Risk Mitigation for Energy Transitions in Manufacturing Supply Chain: A Graph Theoretic Perspective

Abstract: This study investigates the critical risks associated with energy transitions (ETs) affecting the energy supply chain within India's manufacturing sector. Employing the Graph Theoretic and Matrix Approach (GTMA), the research offers a structured decision-making framework that captures the interdependencies and dynamic interactions among key risk factors. GTMA facilitates a comprehensive evaluation of complex systems by identifying, modeling, and prioritizing the relative intensity of each risk component. The study proposes targeted risk mitigation strategies aimed at enhancing transparency, resilience, and efficiency throughout the transition process. The findings reveal that safety and security risks, along with political and regulatory uncertainties, emerge as the most significant barriers to effective energy transition. The outcomes contribute valuable guidance for policymakers and industry stakeholders by emphasizing the importance of robust energy governance, market-based incentives, and technological innovation in supporting a sustainable energy future for India's manufacturing sector.

Keywords: Energy transitions, Risk factors, Manufacturing sector, Graph-theoretic and matrix approach, Supply chain resilience

JEL Codes: Q40; L60, D81, L23, C63, C61

1. Introduction

Energy serves as a cornerstone of economic development, underpinning industrial activity, transportation, technological advancement, and household consumption (DeCotis, 2020). However, the global reliance on fossil fuels continues to pose significant environmental challenges. These concerns catalyse international climate governance frameworks, beginning with the Kyoto Protocol adopted at COP3, which established binding targets for greenhouse gas (GHG) emissions reductions among industrialized nations (UNFCCC, 1997). The imperative to decarbonize the energy sector while maintaining economic growth has since become central to the global policy agenda. Transitioning to low-carbon energy systems is not only essential for mitigating climate change but also critical for enhancing energy security and long-term economic resilience (Banerjee & Taplin, 1998; Thavasi & Ramakrishna, 2009). Most recently, COP29 has reaffirmed global commitment by advocating for intensified efforts in energy transition, emissions abatement, and climate adaptation, particularly in the context of achieving net-zero pathways (UNFCCC, 2024).

Greenhouse gas (GHG) emissions and climate change represent critical global challenges that demand urgent economic evaluation and policy intervention to mitigate their far-reaching consequences (Ely

Lecture et al., 2008; Fabra & Reguant, 2024). Industrial sectors face mounting pressures to balance growth with environmental responsibility and the transition to sustainable energy systems (Karwowski et al., 2025). Projections suggest that climate change will significantly elevate energy demand, especially across the industrial and service sectors of developing economies (Ruijven et al., 2019). Notably, industries including food processing, fast-moving consumer goods (FMCG), electronics, automotive, and construction account for nearly half of global industrial GHG emissions (World Economic Forum, 2022). Moreover, approximately 75% of total global emissions originate from the fossil fuel-based energy sector, underscoring its dominant role in climate dynamics (UNDP, 2024).

As the global energy paradigm shifts from fossil fuels to renewables, the urgency of adopting sustainable energy sources becomes increasingly apparent (Yang et al., 2024). Within this context, India's manufacturing sector warrants particular attention, contributing roughly one-sixth of the nation's total GHG emissions. Additionally, energy-intensive sectors such as power generation, transportation, and fossil fuel operations, closely linked to manufacturing, collectively account for approximately 45% of national emissions (see Figure 1). To address these concerns, the Indian government has committed to installing 500 GW of renewable energy capacity and sourcing 50% of its electricity from non-fossil fuel sources by 2030, with a broader goal of achieving net-zero emissions by 2070. Facilitating a sustainable energy transition (ETs) is therefore critical not only for reducing emissions but also for enhancing energy security, ensuring equitable access, and fostering long-term environmental and economic resilience (Pliousis et al., 2019).

The pathway toward sustainable energy transitions (ETs) is fraught with multifaceted risks that may impede its implementation and long-term viability. Key challenges include limited institutional understanding, inadequate technological capabilities, and insufficient readiness to embrace systemic change. Structural barriers further constrain the pace and scalability of energy transition efforts. Moreover, the shift toward clean energy introduces geopolitical tensions by altering global power structures, trade dynamics, and strategic resource dependencies. These issues are compounded by entrenched fossil fuel interests, ideological divisions over climate policy, and the prioritization of short-term economic gains over long-term sustainability (Wasan et al., 2024).

Supply chain vulnerabilities represent a particularly critical area of concern. Disruptions, whether from geopolitical instability, natural disasters, or policy shifts, can significantly reduce the operational effectiveness of energy systems, leading to financial losses and systemic inefficiencies (Emiliozzi et al., 2025). In this context, building supply chain resilience becomes imperative. A resilient energy supply network enhances the system's ability to absorb shocks, sustain operations, and maintain energy security, particularly under conditions of environmental and market uncertainty (Wong & Ngai, 2024; Rajabzadeh & Wiens, 2024). Furthermore, energy storage systems are increasingly vital to the clean energy transition. By mitigating the intermittency of renewable sources such as wind and solar, storage technologies ensure grid reliability and facilitate the integration of variable energy supplies into the broader system (Kalair et al., 2021).

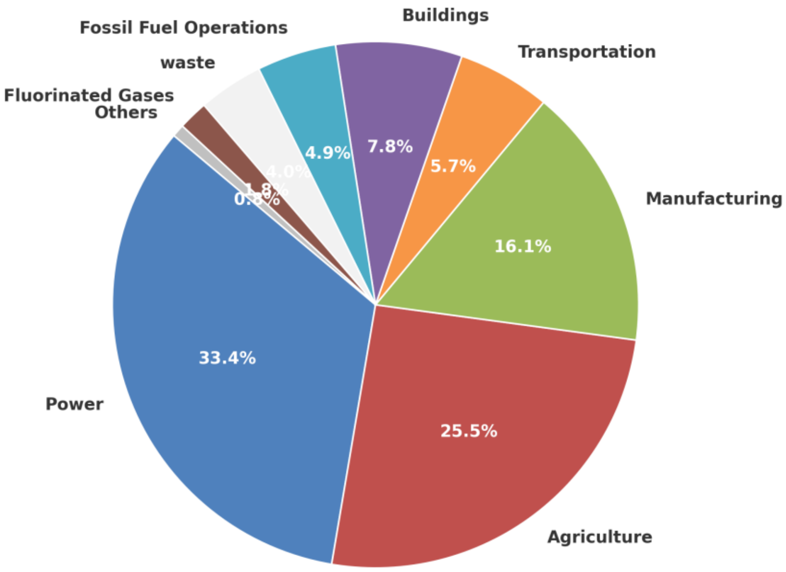


Figure 1. Distribution of GHG emissions in India by sector (Statista, 2025)

Despite growing global attention to sustainable energy transitions (ETs), comprehensive studies that integrate risk management within the ETs process, particularly from diverse disciplinary perspectives, remain limited. This gap is especially pronounced in the context of the manufacturing sector, where systematic risk assessments during transitional phases are notably scarce. Given the sector's significant contribution to greenhouse gas emissions and its complex interlinkages with energy systems, there is a pressing need for an integrated transition mechanism that not only identifies and mitigates risks but also establishes actionable goals and strategies for achieving sustainable ETs outcomes (Lin et al., 2024). The study's theoretical foundation is based on the transition process; leveraging the diffusion of innovation (DOI) and socio-technical transitions theories (STT) can ensure a more seamless and effective implementation. To address these gaps, the study aims:

H1: To analyse risk factors in the energy transition of the Indian manufacturing sector.
H2: To propose a risk mitigation strategy for a better transition process.

