliers based on distinct criteria ranging from cost efficiency to sustainability and recycling capabilities. These criteria, quantified for suppliers across different regions, reflect the intricate balance between economic considerations, such as purchasing costs, and capacities. This methodical assessment aims to reveal cost-effective and sustainable partnerships that bolster the supply chain's reliability and efficiency, ensuring a stable procurement of raw materials and products. The performance scores reported in Appendices B and C were obtained through expert-based assessment. First, each expert independently evaluated the supplier alternatives with respect to the selected criteria. The individual evaluations were then reviewed and aggregated to obtain the final crisp scores used in Appendix B. For Appendix C, expert judgments were expressed using linguistic assessments and converted into fuzzy numbers to capture uncertainty and subjective variation in the evaluation process.

Transitioning to a more nuanced evaluation, Appendix B introduces the Fuzzy CoCoSo input data, enhancing the decision-making framework with the flexibility of fuzzy logic to handle uncertainties and subjective judgments inherent in supplier selection. This adaptation allows for a more refined analysis, where criteria weights and supplier scores are expressed in ranges, reflecting the inherent variability and uncertainty in assessing supplier performance across different dimensions. Such an approach acknowledges the complexity of real-world scenarios, where exact values are often elusive, and decisions must be made under conditions of partial knowledge. By incorporating fuzzy logic, this advanced methodology provides a comprehensive and adaptable framework for evaluating suppliers, ensuring that decisions are robust, nuanced, and reflective of the multifaceted nature of supplier relationships in the contemporary business landscape. To verify the reliability of the BWM-based weight elicitation process, the consistency ratio was calculated for the expert comparisons. The obtained consistency ratios were within the acceptable range, indicating that the pairwise comparisons were sufficiently reliable and that the derived criteria weights could be used in the subsequent CoCoSo and Fuzzy CoCoSo analyses.

4.3 Suppliers' characteristics

Supplier Tehran 1 specializes in advanced wind turbine components with high-cost efficiency and moderate carbon emissions. Yazd, known for its sustainable practices, excels in waste management and renewable energy utilization. Isfahan, a leader in innovative recycling technologies, has the highest material recycling rate and renewable energy integration. Tabriz focuses on large-scale production capacity and workplace safety, maintaining robust environmental standards. Tehran 2 is characterized by its efficient logistics network and moderate capacity, prioritizing cost-effectiveness. Tehran 3 offers strong job security and advanced reuse facilities, supporting circular supply chain initiatives. Lastly, Ahvaz stands out for its high renewable energy usage and comprehensive recycling facilities, demonstrating strong environmental stewardship.

The weightings used in the CoCoSo method, as presented in Appendix A, are designed to ensure a balanced evaluation of suppliers across multiple criteria. In the CoCoSo method, three weights (0.113 each) are equal, reflecting a consensus from experts using the Best Worst Method (BWM) for weightings (Khazaei et al., 2021b). BWM is a multi-criteria decision-making approach that involves selecting the best (most important) and worst (least important) criteria from a set, then evaluating other criteria relative to these extremes. This method provides a structured way to determine optimal weights for each criterion, ensuring consistency and reducing judgmental error in decision-making (Ramezani et al., 2021). The equal weighting was based on expert consensus, indicating that these criteria were considered equally important in the context of the evaluation. The equal weights help ensure a fair comparison across these key criteria, without giving undue emphasis to any single aspect. In contrast, the Fuzzy CoCoSo method employs different weightings for each criterion, as shown in Appendix B. This variation reflects the inherent uncertainties and subjective judgments that come into play when experts evaluate different criteria's importance. The use of BWM for determining these weights allows for a more nuanced approach, where experts' opinions on the relative importance of

each criterion are incorporated into the fuzzy logic framework. This approach helps capture the complexities and uncertainties of real-world decision-making, providing a more flexible and adaptable evaluation model.

4.4 CoCoSo and Fuzzy CoCoSo results

The analysis contrasting the results from the CoCoSo and Fuzzy CoCoSo methodologies sheds light on distinct approaches to supplier evaluation. In the CoCoSo method, rankings are determined by evaluating supplier performance across three indices (Ka, Kb, and Kc), which cumulatively produce a final score (K) for each supplier. This method clearly delineates a hierarchy among the suppliers, positioning Isfahan as the top performer, followed by Tehran1 and Tabriz as evidenced by their respective final rankings in Table 2.

