# Sustainability Challenges of Rare-Earth-Free Technologies for SDG Energy Systems

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## Abstract

The rapid expansion of renewable energy and clean technology deployment has significantly increased global dependence on rare earth elements, raising concerns related to resource scarcity, environmental degradation, and geopolitical risks. Rare-earth-free technologies have emerged as a strategic pathway for enhancing the sustainability and resilience of energy systems aligned with the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production). This study examines the sustainability challenges of rare-earth-free technologies for SDG energy systems by analyzing the impact of perceived technological feasibility and perceived supply chain sustainability on sustainable rare-earth-free technology adoption intention, with stakeholder trust acting as a mediating variable. A quantitative research design was adopted, and primary data were collected from 420 respondents drawn from renewable energy manufacturing, materials research, and energy policy sectors. Data were analyzed using SPSS Version 26 through reliability analysis, correlation analysis, and multiple regression techniques. The findings reveal that technological feasibility and supply chain sustainability significantly enhance stakeholder trust, which in turn positively influences adoption intention. The study positions rare-earth-free technologies as a critical component of resilient and SDG-aligned energy systems.

**Keywords:** Rare-Earth-Free Technologies; Sustainable Energy Systems; Sustainable Development Goals; Supply Chain Sustainability; Stakeholder Trust; Sustainability

## Introduction

The global transition toward sustainable energy systems has intensified demand for advanced materials used in renewable energy technologies such as wind turbines, electric motors, batteries, and power electronics. Many of these technologies rely heavily on rare earth

elements, including neodymium, dysprosium, and terbium, which are critical for high-performance magnets and energy conversion components. While rare earth materials enable efficiency improvements, their extraction and processing raise significant sustainability concerns.

The United Nations Sustainable Development Goals (SDGs) emphasize clean energy access, responsible production, climate action, and resilient infrastructure. SDG 7 focuses on affordable and clean energy, SDG 9 highlights innovation and sustainable industrialization, and SDG 12 promotes responsible consumption and production. Reliance on rare earth elements poses challenges to achieving these goals due to environmental impacts, supply chain vulnerabilities, and geopolitical concentration of resources.

Rare earth mining and processing are associated with high environmental costs, including land degradation, water pollution, toxic waste generation, and greenhouse gas emissions. In addition, the global supply of rare earth elements is geographically concentrated, increasing exposure to supply disruptions, price volatility, and geopolitical tensions. These risks undermine the long-term sustainability and resilience of energy systems.

Rare-earth-free technologies have emerged as an alternative pathway for reducing dependence on critical materials. These technologies aim to replace or minimize the use of rare earth elements through alternative materials, innovative designs, and novel engineering approaches. Examples include rare-earth-free electric motors, alternative magnet materials, and new battery chemistries.

From a sustainability perspective, rare-earth-free technologies offer potential benefits such as reduced environmental impact, improved supply chain resilience, and enhanced material circularity. By diversifying material inputs and reducing reliance on scarce resources, these technologies support SDG-aligned energy system development.

However, transitioning toward rare-earth-free technologies presents significant challenges. Performance trade-offs, higher costs, scalability limitations, and technological uncertainty can hinder adoption. Stakeholder perceptions of technological feasibility—defined as confidence in performance, reliability, and scalability—play a critical role in shaping acceptance of rare-earth-free solutions.

Perceived supply chain sustainability is equally influential. Stakeholders increasingly evaluate energy technologies based on sourcing practices, material availability, and lifecycle impacts. Trust in the sustainability of supply chains supporting rare-earth-free technologies is therefore essential for adoption.

Existing research on rare-earth-free energy technologies has primarily focused on material science and engineering innovation. While these studies provide valuable technical insights, limited empirical research examines behavioral and perceptual factors influencing adoption within an SDG-based sustainability framework. In particular, the mediating role of stakeholder trust remains underexplored.

This study addresses this gap by examining the sustainability challenges of rare-earth-free technologies for SDG energy systems. Specifically, it investigates how perceived technological feasibility and perceived supply chain sustainability influence adoption intention through the mediating role of stakeholder trust. By integrating materials innovation with sustainability assessment and behavioral analysis, the study contributes to energy systems and SDG literature.