To evaluate the relative intensity of risk factors (RFs) during the energy transition (ET) phase, this study employs the Graph-Theoretic and Matrix Approach (GTMA). This analytical approach enables a nuanced understanding of interdependent risk elements, thereby contributing to the design of resilient and effective ET strategies. GTMA offers a more integrative and system-oriented modelling framework, making it particularly well-suited for analysing the multifactorial nature of transition-related risks in the manufacturing sector.

The research is set up as follows: An extensive literature review is presented in Section 2 after the introduction. Section 3 describes the risk factors, wherein section 4 showcases methodology, followed by section 5 with quantification of the Factors. Section 6 presents the results and discussion, along with the study's implications, and Section 7 presents the conclusion.

2. Literature Review

The GHG emissions, mostly from burning fossil fuels, cause global climate change and necessitate the phase-out of fossil fuels (Thollander et al., 2012). Reducing reliance on conventional energy and accelerating the transition to a low-carbon energy future in the industry requires energy efficiency and conservation initiatives, coupled with strategic government initiatives (Edomah, 2019). Long-term strategic cooperation between government, academic institutions, research institutes, and industry players is necessary to achieve efficient Transition. Effective energy policies supported by technological innovation are essential to address energy challenges, promote energy security and decarbonization, and enable a future with environmentally friendly energy (Chen et al., 2019; Skjærseth, 2021). Current research has focused on a sustainable energy mix to reduce environmental impact and provide long-term energy security. India uses a fair quantity of wind energy because of its extensive coastline, even though its offshore wind energy potential is unrealized (Sadorsky, 2021). Despite the potential of renewable energy sources, barriers to their widespread adoption include limited scalability, inconsistent power generation, and inadequate infrastructure (Dutt & Ranjan, 2022; Gupta et al., 2021; Kumar et al., 2021; Zhou et al., 2022). Addressing these challenges requires concerted investment, policy, and innovation efforts to provide a smooth transition to sustainable energy systems (Lin et al., 2024). Transitioning to clean energy and developing a sustainable energy future has brought several managerial challenges. The demand-supply management, infrastructure development, policy execution, technological innovation, and stakeholder involvement are just a few of the many challenges. Energy policy and management have been extensively studied. However, new information on transition, technological development, the demand-supply balance, energy conservation and sustainability, political unpredictability, and energy supply chain digitization keeps coming to light. Keeping this in context, this article aims to examine the risk factors associated with the ET process and propose a smoother transition mechanism by prioritizing the risk factors. The literature and other articles provided 27 such risks, which are then clubbed into 6 major categories documented as risk factors in this article. The theoretical foundations of the risk factors are provided in subsection 2.1.

2.1 Theoretical foundation

2.1.1 Socio-technical transitions (STT) theory

The STT theory integrates social, technical, and institutional elements to highlight the systemic character of ET. This approach provides a comprehensive knowledge of the intricate interactions between energy systems, policy, and societal behavior. It is based on frameworks such as Transition Management (Loorbach & Rotmans, 2010) and the Multi-Level Perspective (MLP) (Geels, 2002, 2010). Considering market dynamics, policy interventions, and cultural changes makes it easier to identify the best routes for implementing sustainable technology. This theory also highlights possible risks, including resistance from entrenched fossil fuel interests, a lack of social stability of new technology, knowledge gaps, ethical concerns, sociopolitical disagreement, governance complexities, and difficulties in bringing diverse stakeholders together (Geels, 2010; Köhler et al., 2019). Further risks are presented by the unpredictability of the spread of technology and societal acceptance (Chappin & van der Lei, 2014; Demski et al., 2015). Despite these risks, socio-technical frameworks are crucial in directing sustainable transitions by encouraging stakeholder cooperation, creativity, and resilience (Berkes & Folke, 1998; Markard et al., 2012; Farla et al., 2012). RFs, including Technological capability, political complexities, and stakeholder interest, have been addressed in the socio-technical transactions theory, which is essential for assessing the risk of ETs in the manufacturing sector (Farla et al., 2012; Geels, 2002). This theory supports innovation, addresses sector-specific challenges, makes the industry more resilient and adaptable, and helps develop sustainable routes by incorporating multi-level viewpoints (Geels, 2002; Köhler et al., 2019).

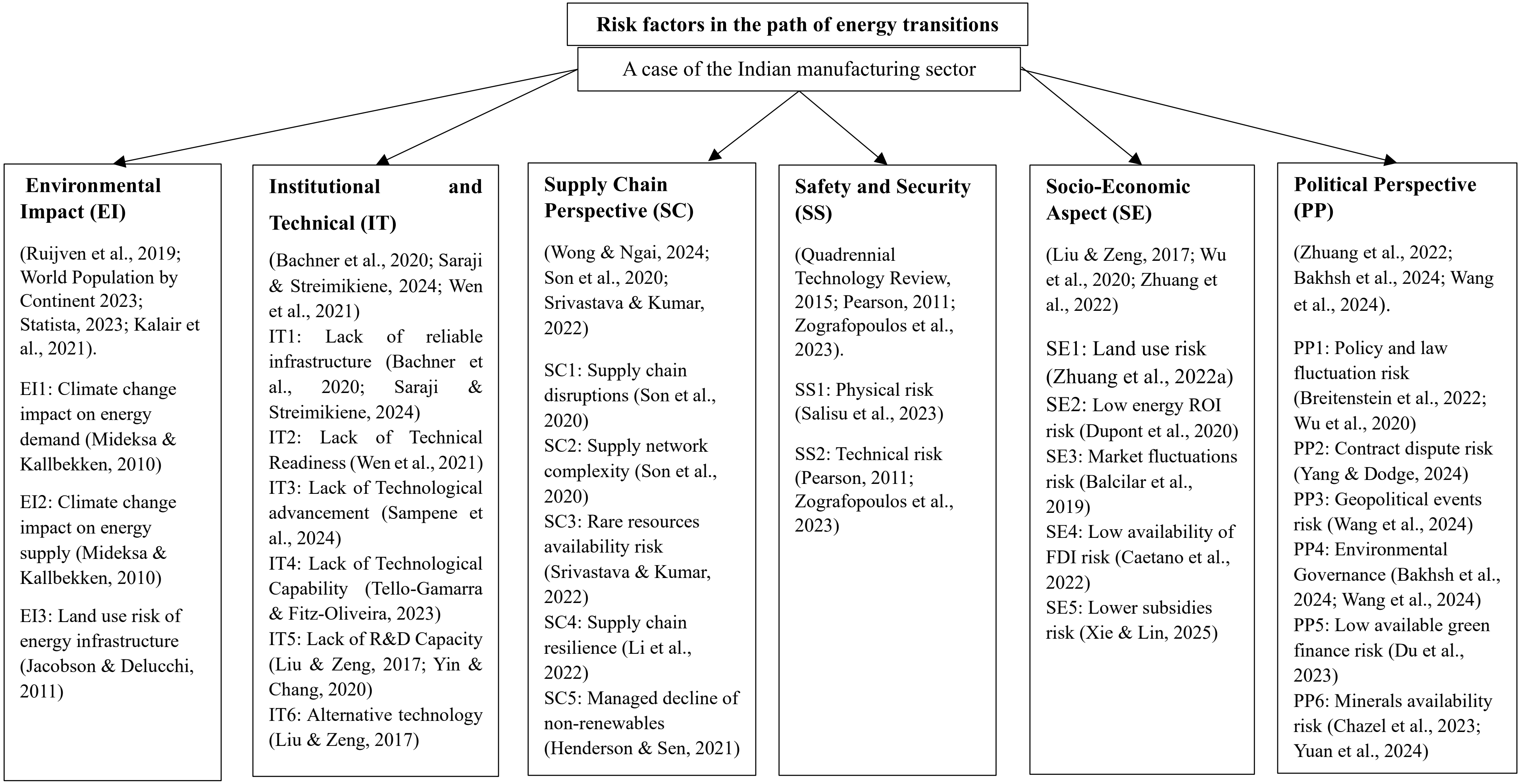
2.1.2 Diffusion of innovation (DOI) theory