Table 2. CoCoSo final results.

Supplier	Ka	Ranking	Kb	Ranking	Kc	Ranking	K	Final Ranking
Tehran 1	0.1610	1	2.8471	3	0.9855	1	2.0985	2
Yazd	0.1335	6	2.3773	6	0.8173	6	1.7472	6
Isfahan	0.1511	4	3.0121	1	0.9246	4	2.1119	1
Tabriz	0.1527	3	2.9329	2	0.9347	3	2.0881	3
Tehran 2	0.1116	7	2.0000	7	0.6829	7	1.4656	7
Tehran 3	0.1357	5	2.6254	4	0.8309	5	1.8639	5
Ahvaz	0.1544	2	2.6050	5	0.9452	2	1.9594	4

Conversely, the Fuzzy CoCoSo method integrates fuzzy logic to manage uncertainty and imprecision inherent in supplier evaluations. This method derives Fuzzy Fi scores across three components (Fuzzy Fia, Fuzzy Fib, and Fuzzy Fic), which are then translated into definitive Crisp Fi values. These values are aggregated into a Final Score Fi, culminating in a nuanced ranking of supplier performance. According to the Fuzzy CoCoSo analysis shown in Table 3, Isfahan also ranks highest, affirming its superior performance. However, in this fuzzy context, Ahvaz and Tabriz receive elevated rankings relative to their CoCoSo outcomes, illustrating how the incorporation of uncertainty affects supplier assessment.

Table 3. Fuzzy CoCoSo final results.

Supplier	Fuzzy Fia			Fia		Fuzzy Fib			Fib		Fuzzy Fic			Fic		Final Score	Ranking
Tehran 1	0.091	0.139	0.237	0.155	4.406	8.121	13.108	8.545	0.586	0.770	0.910	0.756	4.153			4	
Yazd	0.073	0.130	0.226	0.143	3.297	6.903	11.602	7.267	0.471	0.718	0.869	0.686	3.591			6	
Isfahan	0.114	0.161	0.260	0.178	7.528	11.852	16.903	12.094	0.740	0.890	1.000	0.877	5.620			1	
Tabriz	0.106	0.154	0.253	0.171	6.634	10.774	15.705	11.038	0.684	0.855	0.973	0.838	5.181			3	
Tehran 2	0.073	0.138	0.235	0.149	4.295	8.454	13.098	8.616	0.473	0.764	0.904	0.714	4.130			5	
Tehran 3	0.035	0.126	0.222	0.128	2.000	6.419	10.928	6.449	0.225	0.697	0.855	0.592	3.177			7	
Ahvaz	0.103	0.153	0.250	0.168	6.938	11.021	15.529	11.163	0.664	0.846	0.961	0.824	5.209			2	

The comparison between these methodologies reveals that while CoCoSo offers a direct and structured evaluation, Fuzzy CoCoSo introduces flexibility by accommodating uncertainties in the assessment process. This adaptability leads to variations in the rankings, showcasing the sensitivity of supplier evaluation to the chosen method. Isfahan's consistent top position across both methods highlights its strong performance across all criteria. The variations seen in other suppliers' rankings under different methodologies underscore the importance of choosing a suitable evaluation method that matches the decision-maker's uncertainty tolerance and the particular demands of the supplier selection process.

4.5 Sensitivity analysis

As part of the sensitivity analysis, we introduced variations of $\pm 2\%$ and $\pm 5\%$ to the input data for both the CoCoSo and Fuzzy CoCoSo models. These percentages were selected to examine the impact of minor data fluctuations on the final decision-making outcomes for a set of alternatives. This approach helps evaluate the stability and reliability of the models under varying conditions, providing insights into their robustness in real-world applications where input data may be subject to slight inaccuracies or uncertainties. This methodical analysis aimed to uncover the inherent sensitivity of the models to fluctuations in input data, thereby providing insights into the stability and reliability of the models under conditions of uncertainty. The outcomes highlighted a distinct responsiveness across the alternatives, showcasing how even minor perturbations in the input data could lead to noticeable shifts in the models' outputs. Such findings underscore the critical importance of data accuracy and the need for robust decision-support systems that can accommodate and adapt to data variability, thereby ensuring that decision-makers can rely on the resilience and adaptability of these models in real-world scenarios marked by inherent uncertainties and dynamic changes.

