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A framework for sustainable circular energy supply chain management with an Industry 4.0 approach: Application of the Fuzzy-ISM method in Iran's oil and petrochemical industries

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1. ABSTRACT

With the expansion of sustainability requirements, the transition to a circular economy in the energy industry become a strategic necessity. The aim of the research is to provide a framework for explaining the relationships between factors affecting the sustainable circular energy supply chain based on Industry 4.0. The research is qualitative-quantitative. The population is managers of the Iranian oil and petrochemical industry, 22 people interviewed using snowball sampling. Fuzzy Interpretive Structural Modeling used to analyze the relationships. Industry 4.0 technologies and supply chain digitalization play the main driving role of the system, data management and smart decision-making play an intermediary role. Governance and policy-making act as the institutional infrastructure, and operational performance and supply chain resilience as the final output of the system. Oil and petrochemical industry managers make targeted investments in digital energy technologies, integrate ESG requirements into energy supply chain strategy, and develop digital human resources skills.

Keywords: Circular economy, Industry ۴/۰, Energy supply chain, Sustainability, Oil and petrochemical industry

2. INTRODUCTION

Introduction The growing global emphasis on sustainability, resource efficiency, and environmental protection has accelerated the transition toward circular economy (CE) models across energy-intensive industries. The energy sector particularly oil, gas, and petrochemical industries faces increasing pressure to reduce carbon emissions, optimize resource utilization, and improve environmental performance while maintaining operational efficiency and economic competitiveness. Traditional linear supply chain models, which follow a take-make-dispose approach, are increasingly being replaced by circular supply chain systems that emphasize resource recovery, waste minimization, lifecycle optimization, and sustainable production. At the same time, the emergence of Industry 4.0 technologies including the Internet of Things (IoT), big data analytics, artificial intelligence (AI), cloud computing, and cyber-physical systems has created new opportunities for improving transparency, traceability, real-time monitoring, and intelligent decision-making in energy supply chains. These digital technologies are considered key enablers of circular economy implementation because they facilitate data-driven optimization of resource flows, predictive maintenance, energy efficiency, and smart asset lifecycle management. Despite growing research on circular economy and Industry 4.0, there is still a lack of integrated frameworks that explain how technological, data-driven, governance, and operational factors interact to enable

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sustainable circular energy supply chains. Moreover, energy supply chains operate under high uncertainty, technological complexity, and multi-stakeholder environments, which require advanced modeling approaches capable of handling ambiguity and expert knowledge. Therefore, this study aims to develop a structural framework for sustainable circular energy supply chain management based on Industry 4.0 using Fuzzy Interpretive Structural Modeling (Fuzzy-ISM) and Fuzzy MICMAC analysis.

3. MATERIALS AND METHODS

This study adopts an applied research approach with a mixed qualitative-quantitative methodology. Initially, a comprehensive literature review was conducted to identify key factors influencing sustainable circular energy supply chain management in the context of Industry 4.0. The identified factors were then refined and validated through expert consultation. The empirical phase of the research relied on expert judgment collected from specialists in the energy sector, supply chain management, sustainability management, and digital transformation. A purposive sampling method was used to select experts with significant academic or industrial experience. Expert opinions were collected using structured questionnaires based on pairwise comparison of factors using linguistic variables. To analyze complex interrelationships among factors under uncertainty, Fuzzy Interpretive Structural Modeling (Fuzzy-ISM) was applied. Fuzzy logic was integrated into ISM to capture the vagueness and subjectivity of expert judgments. The Fuzzy-ISM process involved developing the Structural Self-Interaction Matrix (SSIM), converting it into the initial reachability matrix, generating the final reachability matrix, and determining hierarchical levels among variables. In addition, Fuzzy MICMAC analysis was used to classify variables based on driving power and dependence power. This method allowed the identification of driver variables, linkage variables, dependent variables, and autonomous variables, providing deeper insight into the systemic structure of sustainable circular energy supply chains.

4. RESULTS AND DISCUSSION

The results reveal a multi-layered structural model representing the hierarchical relationships among technological, data-driven, governance, and operational factors. Industry 4.0 technologies and supply chain digitalization were identified as the primary driving forces of the system, possessing high driving power and low dependence. These technologies form the foundational layer that enables other sustainability-related capabilities. Data management, big data analytics, and intelligent decision-making systems were identified as linkage variables. These factors showed both high driving and high dependence power, indicating their critical role in maintaining system stability. They act as mediators between technological infrastructure and higher-level sustainability outcomes. Governance mechanisms, regulatory frameworks, and sustainability-oriented policies were positioned as institutional enablers. These variables influence system coordination, standardization, and implementation effectiveness across the supply chain network. Operational circular economy practices, including waste recovery, asset lifecycle management, and resource reuse, were located at higher hierarchical levels. These factors were found to be strongly dependent on technological readiness, data maturity, and governance support. Finally, sustainable supply chain performance and supply chain resilience were identified as dependent variables. These outcomes represent the final results of interactions among technological, data, governance, and circular operational factors.

5. CONCLUSION

The findings of this study highlight that sustainable circular energy supply chain management is not driven by isolated initiatives but rather emerges from the systemic interaction of multiple enabling layers. The results confirm that Industry 4.0 technologies serve as fundamental transformation drivers. Without digital infrastructure, it is difficult to achieve transparency, traceability, and real-time optimization required for circular supply chain implementation. The mediating role of data-driven capabilities emphasizes that digital technologies alone are insufficient unless supported by advanced data analytics, integrated information platforms, and intelligent decision-support systems. This reinforces the concept that data maturity is a prerequisite for sustainable digital transformation in energy supply chains. The study also demonstrates the critical role of governance and institutional support. Regulatory alignment, sustainability policies, and standardized data governance frameworks are necessary to ensure coordinated implementation of circular economy strategies across multi-tier supply chain networks. From an operational perspective, circular economy practices such as resource recovery and lifecycle optimization are found to be outcome-oriented rather than driver-oriented. This indicates that organizations must first invest in technological and institutional readiness before expecting measurable circular performance improvements. Overall, this research contributes theoretically by integrating circular economy, Industry 4.0, and energy supply chain sustainability into a unified structural framework. Methodologically, it demonstrates the effectiveness of combining fuzzy logic with structural modeling techniques to analyze complex sustainability systems under uncertainty. From a practical perspective, the study provides a strategic roadmap for policymakers and energy sector managers. Organizations should prioritize digital infrastructure development, data governance implementation, and cross-organizational collaboration platforms to accelerate circular transformation. Future research can extend this model by integrating quantitative validation methods such as structural equation modeling, applying system dynamics to study temporal system behavior, and examining the role of advanced artificial intelligence and blockchain technologies in circular energy supply chains. In conclusion, sustainable circular energy supply chain performance is a systemic outcome driven by digital transformation, data intelligence, institutional governance, and circular operational practices. The transition toward circular energy systems requires coordinated technological, organizational, and policy-level transformation strategies.

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