Journal of Environmental Economics & Chemical Processes (JEECP)

https://doi.org/10.22034/jeecp.2026.2088427.1021

Journal Homepage: *WWW.JEECPJournal.com*

Journal of Environmental Economics & Chemical Processes (JEECP)

ORIGINAL RESEARCH PAPER

Financial Engineering for Green Industrial Transition: Designing Risk-Sharing and Technology-Matching Instruments for Low-Carbon Chemical and Energy-Intensive Processes

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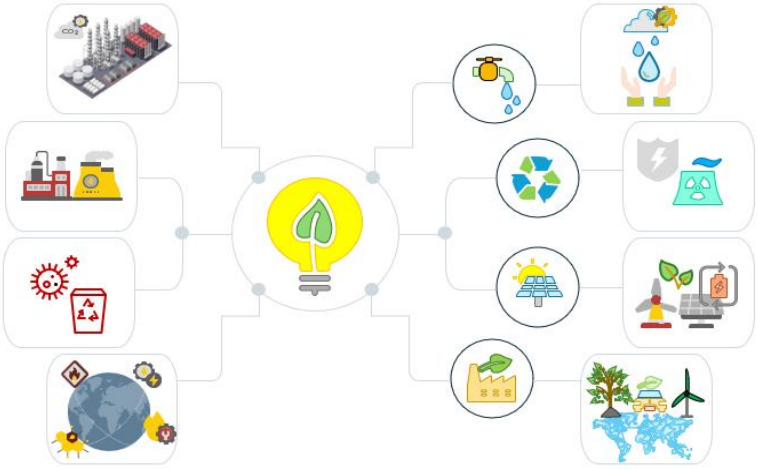
P A P E R I N F O

Paper history:
Received: 06/20/2026
Revised: 07/27/2026
Accepted in revised form: 08/05/2026
Published: 09/30/2026

***Keywords*:**
Financial engineering;
green finance; chemical processes;
industrial decarbonization;
transition finance;
risk-sharing; carbon contracts for difference.

A B S T R A C T

Low-carbon transition in chemical and energy-intensive industries requires more than technological readiness; it also requires financial structures capable of allocating technological, market, policy, and environmental-verification risks. This study developed a financial engineering framework for matching green industrial technologies with appropriate risk-sharing and financing instruments. An exploratory sequential mixed-methods design was used. First, semi-structured interviews with 24 experts in financial engineering, environmental economics, chemical engineering, project finance, and sustainability policy identified the main dimensions of finance–technology matching. Second, a two-round Delphi panel of 19 experts validated and refined the framework. Third, the fuzzy Technique for Order Preference by Similarity to Ideal Solution, a fuzzy multi-criteria decision analysis (MCDA) procedure, used 42 valid expert questionnaires to prioritize matching criteria and rank financial engineering instruments. Fourth, the framework was examined through four structured plausibility applications green ammonia, renewable methanol, carbon capture and utilization, and circular plastics or advanced recycling rather than company-level empirical case studies. Technology maturity, revenue certainty, and capital intensity received the greatest criterion weights. At the aggregate screening level, blended finance, public guarantees, offtake-backed project finance, and carbon contracts for difference were most suitable for high-risk transition profiles, whereas green bonds and sustainability-linked loans were more suitable for mature and verifiable projects. The aggregate ranking does not imply universal superiority of instruments; suitability depends on the dominant risk profile. The study contributes by positioning financial engineering as an active mechanism for mobilizing capital, allocating risk, stabilizing revenue, and strengthening the credibility of green industrial investment.



1. Introduction

The transition toward low-carbon industrial production has become one of the central challenges of environmental economics, energy policy, and chemical process innovation. While power generation and transport electrification have received substantial policy and financial attention, chemical and energy-intensive industries remain harder to decarbonize because they rely on fossil feedstocks, high-temperature process heat, long-lived capital assets, complex supply chains, and emission-intensive intermediate products [1,2]. The chemical sector is particularly important because it supplies essential inputs to agriculture, construction, pharmaceuticals, plastics, textiles, packaging,

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ISSN: 3116-0050
URL: https://www.jeecpjournal.com/article_735555.html

Please cite this article as: A. Zamanpour, *Journal of Environmental Economics & Chemical Processes (JEECP)*, 2026, *3*(3), 145-152. https://doi.org/10.22034/jeecp.2026.2088427.1021