Table 4. Sensitivity analysis of CoCoSo and Fuzzy CoCoSo.

Alternatives	Crisp CoCoSo		Fuzzy CoCoSo	
	K ($\pm 2\%$)	K ($\pm 5\%$)	Fi ($\pm 2\%$)	Fi ($\pm 5\%$)
Tehran 1	1.937	1.916	3.345	3.485
Yazd	1.467	1.414	3.163	3.355
Isfahan	2.809	2.758	3.862	4.081
Tabriz	2.514	2.492	3.245	3.392
Tehran 2	1.754	1.752	3.608	3.819
Tehran 3	1.923	1.889	3.257	3.387
Ahvaz	2.073	2.046	2.670	2.749

The sensitivity analysis of both Crisp CoCoSo and Fuzzy CoCoSo models (Table 4 and Figure 3), incorporating input data adjustments of $\pm 2\%$ and $\pm 5\%$, illuminates the potential impact of minor data variations on final decision-making outcomes. This examination is instrumental in gauging the resilience and susceptibility of each model to changes in input data, offering valuable insights for enhancing decision accuracy and reliability.

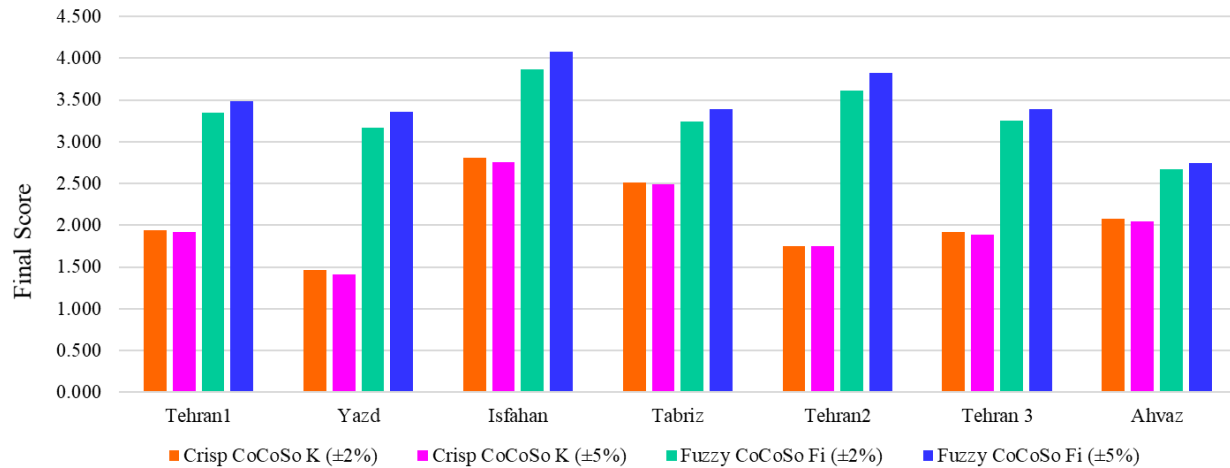


Figure 3. CoCoSo and Fuzzy CoCoSo results in sensitivity analysis.

In the Crisp CoCoSo model, variability analysis reveals significant sensitivity in the ranking of alternatives like Isfahan, which exhibits the largest score fluctuation (2.809 to 2.758 with a $\pm 2\%$ change and a more pronounced divergence with $\pm 5\%$). This suggests its position is particularly susceptible to input alterations. Conversely, Tehran2 demonstrates remarkable stability (1.754 to 1.752 with a $\pm 2\%$ change), underscoring its robustness against input variability. The nuanced changes across alternatives hint that even minor data modifications could potentially shuffle the rankings, especially among closely scored options such as Tehran1, Tabriz, and Tehran2. The Fuzzy CoCoSo model, by comparison, reveals a heightened sensitivity to input data adjustments, as seen through wider score gaps for both $\pm 2\%$ and $\pm 5\%$ changes. For instance, Isfahan's score increments from 3.862 to 4.081 with a $\pm 5\%$ change highlights its considerable responsiveness. Despite this variability, alternatives like Tehran2 consistently exhibit greater sensitivity in both models, suggesting some options inherently possess a higher volatility to input shifts across different analytical frameworks. The incorporation of fuzziness appears to magnify the effects of data variations, possibly due to considering a broader array of evaluative possibilities, rendering the system more attuned to input data changes. These dynamic underscores the critical balance between precision and adaptability in decision-making tools, especially under conditions of uncertainty.