The Valente & Rogers (1995) DOI theory provides a novel concept, and technology proliferates within social systems by emphasizing individual and collective demands. Instead of concentrating on convincing people to change, the idea reframes change in transitions as the adaptation or reinvention of innovations (Robinson, 2009). The diffusion process enables innovations to gradually spread through specific channels among members of a social system (Rogers et al., 2014). When applied to transitions, this theory focuses on comprehending the processes by which innovations proliferate throughout organizational and societal contexts (Fichman, 1999). This approach emphasizes adaptability and diffusion and offers insightful viewpoints on promoting systemic changes, such as ETs, by coordinating innovations with organizational and social demands. Parameters such as proximity to renewable energy plants, social mindset toward sustainability, green innovation subsidies, high costs, and capability concerns substantially impact firms' innovation in sustainable energy (Horbach & Rammer, 2018). Innovation diffusion is crucial in propelling technological changes by clarifying how new technologies are embraced and used after initial adoption, emphasizing their effects on performance and contextual flexibility (Baiyere et al., 2020). The theory promotes innovation using technology-driven insights to enhance decision-making, improve sustainable ETs, and become more competitive and efficient in the changing energy market (Akter et al., 2020; Kava et al., 2024).

3. Risk factors in the path of energy transitions in the Indian manufacturing sector

Emissions from traditional energy usage have been a challenge in manufacturing industries. Switching from fossil fuels to sustainable energy sources is a way to lower emissions and provide inexpensive, clean energy in the face of environmental change and economic expansion (Xiang et al., 2022). The risks can potentially hamper the transition process. Incomplete knowledge makes these challenges worse (Pizarro-Irizar et al., 2020). The risk factors are determined through an extensive literature review and expert inputs as shown in Figure 2.

Climate change will increase the number of yearly days with average temperatures over 27.5°C and below 12.5°C by changing the exposure to temperature (Ruijven et al., 2019). More than 80% of the world's population lives in these regions, which will present enormous adaptation issues as they attempt to fulfill the growing energy demand to sustain economic services in the face of changing climate conditions (Ruijven et al., 2019; World Population by Continent 2023; Statista, 2023). The unreliable infrastructure is a major obstacle to reaching ET objectives and slows the move to a low-carbon path (Bachner et al., 2020; Saraji & Streimikiene, 2024). Modern technologies greatly enhance the quality and operating efficiency of integrated energy systems (Sampene et al., 2024). There are risks associated with alternative technologies' replaceability and replication (Liu & Zeng, 2017; Wen et al., 2021). The supply chain disruption can seriously affect businesses by lowering their operational effectiveness and resulting in significant losses. Because the environmental uncertainties are significant, supply chain resilience is essential for preserving operational stability and reducing financial risks (Wong & Ngai, 2024). To secure a controlled decline in traditional energy sources alongside modifications to the current energy system, $0.6-0.8 trillion will be utilized annually on conventional fuels like oil and gas (Henderson & Sen, 2021). Unpredictable disasters like the COVID-19 epidemic emphasize the need for resilient energy networks to withstand disruptions and improve demand-supply mapping (Li et al., 2022).Damage to production, supply, and storage networks is crucial because it compromises the reliability and efficiency of energy delivery systems, making the ET process much more difficult.



Risk factors in the path of energy transitions

A case of the Indian manufacturing sector

Environmental Impact (EI)

(Ruijven et al., 2019; World Population by Continent 2023; Statista, 2023; Kalair et al., 2021).

EI1: Climate change impact on energy demand (Mideksa & Kallbekken, 2010)

EI2: Climate change impact on energy supply (Mideksa & Kallbekken, 2010)

EI3: Land use risk of energy infrastructure (Jacobson & Delucchi, 2011)

Institutional and Technical (IT)

(Bachner et al., 2020; Saraji & Streimikiene, 2024; Wen et al., 2021)

IT1: Lack of reliable infrastructure (Bachner et al., 2020; Saraji & Streimikiene, 2024)

IT2: Lack of Technical Readiness (Wen et al., 2021)

IT3: Lack of Technological advancement (Sampene et al., 2024)

IT4: Lack of Technological Capability (Tello-Gamarra & Fitz-Oliveira, 2023)

IT5: Lack of R&D Capacity (Liu & Zeng, 2017; Yin & Chang, 2020)

IT6: Alternative technology (Liu & Zeng, 2017)

Supply Chain Perspective (SC)

(Wong & Ngai, 2024; Son et al., 2020; Srivastava & Kumar, 2022)

SC1: Supply chain disruptions (Son et al., 2020)

SC2: Supply network complexity (Son et al., 2020)

SC3: Rare resources availability risk (Srivastava & Kumar, 2022)

SC4: Supply chain resilience (Li et al., 2022)

SC5: Managed decline of non-renewables (Henderson & Sen, 2021)

Safety and Security (SS)

(Quadrennial Technology Review, 2015; Pearson, 2011; Zografopoulos et al., 2023).

SS1: Physical risk (Salisu et al., 2023)

SS2: Technical risk (Pearson, 2011; Zografopoulos et al., 2023)

Socio-Economic Aspect (SE)

(Liu & Zeng, 2017; Wu et al., 2020; Zhuang et al., 2022)

SE1: Land use risk (Zhuang et al., 2022a)

SE2: Low energy ROI risk (Dupont et al., 2020)

SE3: Market fluctuations risk (Balcilar et al., 2019)

SE4: Low availability of FDI risk (Caetano et al., 2022)

SE5: Lower subsidies risk (Xie & Lin, 2025)

Political Perspective (PP)

(Zhuang et al., 2022; Bakhsh et al., 2024; Wang et al., 2024).

PP1: Policy and law fluctuation risk (Breitenstein et al., 2022; Wu et al., 2020)

PP2: Contract dispute risk (Yang & Dodge, 2024)

PP3: Geopolitical events risk (Wang et al., 2024)

PP4: Environmental Governance (Bakhsh et al., 2024; Wang et al., 2024)

PP5: Low available green finance risk (Du et al., 2023)

PP6: Minerals availability risk (Chazel et al., 2023; Yuan et al., 2024)

Figure 2. Risk factors and subfactors in energy transition

The ETs could make this more challenging, as it would repurpose agricultural land for generating and distributing energy (Zhuang et al., 2022). Furthermore, increased manufacturing activity due to foreign direct investment (FDI) raises the energy demand (Caetano et al., 2022). Subsidies, feed-in tariffs, and tax incentives contribute to the ET by reducing the cost of renewable energy sources and encouraging innovation (Jenner et al., 2013). Reduced subsidies could impede progress since there would be less funding for innovation and support, which would increase reliance on fossil fuels. The efficiency and speed of ETs can be greatly impacted by political risk; ineffective governance may cause the transition to renewable energy to be delayed and jeopardize environmental stability (Bakhsh et al., 2024; Wang et al., 2024; Yang & Dodge, 2024). Wars, armed conflicts, and political unrest are examples of geopolitical events that pose a danger to the stability and advancement of renewable energy markets (Blondeel et al., 2024; Chishti et al., 2023; Wang et al., 2024). Forecasting and directing ET pathways require understanding how the market reacts to these dynamics.