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electronics, and energy systems. Consequently, decarbonizing chemical and related process industries is not simply an environmental issue; it is also a financial, technological, industrial, and macroeconomic problem that requires coordinated investment, risk allocation, and policy design. Recent global assessments have shown that achieving net-zero pathways requires a rapid increase in clean-energy and industrial decarbonization investment [2-4]. However, the investment problem is not only about the total amount of capital. It is also about the fit between financial instruments and technological risk. Many low-carbon chemical technologies, including green hydrogen-based ammonia, renewable methanol, electrified chemical production, carbon capture and utilization, circular plastics, and bio-based feedstock routes, face different combinations of technology readiness, market risk, policy uncertainty, offtake uncertainty, feedstock volatility, and carbon-price exposure [5-11]. Traditional corporate finance and project finance mechanisms often fail to match this risk profile, especially where technologies are not yet commercially mature, carbon markets are incomplete, and green product premiums remain uncertain.

For this reason, financial engineering is increasingly relevant to environmental economics and chemical process transition. In the present study, financial engineering refers to the design of financial instruments, contractual mechanisms, risk-sharing structures, and finance–technology matching arrangements that can mobilize capital for low-carbon industrial processes while distributing risks among firms, investors, lenders, governments, and technology providers. This perspective goes beyond the generic expansion of green finance. It asks which financial structures are suitable for which decarbonization technologies, at which stage of maturity, and under which policy conditions. For example, mature energy-efficiency projects may be financed through green loans or performance-based contracts, whereas first-of-a-kind chemical process technologies may require blended finance, guarantees, contracts for difference, public procurement, offtake agreements, transition bonds, or sustainability-linked instruments tied to measurable emission-reduction milestones [5-8,12-14].

Chemical process decarbonization has several distinctive features that justify a dedicated financial engineering framework. First, carbon is not only emitted as energy-related CO2; it is also embedded in many chemical products, especially plastics and organic chemicals [15-21]. Second, the sector requires large quantities of clean electricity, hydrogen, sustainable carbon sources, and carbon management infrastructure, which means that technology investment depends on wider energy-system transformation [9-11,22,23]. Third, green chemical products often compete with conventional fossil-based products that are cheaper under current market conditions unless carbon costs, procurement policies, or green premiums are introduced [7,8]. Fourth, environmental performance is difficult to evaluate with a single metric because chemical process innovation may involve trade-offs among energy use, process emissions, water use, toxicity, feedstock availability, circularity, and life-cycle impacts [15-21]. These characteristics make simple debt finance insufficient and create a need for structured instruments that allocate risk according to technological, environmental, and commercial uncertainty. The financing gap in industrial decarbonization is particularly important for emerging and developing economies, where industrial demand continues to grow but access to long-term affordable capital is limited [5,6,24]. In these contexts, the cost of capital for low-carbon projects can be high, policy frameworks may be unstable, and firms may lack the balance-sheet capacity to absorb technology risk. At the same time, delaying the transition may increase exposure to future carbon border measures, stranded assets, import dependency, and competitiveness losses. Therefore, the design of financial instruments for green industrial transition must be compatible with both environmental goals and industrial development priorities.

Existing literature has established a strong foundation in green finance, climate risk, green bonds, sustainable investment, and central bank responses to climate change [25-37]. However, much of this literature remains either macro-financial or at the market level, with less attention to the specific financial architecture required for chemical and process-industry decarbonization. Similarly, the chemical engineering literature has extensively examined pathways such as carbon capture and utilization, renewable methanol, green ammonia, plastics circularity, and electrification [9-11,15-23], but it has often treated financing as an external enabling condition rather than as an endogenous design variable. This creates a research gap at the intersection of environmental economics, chemical process transition, and financial engineering. Accordingly, this study proposed a finance–technology matching approach for green industrial transition. The approach classified low-carbon chemical and energy-intensive process technologies according to maturity, capital intensity, revenue certainty, emission-reduction measurability, policy dependence, market adoption risk, infrastructure dependence, and investor risk tolerance. It then linked each technology profile with suitable financial engineering instruments, including green bonds, transition bonds, sustainability-linked loans, blended finance, guarantees, contracts for difference, offtake-backed project finance, carbon-credit monetization, insurance instruments, and public-private investment vehicles [12-14,24,38-42]. The main contribution of the study is to reposition financial engineering as a bridge between environmental policy, industrial decarbonization, and chemical process innovation.