The sensitivity analysis underscores the paramount importance of precise and reliable data in the decision-making process. For alternatives with narrow scoring margins, slight data adjustments can lead to different recommendations, emphasizing the necessity for decision-makers to account for the stability of their selections amidst uncertain conditions. Choosing between the Crisp and Fuzzy CoCoSo models should reflect the specific decision context's inherent uncertainties. In scenarios marked by ambiguous or subjective data, the Fuzzy CoCoSo model may offer richer insights, albeit with a predisposition towards greater input sensitivity. Moreover, recognizing the volatility of different alternatives can aid in risk management, identifying which options are more susceptible to shifts in the decision-making landscape, a consideration crucial for strategic planning and contingency management.

4.6 Criteria-wise Performance Interpretation

To deepen the interpretation of the ranking results, a criteria-wise comparison of supplier performance was conducted using the input data reported in Appendix B. Figure 4 presents a normalized heatmap of supplier performance across the 10 evaluation criteria. For benefit criteria, higher normalized values indicate better performance, while for cost-type criteria, including Cost (C1) and Carbon Emissions Per Unit (C3), lower original values were converted into higher normalized performance scores. This visualization helps identify the criteria that most strongly differentiate the supplier alternatives.

The criteria-wise comparison shows that no supplier dominates across all criteria. Instead, each supplier has a distinct performance profile. Isfahan achieves the highest final ranking because it performs strongly on several high-impact sustainability and circular supply chain criteria, particularly Renewable Energy Utilization (C4), Workplace Safety (C5), Job Security (C6), and Material Recycling Rate (C8). These strengths compensate for its weaker performance in some cost-type or reverse-logistics-related criteria. Since Job Security (C6) has the highest weight in the crisp CoCoSo model, Isfahan's strong performance in this criterion is particularly important in explaining its leading position. Moreover, its high performance in renewable energy utilization and material recycling rate makes it highly aligned with the deep decarbonization and circular economy objectives of the study.

Tabriz also shows strong performance in several technical and environmental criteria, especially Capacity (C2), Carbon Emissions Per Unit (C3), Renewable Energy Utilization (C4), Workplace Safety (C5), and Material Recycling Rate (C8). This explains why it remains among the top-ranked alternatives in the crisp CoCoSo results. Ahvaz performs particularly well in Waste Management (C7), Material Recycling Rate (C8), and moderate social performance, which explains why it becomes more attractive in the Fuzzy CoCoSo model, where uncertainty and judgmental flexibility are better captured. Tehran 1 performs well in Product Return Ease (C10), Waste Management (C7), and Recycling and Reuse Facilities (C9), suggesting that it has relatively strong reverse logistics and circularity capabilities. However, its lower performance in renewable energy utilization and workplace safety limits its overall ranking.

By contrast, Yazd and Tehran 2 show weaker overall performance across several important criteria. Yazd has moderate performance in waste management, material recycling, and recycling facilities but weaker performance in renewable energy utilization and job security. Tehran 2 benefits from a relatively favorable cost position but performs weakly in Capacity (C2), Renewable Energy Utilization (C4), Material Recycling Rate (C8), Recycling and Reuse Facilities (C9), and Product Return Ease (C10). Therefore, Tehran 2's case demonstrates that cost advantage alone is not sufficient for achieving strong performance in a deep decarbonization-oriented supplier selection framework.