4. Research Methodology

This study aims to evaluate the risks associated with the energy transitions (ETs) process in the Indian manufacturing sector. Given the complex and exploratory nature of the research, a pragmatic mixed-method approach has been adopted. The investigation begins with an extensive literature review to identify key risk factors (RFs) and their subcomponents. A qualitative phase follows to capture expert insights, which is then complemented by a quantitative assessment to systematically evaluate the intensity of the identified risks. This methodological integration aligns with the overarching research objective to develop a comprehensive and actionable framework for mitigating ET-related risks, consistent with the pragmatic paradigm outlined by Creswell and Poth (2016).

Experts from both academia and industry were purposefully selected for data collection to ensure a well-rounded and application-oriented perspective, as shown in Table 1. To enhance the reliability and validity of the responses, participants were thoroughly briefed on the study's objectives, and care was taken to ensure that their interpretations aligned with the researchers' intent. Reliability and validity of the data captured from the experts were assessed to showcase the consistency and agreement among the respondents. However, as noted by Bethlehem (2010) and Diefenbach (2009), qualitative data collection can be prone to unconscious bias, influenced by respondents' emotions or the researchers' values. To address this concern, the Five Ps framework, Prior, Planning, Prevents, Poor, and Performance, was applied (Gawne, 2008). This involved conducting background research on each participant's institutional sustainability commitments, review of corporate sustainability reports, and analysis of related policy documentation to enhance the accuracy and contextual relevance of responses. In total, 25 expert responses were captured, a sample size deemed adequate for qualitative research of this nature (Mason, 2010). The combined methodology supports a rigorous and policy-relevant understanding of energy transition risks in one of the most emission-intensive sectors of the Indian economy.

Table 1. Experts' profile

Sl. No.	Current Job Profile	Highest Education	Years of Relevant Experience
1	Director	Masters	30
2	Add. General Manager (Strategy | Enterprise Risk | Technical Services | Projects)	Bachelors	32
3	Global Process Owner- Energy Trading	Masters	18
4	Finance	Masters	16
5	AGM Operations	Bachelors	22
6	Chairman, CEO, Director, and Professor	Masters	31
7	Program Manager-Logistics	PhD	23
8	Professor	PhD	11
9	CEO	Masters	20
10	Key Account Management, Strategy, Operations	Masters	18
11	Assistant Professor	Masters	13
12	Global Project Management	Masters	12
13	Sr. Manager - Brand and Activation India	Masters	21
14	Automotive components Sales	Masters	15
15	Transformation Solution Architect	Masters	8
16	Government of India	Masters	19
17	Project Manager	Bachelors	15
18	Project Director	Masters	20
19	Senior PM	Masters	15
20	Account Director	Masters	30
21	Director	Masters	35
22	Operations Manager	Masters	15
23	Head SCM	Masters	15
24	Head Sales	Masters	20
25	Head Operations	Bachelors	20

4.1 Graph Theoretic and Matrix Approach

The authors have used the GTMA technique, which conducts matrix-based computations that reduce calculation burden and handle a larger number of attributes and pairwise interdependence comparisons. It has been widely used in the field of manufacturing and service operations (Gupta & Singh, 2020), industry 4.0 risk assessment (Virmani et al., 2023), green supply chain management adoption barriers assessment in the Indian mining sector (Muduli et al., (2013), industrial TQM evaluation (Grover et al., 2004). This study uses GTMA to assess the risks associated with ET in the Indian manufacturing sector and formulate a better transition strategy with minimum risk. There are five parts to the GTMA framework: (1) Identifying the sub-barriers; (2) Digraph Representation; (3) Matrix representation; (4) Permanent function determination; and (5) Measurement of risk intensity. By using GTMA, we have developed a three-parameter digraph representation of a system, as shown in Figure 3, and the cause-and-effect diagram of risks is shown in Figure 4. A cause-and-effect diagram is a fishbone diagram that organises and visually represents the risks and sub-causes and how they contribute to the overall problem.

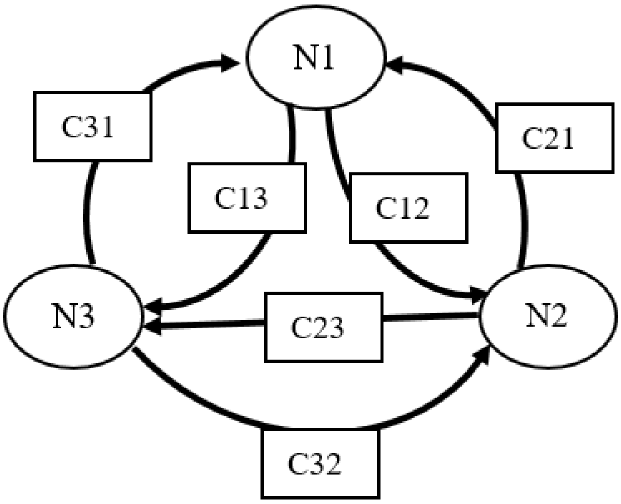


Figure 3: Three-factor system's digraph representation

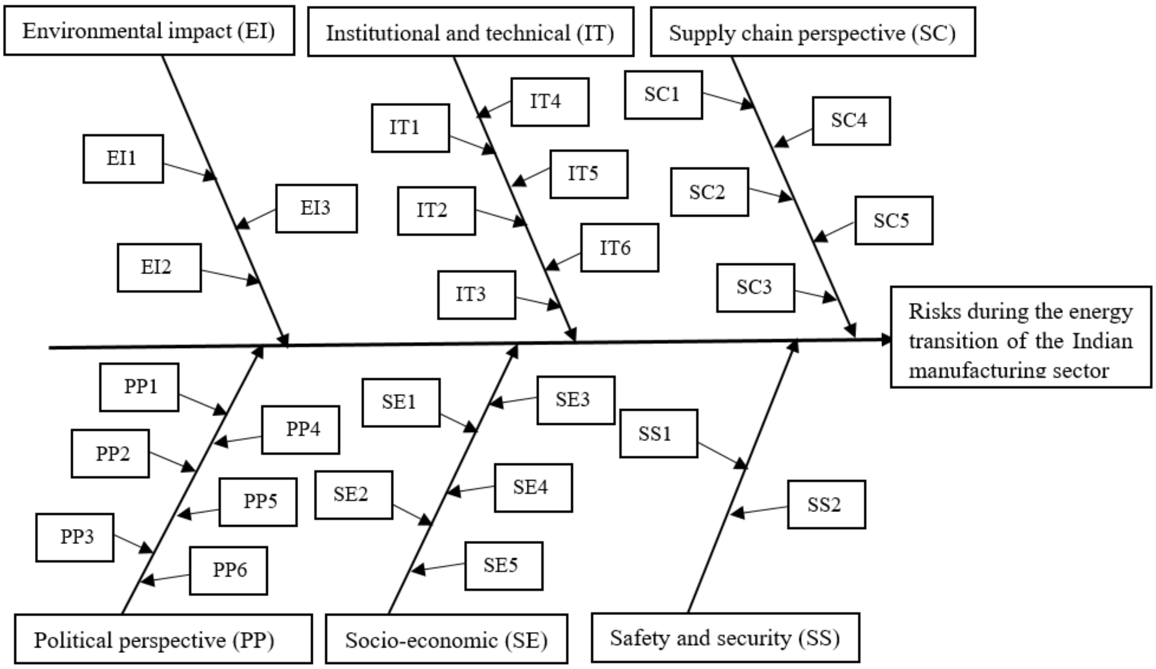


Figure 4: Cause and effect diagram of risks

4.2 Reliability and Validity

The reliability and validity of the expert responses have been tested using Cronbach's alpha (α), composite reliability (CR), and average variance extracted (AVE), and are shown in Table 2. The (α) values range from 0.822 to 0.949, which are well above 0.7, indicating excellent internal consistency in the survey. The CR values, which range from 0.746 to 0.938, also exhibit a similar trend. The AVE values are more than 0.5 except in one scenario; however, the higher CR value negates it and shows an acceptable degree of variation in the survey responses. These metrics make the survey reliable internally and validate the subgrouping. The Inter-Rater Reliability Index is 0.967 with a 95% confidence interval (Interval values: 0.945-0.983), showcasing strong agreement among the respondents.