To operationalize this gap, the study pursued four objectives: (1) identify the criteria that determine compatibility between low-carbon industrial technologies and financial engineering instruments; (2) prioritize those criteria; (3) differentiate the suitability of financing instruments across technology profiles that vary in maturity, capital intensity, revenue certainty, environmental-verification requirements, policy dependence, infrastructure dependence, market adoption risk, and investor risk tolerance; and (4) examine the internal coherence and practical plausibility of the framework across four selected technology applications.

Accordingly, the study addressed the following research questions:

RQ1. Which criteria determine compatibility between low-carbon industrial technologies and financial engineering instruments?

RQ2. How should the identified finance–technology matching criteria be prioritized?

RQ3. Which financial engineering instruments are most suitable for technologies with different maturity, capital, revenue, policy, infrastructure, market-adoption, verification, and investor-risk profiles?

RQ4. How does the proposed framework operate across green ammonia, renewable methanol, carbon capture and utilization, and circular plastics or advanced recycling?

1.2. Literature Review

1.2.1. Green industrial transition and the challenge of chemical process decarbonization

The global net-zero transition has shifted the focus of environmental policy from isolated emission-reduction projects toward systemic industrial transformation. The IPCC emphasized that limiting warming requires rapid and deep reductions across energy, industry, transport, buildings, and land systems [1]. The IEA similarly argued that the net-zero pathway depends on accelerated deployment of clean technologies, infrastructure investment, energy efficiency, electrification, hydrogen, carbon capture, and low-emission fuels [2]. However, chemical and energy-intensive industries are among the most difficult sectors to transform because they combine process emissions, dependence on fossil feedstocks, high capital intensity, and globally competitive product markets.

The chemical industry is distinctive because it converts hydrocarbon feedstocks into materials that enter almost every industrial value chain. Levi and Cullen mapped global chemical flows and showed that fossil feedstocks are deeply embedded in chemical production and product use [20]. Zheng and Suh further demonstrated that plastics contribute significantly to global carbon emissions across production, conversion, and end-of-life stages [19]. These findings indicate that chemical decarbonization cannot be reduced to switching electricity sources. It requires changes in feedstock, process design, product circularity, carbon management, and demand-side systems.

Several technological pathways have been proposed. Kätelhön et al. showed that carbon capture and utilization could contribute to climate mitigation if powered by low-carbon energy and integrated with appropriate process design [15]. Artz et al. reviewed CO2 conversion technologies and emphasized that catalytic performance, system boundaries, life-cycle assessment, and energy inputs are crucial for evaluating sustainability [17]. Hepburn et al. highlighted the technological and economic potential of CO2 utilization and removal but cautioned that climate benefits depend on scale, permanence, energy source, and displacement effects [18]. Gabrielli et al. argued that a net-zero chemical industry may require combinations of carbon capture and storage, carbon capture and utilization, biomass, recycling, and low-carbon hydrogen rather than a single dominant pathway [16]. More recent work on circular carbon strategies has strengthened this integrated perspective. Meys et al. argued that net-zero plastics would require circular carbon management involving recycling, biomass, CO2 utilization, and renewable energy [21]. Renewable methanol has also been discussed as a platform chemical and fuel that could connect green hydrogen, captured carbon, and industrial demand [11]. In ammonia production, low-carbon hydrogen is central because conventional ammonia production is highly dependent on fossil fuels [9,10]. These studies collectively show that chemical process decarbonization is technologically feasible but financially demanding, infrastructure-dependent, and exposed to substantial commercialization risk.

1.2.2. Climate finance, green finance, and the limits of generic instruments

Green finance has expanded rapidly through green bonds, sustainable loans, climate funds, and ESG investment products. The literature generally finds that green financial instruments can reduce financing costs, improve investor signaling, and align capital markets with environmental objectives under certain conditions. Flammer showed that corporate green bonds can generate positive environmental signals and may be associated with improved environmental performance and investor response [32]. Tang and Zhang found that shareholders may benefit from green bond issuance because such issuance can attract investor attention and improve liquidity [33]. Zerbib documented the existence of a green bond premium, although its magnitude depends on

issuer, rating, currency, and market conditions [34]. Tolliver et al. examined drivers of green bond market growth and highlighted the importance of policy support, market credibility, and institutional development [35].