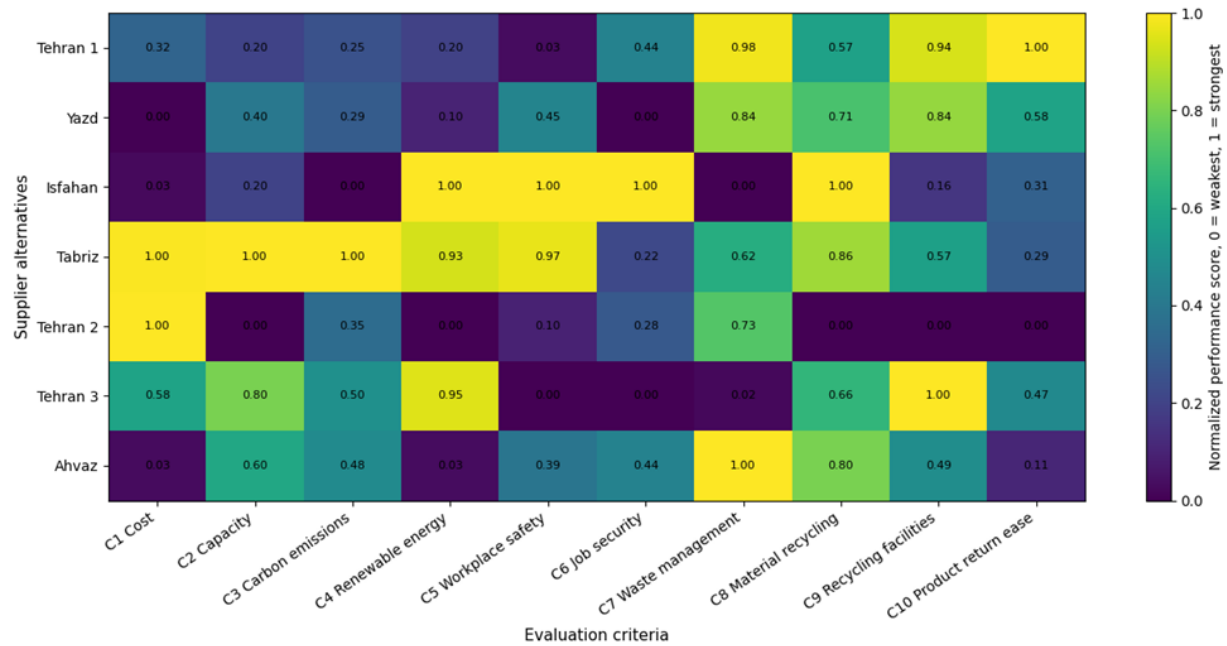


Figure 4. Normalized criteria-wise performance heatmap of supplier alternatives.

The sensitivity analysis provides additional decision-support insights beyond score fluctuations. Under the crisp CoCoSo scenarios, the leading alternatives remain relatively stable, with Isfahan maintaining the strongest position under both $\pm 2\%$ and $\pm 5\%$ perturbations. This indicates that, when decision-makers rely on precise input data, Isfahan can be considered the most robust supplier choice. Tabriz also remains a strong candidate under crisp perturbations, mainly because of its strong performance in capacity, emissions, renewable energy utilization, and workplace safety. Therefore, for decision-makers prioritizing operational scale and measurable environmental performance, Tabriz may serve as a reliable secondary option.

The Fuzzy CoCoSo results provide a different but complementary perspective. Because fuzzy modeling captures uncertainty in expert judgments, alternatives with broader or more flexible sustainability performance profiles may become more attractive under uncertainty. In this context, Ahvaz improves in the base Fuzzy CoCoSo ranking compared with the crisp CoCoSo ranking, suggesting that its performance in circular and sustainability-related dimensions becomes more favorable when ambiguity in expert evaluations is considered. This is important for real-world decision-making because supplier data in renewable energy supply chains are often incomplete, imprecise, or judgment-based. Therefore, if decision-makers face high uncertainty in supplier assessments, the Fuzzy CoCoSo results suggest that Ahvaz and Tabriz should receive closer managerial attention alongside Isfahan.

From a practical perspective, the comparison between crisp and fuzzy models indicates that supplier selection should not be treated as a single deterministic ranking exercise. If the decision environment is data-rich and performance values are reliable, the crisp CoCoSo ranking provides a direct and transparent basis for supplier selection. However, if supplier data are uncertain, incomplete, or based heavily on expert judgment, the Fuzzy CoCoSo ranking

provides a more cautious decision-support perspective. In both cases, Isfahan remains the most consistent alternative, supporting its selection as the benchmark supplier. At the same time, the sensitivity results show that Ahvaz and Tabriz should be considered as strategically important alternatives, especially under uncertain or sustainability-oriented decision conditions.