Table 2. Reliability and Validity Scores

Risk	Cronbach's Alpha (α)	CR	AVE
1	0.833	0.839	0.636
2	0.949	0.938	0.717
3	0.933	0.901	0.648
4	0.822	0.746	0.60
5	0.886	0.901	0.646
6	0.875	0.808	0.42

5. Quantification of Risk Factors

The authors have used GTMA to evaluate and assess the risks that prevent the smooth ET process in the Indian manufacturing sector. Table 3 explains the linguistic scale for the inheritance of factors, while Table 4 shows the relative factor importance of ET risks.

Table 3. Linguistic scale for the inheritance of Factors

Qualitative rating	Value corresponding
Exceptionally high	9
Very high	8
High	7
Above average	6
Average	5
Below average	4
Low	3
Very low	2
Exceptionally low	1

Table 4. Relative factor importance

Description	Attributes' relative significance	
	r_{ij}	r_{ji}
One Risk is exceptionally significant than the other	10	0
One Risk is extremely significant than the other	9	1
One Risk is much more significant than the other	8	2
One Risk is more significant than the other	7	3

One Risk is slightly more significant than the other	6	4
Both risks are equally important	5	5

5.1 Behavioural digraph

The behavioural digraph is made with nodes representing factors and edges representing their inter-relationships to display the RFs and sub-factors in the transition. In this study, six RFs have been identified. Figure 5 illustrates this by showing the challenges (Fi) as nodes and their dependencies (r_{ij}), where the direct link, r_{ij}, connects node i to j.

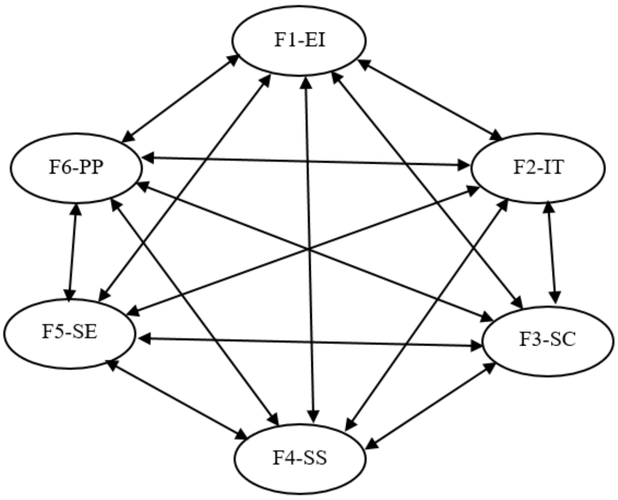


Figure 5: Behavioural digraph for the RFs

The behavioural digraph for the first risk (Environmental impact) is shown in Figure 6. The sub-challenges for the same are represented by nodes F_1^1, F_2^I, and $F3^I$, and their interdependencies are denoted by r_{ij}^I.

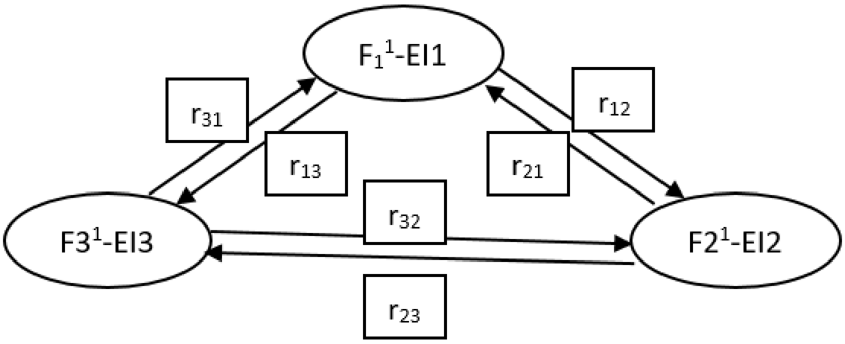


Figure 6: Behavioural digraph of Environmental risk

5.2 Matrix representation

The six RFs in ET found in this study, and their interrelationships, are represented by a 6x6 matrix, which represents the behavioural digraph of factors as shown in equation 1.

$$\mathrm{S}=\begin{bmatrix} \mathrm{F}_1 & \mathrm{r}_{12} & \mathrm{r}_{13} & \mathrm{r}_{14} & \mathrm{r}_{15} & \mathrm{r}_{16} \\ \mathrm{r}_{21} & \mathrm{F}_2 & \mathrm{r}_{23} & \mathrm{r}_{24} & \mathrm{r}_{25} & \mathrm{r}_{26} \\ \mathrm{r}_{31} & \mathrm{r}_{32} & \mathrm{F}_3 & \mathrm{r}_{34} & \mathrm{r}_{35} & \mathrm{r}_{36} \\ \mathrm{r}_{41} & \mathrm{r}_{42} & \mathrm{r}_{43} & \mathrm{F}_4 & \mathrm{r}_{45} & \mathrm{r}_{46} \\ \mathrm{r}_{51} & \mathrm{r}_{52} & \mathrm{r}_{53} & \mathrm{r}_{54} & \mathrm{F}_5 & \mathrm{r}_{56} \\ \mathrm{r}_{61} & \mathrm{r}_{62} & \mathrm{r}_{63} & \mathrm{r}_{64} & \mathrm{r}_{65} & \mathrm{F}_6 \end{bmatrix} \qquad (1)$$

Here, Fi is the value of the RFs that the nodes represent, and r_{ij} is the edge-based relative significance of risk i over risk j. The "Environmental impact" risk consists of three sub-factors, and the behavioural digraph is a 3×3 matrix:

$$E=\begin{bmatrix} F_1^1 & r_{12}^1 & r_{13}^1 \\ r_{21}^1 & F_2^1 & r_{23}^1 \\ r_{31}^1 & r_{32}^1 & F_3^1 \end{bmatrix};\ \mathrm{E}=\begin{bmatrix} 8 & 7 & 8 \\ 3 & 7 & 8 \\ 2 & 2 & 7 \end{bmatrix} \qquad (2)$$

Here F_1^1, F_2^1 and F_3^1 represent E1, E2 and E3 respectively. Furthermore, r_{ij}^1 shows the relative significance of the ith sub-factor over the jth in Environmental risk. The remaining matrix is developed using the same approach.