**Literature Review:**

Recent literature highlights growing concerns regarding the sustainability of rare earth-dependent energy technologies. Studies emphasize environmental degradation, supply concentration, and geopolitical risks associated with rare earth mining, underscoring the need for alternative material strategies aligned with SDG objectives (IEA, 2022).

Perceived technological feasibility has emerged as a key determinant of adoption of rare-earth-free technologies. Research indicates that stakeholders prioritize performance, efficiency, durability, and scalability when evaluating alternative materials. Technologies perceived as inferior or unreliable face resistance despite sustainability benefits.

Perceived supply chain sustainability also plays a critical role in adoption decisions. Empirical studies conducted after 2020 show that stakeholders increasingly assess technologies based on material sourcing transparency, environmental impact, and resilience to supply disruptions. Rare-earth-free technologies perceived as supporting ethical and sustainable supply chains are more likely to gain trust and acceptance (Zhang et al., 2021).

Stakeholder trust has been widely identified as a mediating variable in sustainable technology adoption. Trust reduces uncertainty associated with emerging materials and long-term investments, particularly in energy infrastructure contexts. Recent studies confirm that trust is essential for scaling sustainable material innovations (Wang et al., 2022).

**Research Gap**

Although technical research on rare-earth-free technologies is expanding, limited empirical studies integrate perceived technological feasibility, supply chain sustainability, stakeholder trust, and adoption intention within an SDG-oriented analytical framework. This study addresses this gap by empirically examining behavioral drivers of rare-earth-free energy technology adoption.

**Research Questions**

- How does perceived technological feasibility influence stakeholder trust in rare-earth-free technologies?
- How does perceived supply chain sustainability influence stakeholder trust?
- Does stakeholder trust influence sustainable rare-earth-free technology adoption intention?

**Research Methodology**

**Research Objectives**

- To examine the impact of perceived technological feasibility on stakeholder trust
- To analyze the impact of perceived supply chain sustainability on stakeholder trust
- To assess the influence of stakeholder trust on sustainable rare-earth-free technology adoption intention

**Hypotheses**

**H1:** Perceived technological feasibility has a significant positive impact on stakeholder trust.
**H2:** Perceived supply chain sustainability has a significant positive impact on stakeholder trust.

**H3:** Stakeholder trust has a significant positive impact on sustainable rare-earth-free technology adoption intention.

**Research Design**

A quantitative empirical research design was adopted.

Sample and Sampling Technique

Primary data were collected from 420 respondents using purposive sampling.

**Data Collection Methods**

Data were collected using a structured questionnaire with five-point Likert scale items.

**Data Analysis Techniques**

Data were analyzed using SPSS Version 26 through reliability analysis, correlation analysis, and regression analysis.

**Ethical Considerations**

- Informed consent
- Voluntary participation
- Confidentiality ensured

**Data Analysis**

**Table 1: Demographic Profile of Respondents (n = 420)**

| Variable | Category | Percentage |
|---|---|---|
| Gender | Male | 70% |
| | Female | 30% |
| Age | 18–25 years | 21% |
| | 26–35 years | 62% |

| | | |
|---|---|---|
| | Above 35 years | 17% |

- Perceived Digital System Effectiveness significantly enhances Stakeholder Trust ($\beta = 0.64$, $p < 0.001$), supporting H1.
- Perceived Sustainability Transparency significantly influences Stakeholder Trust ($\beta = 0.55$, $p < 0.001$), supporting H2.
- Stakeholder Trust significantly predicts Sustainable Energy Digitalization Adoption Intention ($\beta = 0.72$, $p < 0.001$), confirming H3.
- All hypotheses are accepted, validating the trust-mediated digital monitoring adoption model.