5. Discussion and Managerial Insights

The findings of this study provide practical insights into how deep decarbonization indicators can be used to support supplier evaluation in a sustainable closed-loop wind energy supply chain. The results show that supplier selection should not be based only on traditional economic and technical factors, such as cost and capacity. Instead, managers should also consider environmental, social, and circular supply chain criteria, including carbon emissions per unit, renewable energy utilization, workplace safety, job security, waste management, material recycling rate, recycling and reuse facilities, and product return ease. The consistency between the CoCoSo and Fuzzy CoCoSo results, particularly the top ranking of Isfahan, indicates that suppliers with stronger performance across sustainability and circularity-related indicators are better positioned to support deep decarbonization objectives.

The ranking results can be translated into supplier-specific improvement strategies. Isfahan, which ranked 1st in both CoCoSo and Fuzzy CoCoSo, can be considered a benchmark supplier. Managers should maintain Isfahan's strong performance by strengthening traceability systems, expanding recycling partnerships, and using this supplier as a pilot case for advanced repair, refurbishment, and recycling programs in the wind energy sector. Ahvaz ranked 4th in the crisp CoCoSo model but improved to 2nd in the Fuzzy CoCoSo model, suggesting that it performs well under uncertainty, particularly in sustainability-related dimensions. Ahvaz should focus on improving operational reliability, documenting environmental performance, and converting its circular capabilities into measurable supplier commitments. Tabriz ranked among the top 3 alternatives and appears to be a strong candidate for large-scale supply activities. However, its future improvement should focus on product return mechanisms, material recovery, and systematic carbon monitoring.

Tehran 1 ranked 2nd in the crisp CoCoSo model but 4th in the Fuzzy CoCoSo model, indicating that its performance is relatively strong but more sensitive when uncertainty is considered. Therefore, Tehran 1 should prioritize renewable energy use, emissions monitoring, and more transparent reporting of circular supply chain practices. Tehran 3 showed moderate performance and should focus on improving workplace safety, waste management, and supplier-level environmental management systems. Yazd ranked 6th in both models, suggesting that it requires targeted improvement before it can become a strong decarbonization-oriented supplier. Its priorities should include increasing renewable energy utilization, strengthening job security practices, improving product return systems, and investing in measurable recycling performance. Tehran 2 had the weakest position in the crisp CoCoSo ranking and should be treated as a supplier development case rather than an immediate priority supplier. Although Tehran 2 benefits from relatively low cost, its low performance in capacity, renewable energy use, circular infrastructure, and product return ease indicates that cost competitiveness alone is insufficient for supporting deep decarbonization. Managers should require Tehran 2 to implement a phased improvement plan before assigning it a strategic role in the wind energy supply chain.

At the policy level, the findings can support national energy planning in Iran by showing that wind energy development requires more than expanding installed capacity. A sustainable wind energy transition also requires circular infrastructure for maintenance, repair, refurbishment, recycling, and end-of-life recovery. Policymakers can use the proposed criteria to design supplier qualification standards, green procurement policies, and investment incentives for low-carbon and circular suppliers. The results also suggest that high-performing suppliers such as Isfahan can be used as benchmark cases, while weaker suppliers such as Tehran 2 and Yazd require targeted supplier development programs. This approach can help Iran reduce the environmental footprint of wind energy supply chains, improve domestic supplier capability, and prepare for future growth in wind turbine waste and critical material recovery.

6. Conclusion

This study developed a systems-based decision-making framework for evaluating deep decarbonization indicators in a sustainable closed-loop wind energy supply chain. By integrating CSH, CoCoSo, and Fuzzy CoCoSo, the proposed framework connects qualitative problem structuring with quantitative supplier evaluation. The CSH stage helped identify and organize the main criteria affecting deep decarbonization, including economic and technical performance, social and environmental responsibility, and circular supply chain capabilities. The results demonstrate that supplier evaluation in renewable energy supply chains should not be limited to traditional economic indicators, such as cost and capacity. Environmental and circularity-related indicators, including carbon emissions per unit, renewable energy utilization, waste management, material recycling rate, recycling and reuse facilities, and product return ease, play a critical role in supporting deep decarbonization objectives. These indicators are particularly relevant in the wind energy sector, where end-of-life management, repair, recycling, and refurbishment of wind turbine components are essential for reducing environmental impacts.