5.3 Permanent representation

The permanent function provides a composite measure that captures both the individual effects of factors and their interdependencies, offering a holistic view of complex problems. The general permanent function equation for the challenges can be written as:

$$\begin{aligned} \mathrm{Per}\ (\mathrm{S}) = {} & \prod F_i + \textstyle\sum_i \sum_j \sum_k \cdots \sum_m \sum_n r_{ij}^2 F_k F_l F_m F_n \ldots + \\ & 2 \textstyle\sum_i \sum_j \sum_k \cdots \sum_m \sum_n (r_{ij} r_{jk} r_{ki}) F_l F_m F_n \ldots + 2 \sum_i \sum_j \sum_k \cdots \sum_m \sum_n (r_{ij} r_{jk} r_{kl} r_{li}) F_m F_n \ldots + \\ & \textstyle\sum_i \sum_j \sum_k \cdots \sum_m \sum_n (r_{ij}^2 r_{kl}^2) F_m F_n \ldots + 2 \sum_i \sum_j \sum_k \cdots \sum_m \sum_n (r_{ij} r_{jk} r_{kl} r_{lm} r_{mi}) F_n \ldots + \\ & 2 \textstyle\sum_i \sum_j \sum_k \cdots \sum_m \sum_n (r_{ij} r_{jk} r_{ki}) r_{lm}^2 F_n + \sum_i \sum_j \sum_k \cdots \sum_m \sum_n (r_{ij}^2 r_{kl}^2 r_{mn}^2) \ldots + \\ & 4 \textstyle\sum_i \sum_j \sum_k \cdots \sum_m \sum_n (r_{ij} r_{jk} r_{ki}) (r_{lm} r_{mn} r_{nl \ldots} + 2 \sum_i \sum_j \sum_k \cdots \sum_m \sum_n (r_{ij} r_{jk} r_{kl} r_{li}) r_{mn}^2 \ldots \end{aligned} \qquad (3)$$

The permanent representation of Environmental risk can be written using equation (2):

$$Per\ (\mathrm{EI}) = F_1^1 F_2^1 F_3^1 + F_1^1 r_{23}^1 r_{32}^1 + F_2^1 r_{13}^1 r_{31}^1 + F_3^1 r_{21}^1 r_{12}^1 + r_{31}^1 r_{23}^1 r_{12}^1 + r_{13}^1 r_{32}^1 r_{21}^1 \qquad (4)$$

The permanent value of environmental risk is:

$$F_1 = \text{Per (E)} = Per\begin{bmatrix} F_1^1 & r_{12}^1 & r_{13}^1 \\ r_{21}^1 & F_2^1 & r_{23}^1 \\ r_{31}^1 & r_{32}^1 & F_3^1 \end{bmatrix} = \text{Per}\begin{bmatrix} 8 & 7 & 8 \\ 3 & 7 & 8 \\ 2 & 2 & 7 \end{bmatrix} = 939 \tag{5}$$

The same process is followed to calculate the permanent value of the remaining five RFs.

$$\text{IT}=\begin{bmatrix} 7 & 7 & 6 & 7 & 6 & 7 \\ 3 & 7 & 7 & 7 & 7 & 7 \\ 4 & 3 & 7 & 7 & 7 & 6 \\ 3 & 3 & 3 & 7 & 7 & 7 \\ 4 & 3 & 3 & 3 & 7 & 7 \\ 3 & 3 & 4 & 3 & 3 & 7 \end{bmatrix};\ F_2 = \text{Per (IT)} = \text{Per}\begin{bmatrix} 7 & 7 & 6 & 7 & 6 & 7 \\ 3 & 7 & 7 & 7 & 7 & 7 \\ 4 & 3 & 7 & 7 & 7 & 6 \\ 3 & 3 & 3 & 7 & 7 & 7 \\ 4 & 3 & 3 & 3 & 7 & 7 \\ 3 & 3 & 4 & 3 & 3 & 7 \end{bmatrix} = 13563702 \tag{6}$$

$$\text{SC}=\begin{bmatrix} 7 & 7 & 7 & 7 & 7 \\ 3 & 7 & 6 & 6 & 6 \\ 3 & 4 & 7 & 7 & 7 \\ 3 & 4 & 3 & 7 & 8 \\ 3 & 4 & 3 & 2 & 7 \end{bmatrix};\ F_3 = \text{Per (SC)} = \text{Per}\begin{bmatrix} 7 & 7 & 7 & 7 & 7 \\ 3 & 7 & 6 & 6 & 6 \\ 3 & 4 & 7 & 7 & 7 \\ 3 & 4 & 3 & 7 & 8 \\ 3 & 4 & 3 & 2 & 7 \end{bmatrix} = 462371 \tag{7}$$

$$\text{SS}=\begin{bmatrix} 8 & 7 \\ 3 & 8 \end{bmatrix};\ F_4=\text{Per (SS)} =\text{Per}\begin{bmatrix} 8 & 7 \\ 3 & 8 \end{bmatrix}= 85 \tag{8}$$

$$\text{SE}=\begin{bmatrix} 7 & 7 & 7 & 7 & 7 \\ 3 & 7 & 7 & 7 & 7 \\ 3 & 3 & 7 & 7 & 7 \\ 3 & 3 & 3 & 7 & 7 \\ 3 & 3 & 3 & 3 & 7 \end{bmatrix};\ F_5=\text{Per (SE)} = \text{Per}\begin{bmatrix} 7 & 7 & 7 & 7 & 7 \\ 3 & 7 & 7 & 7 & 7 \\ 3 & 3 & 7 & 7 & 7 \\ 3 & 3 & 3 & 7 & 7 \\ 3 & 3 & 3 & 3 & 7 \end{bmatrix} = 442792 \tag{9}$$

$$\text{PP}=\begin{bmatrix} 8 & 8 & 8 & 8 & 8 & 8 \\ 2 & 8 & 8 & 7 & 8 & 8 \\ 2 & 2 & 8 & 8 & 8 & 8 \\ 2 & 3 & 2 & 8 & 8 & 8 \\ 2 & 2 & 2 & 2 & 8 & 7 \\ 2 & 2 & 2 & 2 & 3 & 8 \end{bmatrix};\ F_6=\text{Per (PP)} = \text{Per}\begin{bmatrix} 8 & 8 & 8 & 8 & 8 & 8 \\ 2 & 8 & 8 & 7 & 8 & 8 \\ 2 & 2 & 8 & 8 & 8 & 8 \\ 2 & 3 & 2 & 8 & 8 & 8 \\ 2 & 2 & 2 & 2 & 8 & 7 \\ 2 & 2 & 2 & 2 & 3 & 8 \end{bmatrix} = 10609904 \tag{10}$$

Following the computation of the index values for each RF, the overall risk index is calculated using equation (2)

$$\text{R}= \text{Per}\begin{bmatrix} 939 & 7 & 6 & 7 & 7 & 7 \\ 3 & 13563702 & 7 & 7 & 6 & 7 \\ 4 & 3 & 462371 & 7 & 7 & 7 \\ 3 & 3 & 3 & 85 & 6 & 7 \\ 3 & 4 & 3 & 4 & 442792 & 6 \\ 3 & 3 & 3 & 3 & 4 & 10609904 \end{bmatrix} = 2.35*10^{30} \tag{11}$$

5.4 Theoretical permanent values

This low value of permanent number indicates that decisions can focus on individual factors since interdependencies are weak. The high permanent value shows that decisions must address the system as a whole, because strong interconnections mean changes in one factor will significantly influence others. Minimum and maximum permanent values are determined for each RF, showing the best and worst values. Assuming that each sub-factor reaches its optimal value (i.e., 1), the theoretical optimum value is determined. The theoretical optimum value for environmental risk (E-best):

$$\text{E-best}=\text{E-min}=\text{Per}\begin{bmatrix}1 & 7 & 8\\ 3 & 1 & 8\\ 2 & 2 & 1\end{bmatrix}=214 \tag{12}$$

Similarly, the theoretical worst value is achieved when the sub-factors reach the worst value (i.e., 9).

$$\text{E-worst}=\text{E-max}=\text{Per}\begin{bmatrix}9 & 7 & 8\\ 3 & 9 & 8\\ 2 & 2 & 9\end{bmatrix}=1366 \tag{13}$$

Likewise, the theoretical worst and best values for the remaining risks are calculated and provided in Table 5.