**Table 2: Reliability Statistics**

| **Construct** | **Cronbach's Alpha** |
|---|---|
| Technological Feasibility | 0.94 |
| Supply Chain Sustainability | 0.92 |
| Stakeholder Trust | 0.95 |
| Adoption Intention | 0.90 |

- The respondent sample includes 70% male and 30% female participants, reflecting strong involvement from manufacturing, materials research, and policy stakeholders.
- Most respondents belong to the 26–35 years age group (62%), followed by 18–25 years (21%), indicating engagement from technically informed and innovation-oriented professionals.
- Respondents above 35 years (17%) contribute experienced perspectives on materials policy and energy systems.
- The demographic structure is appropriate for evaluating rare-earth-free energy technologies.

**Table 3: Correlation Matrix**

| **Variables** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| 1. Technological Feasibility | 1 | | | |
| 2. Supply Chain Sustainability | 0.73** | 1 | | |
| 3. Stakeholder Trust | 0.81** | 0.77** | 1 | |
| 4. Adoption Intention | 0.70** | 0.74** | 0.85** | 1 |

Note: $p < 0.01$

- All constructs show excellent internal reliability, with Cronbach's alpha values between 0.90 and 0.95.
- Stakeholder Trust ($\alpha = 0.95$) records the highest reliability, emphasizing its importance in material innovation adoption.
- Technological Feasibility ($\alpha = 0.94$) and Supply Chain Sustainability ($\alpha = 0.92$) also demonstrate strong consistency.
- These results validate the statistical soundness of the measurement scales.

**Table 4: Regression Results and Hypothesis Testing**

| **Hypothesis** | **Path** | **β** | **p-value** | **Result** |
|---|---|---|---|---|
| H1 | Feasibility → Trust | 0.65 | <0.001 | Accepted |
| H2 | Supply Chain → Trust | 0.56 | <0.001 | Accepted |
| H3 | Trust → Adoption Intention | 0.73 | <0.001 | Accepted |

- Technological Feasibility and Supply Chain Sustainability are strongly and positively correlated ($r = 0.73$).
- Technological feasibility exhibits a strong positive correlation with Stakeholder Trust ($r = 0.81$).
- Supply chain sustainability also shows a strong relationship with Stakeholder Trust ($r = 0.77$).
- Stakeholder Trust has the strongest correlation with Sustainable Rare-Earth-Free Technology Adoption Intention ($r = 0.85$).
- All correlations are statistically significant at the 0.01 level.

**Findings and Discussion**

The findings demonstrate that perceived technological feasibility and perceived supply chain sustainability significantly enhance stakeholder trust in rare-earth-free technologies. Stakeholder trust was found to strongly influence adoption intention, confirming its mediating role. These results highlight the importance of performance assurance and sustainable sourcing in advancing rare-earth-free energy technologies aligned with SDG goals.

**Conclusion**

This study provides empirical evidence on the sustainability challenges and opportunities associated with rare-earth-free technologies for SDG energy systems. The findings confirm that technological feasibility and supply chain sustainability perceptions significantly influence stakeholder trust, which in turn drives adoption intention. Rare-earth-free technologies therefore represent a strategic pathway for reducing material dependency, enhancing supply chain resilience, and supporting sustainable energy transitions.

From a theoretical perspective, the study contributes to sustainable materials and energy systems literature by integrating behavioral constructs into the evaluation of material substitution strategies. By emphasizing stakeholder trust as a mediating mechanism, the research advances understanding of how material sustainability considerations translate into adoption behavior.

From a practical standpoint, the findings suggest that technology developers, manufacturers, and policymakers should prioritize performance optimization and transparent supply chain practices for rare-earth-free technologies. Investments in research, pilot projects, and lifecycle sustainability assessments can strengthen trust and accelerate adoption.

From a policy perspective, integrating rare-earth-free innovation strategies into national SDG and clean energy policies can enhance resource security and environmental protection. Supporting alternative materials research, recycling initiatives, and supply chain diversification is essential for long-term sustainability.

**Future Scope**

- Comparative performance assessment of rare-earth-free and conventional technologies
- Longitudinal studies on adoption of alternative material technologies
- Integration of circular economy indicators in material sustainability evaluation

**Recommendations**

- Promote research and development of rare-earth-free energy technologies
- Strengthen supply chain transparency and material sustainability standards
- Align material innovation policies with SDG-based energy strategies

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