The application of both CoCoSo and Fuzzy CoCoSo showed that Isfahan achieved the highest overall performance among the evaluated supplier alternatives. This consistent result across both crisp and fuzzy models indicates that Isfahan has a strong position in terms of the selected sustainability and circular supply chain criteria. The comparison between the 2 methods also showed that incorporating uncertainty through Fuzzy CoCoSo can affect the relative ranking of some alternatives, especially when expert judgments involve ambiguity or imprecision. Therefore, using both crisp and fuzzy evaluation methods provides a more comprehensive understanding of supplier performance. The sensitivity analysis further confirmed the robustness of the proposed decision-making framework. By applying $\pm 2\%$ and $\pm 5\%$ variations to the input data, the study examined the stability of the supplier rankings under minor data fluctuations. The results showed that the main ranking pattern remained generally stable, particularly for the top-performing alternative. This finding supports the reliability of the proposed framework for decision-making in complex and uncertain supply chain environments.

Despite its contributions, this study has several limitations. The empirical application was limited to Iran's wind energy supply chain. Although this context provides valuable insights into supplier evaluation for renewable energy logistics, the results may not be directly generalizable to other countries, energy sectors, or industrial supply chains without further validation. Moreover, the criteria weights and supplier performance scores were derived from expert judgments. Although the study used a diverse expert panel and applied fuzzy modeling to address uncertainty, expert-based evaluations may still be influenced by subjectivity, professional background, and access to information. Future studies could strengthen the framework by combining expert assessments with operational, environmental, and financial data from real supply chain records.

Future research can extend this study in several directions. First, the proposed framework should be tested in other renewable energy sectors, such as solar, hydrogen, bioenergy, and battery supply chains, to examine its applicability across different sustainability and decarbonization contexts. Comparative studies across multiple sectors or countries could also help identify sector-specific and region-specific deep decarbonization indicators. Second, future studies should develop more detailed and measurable indicators for evaluating circularity and decarbonization performance. For example, future frameworks may include lifecycle greenhouse gas emissions, recycling efficiency, remanufacturing potential, waste recovery rates, energy intensity, supplier compliance with environmental standards, and traceability of recovered materials. Such indicators would improve the practical relevance and measurement accuracy of supplier evaluation models. Third, future research could integrate the proposed MCDM framework with mathematical optimization models. Combining CoCoSo or Fuzzy CoCoSo with models for location-allocation, routing, production planning, or reverse logistics network design would allow decision-makers to move beyond ranking alternatives and toward designing more efficient and low-carbon closed-loop supply chains. Fourth, digital technologies should be further examined as enablers of deep decarbonization in renewable energy supply chains. Technologies such as blockchain, Internet of Things (IoT), artificial intelligence, and digital twins can improve transparency, traceability, predictive maintenance, and lifecycle monitoring of wind turbine components. Future

studies could investigate how these technologies support better data collection, more accurate supplier evaluation, and improved circular supply chain performance.

Author Contributions

Pooria Hashemzahi: Conceptualization; Problem definition; Modelling; Investigating the data; Software; Validation; Analyzing; Writing; Methodology; Conclusion.

Mohammad Mohammadi: Supervision; Conceptualization; Problem definition; Methodology; Verifying the models and results; Reviewing and editing.

Mohammad Saeid Atabaki: Consulting; Problem definition; Validation; Methodology; Conclusion;

Data Availability Statement

Not applicable

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Ethical considerations

The authors avoided data fabrication, falsification, and plagiarism, and any form of misconduct.

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Conflict of interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, ChatGPT was used only for language editing, grammatical correction, and improving readability. The tool was not used for data collection, data analysis, methodology development, result generation, interpretation of findings, or drawing conclusions. The authors reviewed, edited, and approved all AI-assisted language revisions and take full responsibility for the content of the manuscript.

Appendices

Appendix A. Overview of interview panel characteristics.

Interviewee ID	Field of Expertise	Organization Type	Age Range	Highest Degree	Years of Experience
E1	Renewable Energy Systems	Academia	40–50	PhD	15
E2	Environmental Policy	Non-Governmental Org.	30–40	Master's	10
E3	Decarbonization Strategies	Industry	50–60	PhD	20
E4	Supply Chain Analytics	Academia	30–40	PhD	12
E5	Sustainable Logistics	Industry	40–50	Master's	15
E6	Circular Economy	Non-Governmental Org.	30–40	Master's	10
E7	Energy Management	Academia	30–40	PhD	8
E8	Renewable Energy Policy	Governmental Org.	50–60	Master's	25
E9	Corporate Sustainability Practices	Industry	40–50	Master's	18
E10	Carbon Emissions Assessment	Academia	30–40	PhD	10
E11	Environmental Management	Industry	50–60	Bachelor's	25
E12	Recycling and Waste Management	Non-Governmental Org.	40–50	Master's	15
E13	Energy Systems Engineering	Academia	30–40	PhD	7
E14	Industrial Engineering	Industry	30–40	Master's	12
E15	Environmental Science	Academia	40–50	PhD	20
E16	Decarbonization Policy	Governmental Org.	50–60	Master's	25

Appendix B. CoCoSo input data.