5.5 Factor Comparison

A comparative methodology was used to determine the magnitude of each RF's associated risk during the ET in the Indian manufacturing sector. A more accurate comparison may be made by comparing the challenges' similarities and differences coefficients with the optimal and worst-case scenarios (Muduli et al., 2013).

The best-case similarity coefficient equation is:

$$C_{si}=(F_i-B_i)/(W_i-B_i) \tag{14}$$

C_{si}= ith RF's similarity coefficient to the optimal value.

Where F_i= ith RF's Permanent value

B_i= ith factor's optimal value

W_i= ith factor's worst-value

Likewise, the worst-case similarity coefficient equation is:

$$C'_{si}=(W_i-F_i)/(W_i-B_i) \tag{15}$$

C'_{si}= i^{th} factor's similarity coefficient to the worst value

These coefficients act as performance scores for each parameter. Higher values indicate closer alignment with the desired state, guiding decision makers to prioritize weaker areas with lower coefficients for targeted interventions. From the above two equations, it is clear that a smaller C_{si} has greater similarity with the best value and lesser risk intensity in the ET process. In contrast, a smaller C'_{si} possesses higher risk intensity. The coefficients are calculated using equations (14) and tabulated in Table 5.

Table 5. Minimum and maximum values of the permanents function

	Environmental	Institutional and technical	Supply chain perspective	Safety and Security	Socio-economic	Political perspective
Actual	939	13563702	462371	85	442792	10609904
Min (Best)	214	3892998	131861	22	124216	2123468
Max (Worst)	1366	20562838	702429	102	676344	13351628
Coefficient	0.6293	0.5801	0.5792	0.7875	0.577	0.7558

5.6 Sensitivity Analysis

There may be fluctuations and unpredictability in the data used in MCDM. To validate the data and ascertain how variability impacts prioritization, a sensitivity analysis is executed. The researchers can make wiser decisions if they understand how sensitive the various weights are. The weights of the 6 Risks are normalised, and Table A1 (Appendix) shows the results of the sensitivity analysis. Starting with the fifth phase, the study shows that the order is preserved irrespective of the weights. This illustrates how reliable and successful the model is. When data sources are small, this approach is preferable. The graphical portrayal is shown in Figure 7. The figure 7. graphically demonstrates whether changes to the weights assigned have an impact on the final ranking of options. Researchers can assess if minor adjustments to input weights result in notable changes to ranks by inspecting the graphic. This highlights sensitive, robust rankings.

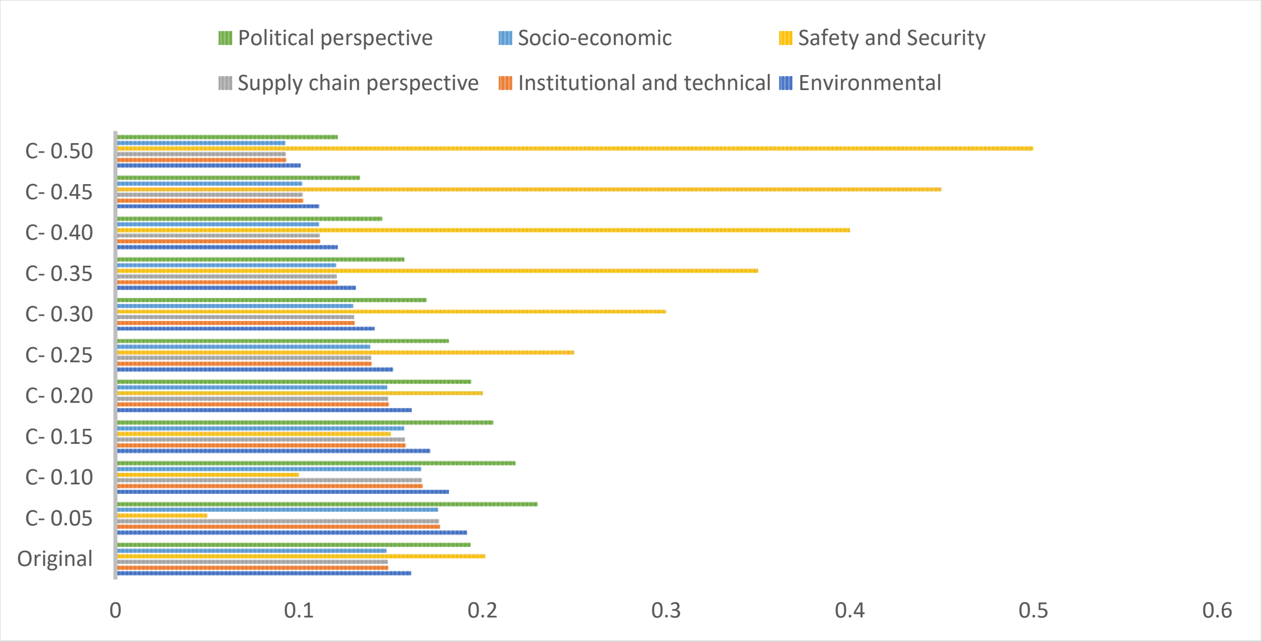


Figure 7. Sensitivity analysis is shown graphically.

6. Managerial Policy Implications

On the polices side, our study offers invaluable insights for managers and companies navigating the complexities of risks in energy transitions. The six different risk categories determined in the energy transition supply chain are initial and exploratory. However, they provide managers and policymakers with timely initiation to address these and develop a robust plan to mitigate these risks. It has been observed that the Indian manufacturing sector faces substantial challenges in implementing sustainable energy transitions. Our study determined that the two most important risk categories, safety and security (SS) and political perspective (PP), require more attention. The results inform the managers to install disaster-resilient structures that can survive natural disasters, and diversification of the supply chain can address such uneven circumstances during catastrophes. Experts found negative perceptions towards security challenges and advancing AI monitoring for energy grids and facilities, early anomaly detection, and strong digital security against cyberattacks are necessary to ensure the security of energy systems(Ahmad et al., 2021; Shin et al., 2021). Our findings are compatible with the latest report of the World Economic Forum, which explored the AI infrastructure to decarbonize and enhance safety and efficiency.[1] The results are also supported by the Association of German Engineers; with Industry 4.0 technologies, the possible saving in material and energy amounts to 25%. [2] It is evident that policy

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[1] https://www.weforum.org/stories/2025/01/energy-ai-net-zero/

[2] https://www.ressource-deutschland.de/service/publikationen/detailseite/studie-industrie-40/

frameworks encouraging investment in renewable energy technology, promoting energy markets, and providing incentives are critical in advancing the ET.

The findings suggest that environmental impact (EI) risk affects renewable energy generation and increases the energy demand in terms of heating and cooling effects. The production and consumption of energy are important drivers of the energy transition. Climate risk assessments and predictive modeling can be used to predict the effects of climate change and implement mitigation strategies for energy operations and supply chains (Ahmad et al., 2021). The UNDP also emphasizes nature, climate, and energy through SDGs to resolve the climate crisis by promoting locally driven climate-resilient footsteps.[3]

The institutional and technical (IT) risk can be minimized through constant improvement in infrastructure, technical readiness, and resilient systems that enable businesses to increase long-term strategic performance and operational efficiency. Overcoming these risks requires enhancing technological capabilities, assisting businesses in overcoming resource constraints, and boosting their capacity for innovation in a dynamic business environment. The industries need to focus on worker upskilling, collaborations for advanced R&D, inclusion of alternative technologies, policies for technological innovations, and support for the industrial adoption of advanced energy technology.