Despite this progress, green finance instruments are often insufficient for hard-to-abate sectors. Mature renewable energy projects can be financed with relatively standardized green bonds or project finance because revenue streams and technologies are clearer. By contrast, chemical process decarbonization may involve first-of-a-kind plants, uncertain technology performance, weak demand for green products, uncertain carbon prices, and complex life-cycle verification. These risks can prevent projects from reaching final investment decisions even when the technology is technically promising [5-8]. Therefore, financial engineering for the chemical sector must move beyond labeling finance as green and must instead structure capital according to project-specific risk. The literature on climate finance also shows that public policy is essential for mobilizing private investment. Financial-sector measures can unlock low-carbon investment only when real-sector demand, policy incentives, and project pipelines are sufficiently developed [6,24]. OECD analyses of industrial decarbonization in emerging and developing economies similarly show that concessional capital, guarantees, blended finance, and policy de-risking are often necessary where commercial risks remain high [5,14]. These insights are especially relevant for chemical processes because investors must evaluate not only financial return but also technology readiness, feedstock access, infrastructure availability, and regulatory stability.

1.2.3. Transition finance and hard-to-abate sectors

Transition finance has emerged to address a limitation of conventional green finance: many high-emitting firms cannot immediately qualify as green, yet they require large investments to reduce emissions in credible, measurable ways. The G20 Transition Finance Framework emphasized that transition finance should support credible decarbonization pathways, avoid greenwashing, and link financing conditions to transparent transition plans [12]. The ICMA Climate Transition Finance Handbook similarly highlighted the importance of issuer-level strategy, environmental materiality, science-based targets, implementation transparency, and reporting [13]. OECD guidance on transition finance stressed that credible corporate transition plans are essential for distinguishing genuine transition investment from the mere reclassification of existing activities [14].

For the chemical and process industries, transition finance is particularly relevant because the sectors encompass both incremental improvements and radical technology shifts. Some firms may reduce emissions through energy efficiency, waste heat recovery, renewable electricity procurement, and process optimization. Others may need to invest in green hydrogen, electrification, carbon capture, circular feedstock systems, and alternative chemical routes. A single green taxonomy may not capture this diversity. Transition finance can therefore provide a more flexible framework, provided that instruments are tied to measurable emissions intensity, capital expenditure alignment, and credible technology roadmaps. However, transition finance also creates risks. If weakly designed, it can finance marginal improvements without supporting deep decarbonization. If overly strict, it may exclude firms in emerging economies or hard-to-abate sectors that need capital most. This tension suggests that financial engineering should combine environmental integrity with practical transition sequencing. Instruments such as sustainability-linked loans, transition bonds, carbon contracts for difference, and blended finance facilities can be structured with step-down coupons, penalty clauses, performance triggers, and third-party verification. These design features can align financing costs with decarbonization milestones while preserving flexibility for industrial firms.

1.2.4. Financial risk, climate transition risk, and industrial investment

Climate-related financial risk has become a central concern for financial institutions and regulators. Bolton et al. introduced the idea of the green swan to describe potentially systemic climate risks that are difficult to model using historical data [25]. The Network for Greening the Financial System developed climate scenarios to help central banks and supervisors assess transition and physical risks under different policy pathways [26]. Campiglio et al. argued that climate change poses challenges for central banks and financial regulators by affecting monetary policy, financial stability, and credit allocation [27]. Dikau and Volz further showed that central banks can promote green finance when sustainability objectives are compatible with their mandates [28].

Climate transition risk is especially important for carbon-intensive industrial assets. Battiston et al. proposed a climate stress-test approach to evaluate the exposure of financial networks to climate-policy shocks [31]. Semieniuk et al. reviewed low-carbon transition risks for finance and emphasized that financial institutions may be exposed through equity, debt, and credit relationships with high-emitting sectors [29]. Monasterolo argued that climate-related financial risk requires forward-looking methods because historical default data do not reflect future policy and technology disruptions [30]. These studies imply that financial engineering for the chemical transition must incorporate climate risk assessment into instrument design.

For example, a loan to a conventional petrochemical plant may face transition risk if future carbon pricing, regulation, or demand shifts reduce profitability. Conversely, a loan to a first-of-a-kind green ammonia plant may face technology and offtake risk. The two projects require different risk-sharing structures. Conventional credit-risk models may misprice both. Therefore, *finance–technology* matching must integrate climate stress testing, life-cycle emission metrics, technology readiness, and policy-scenario analysis. This approach can help lenders and investors distinguish between assets that are transition-aligned, transition-exposed, or potentially stranded.