Weights	0.113	0.113	0.113	0.109	0.109	0.193	0.087	0.036	0.1	0.036
Supplier	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Tehran1	2163	18	6.125	2.625	1.25	5.5	8.5	6.75	8	8.75
Yazd	2449	19	5.875	1.875	2.875	3.5	7.75	7.375	7.375	5.875
Isfahan	2425	18	7.625	8.75	5	8	3	8.625	3	4
Tabriz	1568	22	1.625	8.25	4.875	4.5	6.5	8	5.625	3.875
Tehran2	1564	17	5.5	1.125	1.5	4.75	7.125	4.25	2	1.875
Tehran 3	1936	21	4.625	8.375	1.125	3.5	3.125	7.125	8.375	5.125
Ahvaz	2422	20	4.75	1.375	2.625	5.5	8.625	7.75	5.125	2.625

Appendix C. Fuzzy CoCoSo input data.

Weights	0.168	0.211	0.254	0.276	0.33	0.365	0.118	0.158	0.211	0.095	0.102	0.123	0.095	0.102	0.123
Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Tehran1	0.6375	0.775	0.85	0.125	0.325	0.575	0.375	0.575	0.7625	0.05	0.175	0.35	0.0375	0.1625	0.35
Yazd	0.725	0.875	0.95	0.05	0.15	0.325	0.375	0.575	0.775	0.025	0.1125	0.275	0.05	0.1875	0.375
Isfahan	0.375	0.575	0.7625	0.3	0.5	0.6875	0.45	0.65	0.8375	0.725	0.8875	0.975	0.2875	0.475	0.675
Tabriz	0.1375	0.2625	0.425	0.575	0.775	0.925	0.5	0.7	0.8625	0.65	0.8375	0.9625	0.175	0.35	0.55
Tehran2	0.0625	0.1875	0.375	0.1125	0.275	0.475	0.4	0.6	0.7875	0	0.025	0.15	0.0125	0.0875	0.25
Tehran 3	0.3125	0.5	0.7	0.1125	0.275	0.475	0.5	0.7	0.875	0.75	0.9125	0.9875	0.0125	0.0625	0.2
Ahvaz	0.775	0.925	0.9875	0.775	0.925	0.9875	0.3	0.5	0.7	0.025	0.1	0.25	0.1125	0.275	0.475
Weights	0.178	0.221	0.264	0.025	0.044	0.083	0.168	0.211	0.254	0.276	0.33	0.365	0.118	0.158	0.211
Criteria	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
Tehran1	0.3	0.5	0.7	0.575	0.775	0.925	0.1625	0.35	0.55	0.375	0.575	0.775	0.1625	0.35	0.55
Yazd	0.125	0.2875	0.475	0.525	0.725	0.9	0.1875	0.375	0.575	0.325	0.525	0.725	0.1875	0.375	0.575
Isfahan	0.6	0.8	0.95	0.3	0.5	0.7	0.6125	0.8375	1.0125	0.5	0.7	0.875	0.525	0.725	0.875
Tabriz	0.15	0.325	0.525	0.525	0.725	0.9	0.35	0.55	0.7375	0.325	0.525	0.725	0.35	0.55	0.7375
Tehran2	0.35	0.55	0.7375	0.5875	0.7375	0.8375	0.0875	0.25	0.45	0.4125	0.5875	0.7375	0.0875	0.25	0.45
Tehran 3	0.15	0.325	0.525	0.1375	0.3	0.5	0.0625	0.2	0.4	0.0375	0.1375	0.3	0.0625	0.2	0.4
Ahvaz	0.4	0.6	0.7875	0.875	0.9875	1	0.275	0.475	0.675	0.675	0.875	0.9875	0.275	0.475	0.675

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