The research suggested that supply chain perspective risk can be reduced by investing in local manufacturing, diversifying suppliers, and using digital tools like predictive analytics and real-time tracking to handle complexity and disruptions (Li et al., 2022; Li et al., 2023). Moreover, research findings promote resource optimization via recycling, sustainable sourcing, and controlled fossil-fuel phase-out techniques to support the energy transition supply chain. The study suggested that regulated subsidies can reduce socioeconomic risk and speed up energy transition projects. The technological advances that maximize EROI also mitigate socioeconomic risks, facilitating sustainable ETs in Indian manufacturing industries.

Furthermore, our research provides burgeoning literature on risk analysis in the energy transition supply chain. The study defined the risk priorities, potential RFs can be managed more effectively, financial losses can be reduced, and overall cost efficiency can be improved. Our study provides a structured approach for managers to prioritize upskilling employees, energy supply chain digitalization, supply chain diversification, and advanced climate-resilient structure installation to handle the rapid advancement of technology, adaptability, and capability development. The results also focus on the government as a primary stakeholder in developing and implementing appropriate ET risk mitigation measures for the manufacturing industry.

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[3] https://www.undp.org/asia-pacific/environment-and-energy

Moreover, our suggested strategies offer a structured lens for scholars to analyze the risk associated with the energy transition. The manufacturing industries should formulate energy transition strategies in accordance with the government policies. This would allow senior management to take preventative measures against risks, promoting a more efficient ET process in the sector. It enhances the academic discourse by delineating a precise trajectory of risk in energy transition, providing a refined model for future study to determine the intricate dynamics of energy transition.

7. Theoretical Policy Implications

This study explored the risks associated with the energy transition in the supply chain. A comprehensive set of risks is determined based on two theories, Socio-technical transitions and diffusion of innovation theories, and literature on risk in the supply chain in the energy transition. This study supports the socio-technical transitions theory by showing how systemic energy practices in manufacturing industries require social behaviour, policy, and technology to align. The academic implications of our work are profound, offering a significant extension to DOI by demonstrating how industrial preparedness and innovation diffusion processes in industrial networks affect the adoption and dissemination of energy-efficient technologies. From a methodological standpoint, this research is the inaugural study employing graph theoretic and matrix approach to measure the intensity of the risks in the energy transition.

This study acknowledges several limitations despite the new insights it offers. The findings are preliminary and have limited generalizability because the study was exploratory in nature. Furthermore, the results are specific to the Indian manufacturing sector, and the relevance outside this setting may be limited. Nonetheless, the findings are believed to be applicable to comparable developing nations. The six primary factors included in the GTMA-developed model might not fully capture all of the risks that the Indian manufacturing industries confront in the transition phase. Future studies could be considered with larger geographic regions, allowing comparisons of parallels and differences across different industries and nations to overcome these constraints.

8. Conclusion and Future Gap

The energy transition (ET) represents a pivotal shift across industrial and institutional tiers toward achieving a carbon-neutral, renewable-integrated economy. Within this context, the power, transportation, and fossil fuel sectors, responsible for approximately 45% of total emissions, are intrinsically linked to the manufacturing sector, making it a critical focus area for decarbonization efforts. This study investigates the potential risks that may disrupt the energy transition supply chain within the

Indian manufacturing sector, aiming to develop a systematic framework for risk identification and prioritization.

Through a combination of comprehensive literature review and expert elicitation, the study identifies six principal risk factors influencing the transition process: (i) environmental impact, (ii) institutional and technical limitations, (iii) supply chain dynamics, (iv) safety and security, (v) socio-economic challenges, and (vi) political and regulatory uncertainties. The study's theoretical foundation is anchored in the Socio-Technical Transitions (STT) framework and Diffusion of Innovation (DOI) theory, which together provide a robust lens for understanding the multi-level dynamics and adoption pathways of sustainable innovations. To analyse these interrelated risks, the study employs the Graph Theoretic and Matrix Approach (GTMA). GTMA facilitates holistic system analysis by decomposing complex structures into constituent components and modelling their interdependencies. In this framework, risk factors are represented as nodes, while the edges between them capture the strength and direction of their interrelationships. This structured graph-based representation allows for the derivation of system-level risk scores and supports data-driven decision-making for enhancing transition resilience and strategy development.

This study offers a significant academic contribution by systematically analysing the risks associated with the energy transition (ET) in the Indian manufacturing sector, an area that remains underexplored in existing literature. The research advances the current understanding of ETs through both theoretical grounding and empirical insight. First, the study enriches the theoretical discourse by applying the Socio-Technical Transitions (STT) and Diffusion of Innovation (DOI) theories. These frameworks provide a comprehensive lens to examine how technological systems evolve through interactions with social practices, institutional arrangements, and innovation adoption patterns. This theoretical foundation allows for a deeper understanding of the structural and dynamic complexities underlying energy transitions. Second, the study identifies and quantifies six key risk factors affecting the ET process using the Graph Theoretic and Matrix Approach (GTMA). The results reveal that safety and security (score: 0.7875) and political perspective (score: 0.7558) are the most critical risks, followed by environmental impact (0.6293), institutional and technical limitations (0.5801), supply chain perspective (0.5793), and socio-economic concerns (0.5770). These findings underscore the need for robust policy frameworks and institutional mechanisms that prioritize safety and regulatory stability to enable a secure and efficient energy transition.

Moreover, the study highlights the essential role of technological innovation in overcoming transition-related challenges. It emphasizes the importance of managerial leadership, particularly among senior executives, in driving environmental governance, policy enforcement, and cross-sector collaboration.

Strengthening engagement between industry stakeholders, civil society, and government institutions is crucial to ensuring an inclusive and resilient transition toward sustainable energy systems. It enhances the academic discourse by delineating a precise trajectory of risk in energy transition, providing a refined model for future study to determine the intricate dynamics of energy transition. The findings are preliminary and may have limited generalizability because the study was related to the Indian manufacturing sector. Nonetheless, the findings are believed to be applicable to comparable developing nations. Future studies could be considered with larger geographic regions, allowing comparisons of parallels and differences across different industries and nations to overcome these constraints.

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Appendix

Table A1. Sensitivity Analysis of Outcomes

	Original	**C- 0.05**	**C- 0.10**	**C- 0.15**	**C- 0.20**	**C- 0.25**	**C- 0.30**	**C- 0.35**	**C- 0.40**	**C- 0.45**	**C- 0.50**
Environmental	0.1610	0.1915	0.1815	0.1714	0.1613	0.1512	0.1411	0.1310	0.1210	0.1109	0.1008
Institutional and technical	0.1484	0.1766	0.1673	0.1580	0.1487	0.1394	0.1301	0.1208	0.1115	0.1022	0.0929
Supply chain perspective	0.1482	0.1763	0.1670	0.1577	0.1485	0.1392	0.1299	0.1206	0.1113	0.1021	0.0928
Safety and Security	0.2015	0.0500	0.1000	0.1500	0.2000	0.2500	0.3000	0.3500	0.4000	0.4500	0.5000
Socio-economic	0.1476	0.1756	0.1664	0.1571	0.1479	0.1386	0.1294	0.1201	0.1109	0.1017	0.0924
Political perspective	0.1934	0.2300	0.2179	0.2058	0.1937	0.1816	0.1695	0.1574	0.1453	0.1332	0.1211