1.2.5. Technology-finance matching in chemical and energy-intensive processes

The concept of technology-finance matching is based on the idea that different technologies require different financial structures. Technologies at high readiness levels with stable revenue can attract commercial debt or green bonds. Technologies at demonstration scale may require concessional capital, guarantees, public equity, or blended finance. Technologies facing demand uncertainty may need offtake agreements or green public procurement. Technologies exposed to carbon price uncertainty may benefit from contracts for difference or carbon price floors. Technologies with measurable emission outcomes may be suitable for sustainability-linked finance.

This logic is increasingly visible in industrial decarbonization reports and transition-finance guidance. Hard-to-abate sectors require coordinated action across demand creation, finance, infrastructure, and policy [8,38-40]. Transition finance also requires credible methods for assessing whether financed activities contribute to sectoral decarbonization [12-14]. In the chemical sector, this means financial matching must account for environmental verification. A green ammonia project depends on the carbon intensity of hydrogen production, electricity supply, plant utilization, and downstream use. A renewable methanol project depends on a hydrogen source, a carbon source, and product displacement. A plastics circularity project depends on recycling quality, energy inputs, leakage, and life-cycle emissions. Therefore, financial instruments should not only fund capital expenditure; they should also require performance indicators that reflect actual environmental outcomes.

1.2.6. Research gap and conceptual direction

The reviewed literature shows four main research gaps. First, studies on chemical process decarbonization have produced detailed technological pathways, but they often lack a structured financing framework that explains how risks should be allocated among investors, firms, governments, and customers [15-23]. Second, green finance studies have examined bonds, ESG investment, and climate finance at market level, but they have paid less attention to the specific financing needs of hard-to-abate chemical and process industries [32-37]. Third, transition finance frameworks have clarified the need for credible transition plans, but their operational translation into finance–technology matching instruments remains underdeveloped [12-14]. Fourth, climate-risk literature has advanced scenario analysis and stress testing, but these tools are not yet sufficiently integrated into the design of financial instruments for industrial decarbonization [25-31].

To address these gaps, the present study developed a financial engineering perspective for green industrial transition. The proposed perspective assumed that low-carbon chemical and energy-intensive processes should be financed according to their technological maturity, emission-reduction credibility, capital intensity, revenue certainty, infrastructure dependence, and policy exposure. Instead of treating finance as a passive source of capital, the study treated financial engineering as an active design mechanism that can shape project bankability, risk distribution, and environmental accountability.

2. Method

2.1. Methodology

This study adopted an applied, exploratory, sequential mixed-methods design to develop and validate a finance–technology matching framework for the green industrial transition in chemical and energy-intensive processes. The sequence was aligned with the research questions: qualitative inquiry identified candidate criteria (RQ1), Delphi validation refined the conceptual structure, fuzzy TOPSIS prioritized criteria and financing alternatives (RQ2–RQ3), and structured technology applications examined framework plausibility (RQ4). The four phases were therefore qualitative framework development, expert-based Delphi validation, fuzzy multi-criteria prioritization, and multi-case plausibility assessment. The research focused on low-carbon chemical and energy-intensive industrial processes requiring substantial capital investment, measurable emission-reduction potential, and exposure to technological, market, and policy uncertainty. The unit of analysis was the finance–technology matching decision the alignment between a specified technology-risk profile and an appropriate package of financial engineering instruments rather than an individual firm. Green ammonia, renewable methanol, carbon capture and utilization in chemical production, and circular plastics or advanced recycling were selected as structured plausibility applications because they span different levels of technology maturity, capital intensity, carbon-abatement potential, infrastructure dependence, and revenue uncertainty. These applications were analytical tests of the framework and were not conventional empirical case studies based on company-level or project-

level records. Participants were selected through purposive and snowball sampling. The target population included experts in green finance, financial engineering, environmental economics, chemical engineering, industrial decarbonization, energy transition, banking, capital markets, and sustainability policy. Inclusion criteria were at least eight years of professional or academic experience, familiarity with industrial decarbonization or green finance, and direct knowledge of at least one of the following areas: chemical-process innovation, sustainable finance, project finance, carbon markets, transition finance, environmental policy, or energy-intensive industries. In the qualitative phase, 24 experts participated in semi-structured interviews: 6 specialists in financial engineering and capital-market instruments, 5 in environmental economics and climate finance, 5 chemical or process engineers, 4 specialists in banking and project finance, and 4 policy or sustainability specialists. Interviews continued until thematic saturation was reached. No substantively new category emerged after the twenty-first interview, and three additional interviews were conducted to confirm saturation. In the Delphi phase, 19 experts from the original and extended pool evaluated the extracted dimensions, indicators, and proposed finance–technology matching criteria; all 19 completed both rounds. In the fuzzy TOPSIS phase, 42 valid expert questionnaires were analyzed. This sample size was appropriate for expert-based multi-criteria decision analysis rather than population-level statistical generalization.

All participants met the minimum requirement of eight years of relevant professional or academic experience. The pool included academic researchers, engineers, banking and project-finance specialists, and policy or regulatory practitioners; at least four participants had primary expertise in banking or project finance. The sampling matrix prioritized disciplinary breadth rather than proportional representation by employment sector or geography. Complete public/private, academic/industry, and national distributions were not available in the source manuscript; these counts should be added if they were recorded, and no subgroup comparisons should be claimed without the underlying data. Three instruments were used. First, a semi-structured interview protocol explored barriers to financing low-carbon chemical technologies, technology-specific risks, financial instruments, policy de-risking mechanisms, environmental-verification criteria, and conditions for instrument suitability. Second, a Delphi questionnaire, based on the qualitative findings and the literature review, asked experts to assess the relevance, clarity, necessity, and applicability of each dimension and indicator on a five-point scale. Third, a fuzzy TOPSIS questionnaire asked experts to compare criteria and rate the suitability of financing alternatives for each technology profile. Suitability judgments were converted into five linguistic categories, each represented as a triangular fuzzy number. Because the exact numerical mapping was not included in the source manuscript, the following standard five-level specification is inserted provisionally and must be checked against the original analysis file before submission: very low = (0.00, 0.00, 0.25), low = (0.00, 0.25, 0.50), medium = (0.25, 0.50, 0.75), high = (0.50, 0.75, 1.00), and very high = (0.75, 1.00, 1.00).

Data collection was conducted in four phases. Interviews were conducted online or in person, lasted 45–75 minutes, and were recorded, transcribed, and anonymized with participant consent. The preliminary framework was then circulated to the Delphi panel for two rounds of review. In round 1, experts commented on overlap, wording, and applicability; the research team revised definitions, merged duplicative indicators, and separated criteria that experts judged to have independent effects on decision-making. In round 2, the revised structure was re-rated. In the third phase, all 42 fuzzy TOPSIS respondents evaluated the relative importance of the criteria and rated each financing alternative against each of the four technology profiles. The fourth phase applied the validated framework to the four technology profiles, using the same analytical template: technology maturity, emission-reduction potential, capital requirements, revenue certainty, policy dependence, market demand, infrastructure dependence, environmental verification needs, and suitable financing instruments. Qualitative data were analyzed using thematic analysis. Open coding identified statements concerning financial barriers, technological uncertainty, policy risk, environmental verification, and financing mechanisms. Related codes were consolidated into first-order concepts and then into higher-level categories. Coding decisions, category definitions, and framework revisions were documented in an audit trail, and ambiguous interpretations were revisited against the full transcripts, member feedback, and literature-based categories before integration into the conceptual model. [Author verification required before submission: specify whether one or multiple researchers conducted coding and, if applicable, how coder disagreements were resolved; this information was not available in the source manuscript. The Delphi analysis used mean relevance scores, interquartile ranges (IQRs), qualitative comments, and Kendall's coefficient of concordance (W). A mean score of at least 3.75 was required for retention. IQR $\leq$ 1.00 indicated acceptable consensus, IQR $\leq$ 0.75 indicated high consensus, and IQR $\leq$ 0.50 indicated very high consensus. Items with lower agreement or conceptual overlap were revised, merged, repositioned, or removed. Kendall's W was interpreted as evidence of panel convergence and was statistically significant in both rounds ($p < .001$). For fuzzy TOPSIS, individual triangular fuzzy judgments were aggregated component-wise across experts. Criterion weights were defuzzified, normalized to sum to 1, and applied to the normalized fuzzy decision matrices. The fuzzy positive ideal solution and fuzzy negative ideal solution were then specified, and vertex distances from each alternative to both ideal solutions were calculated. The closeness coefficient for alternative i was computed as $CC_i = D_i^-/(D_i^+ + D_i^-)$, where D_i^+ is the distance from the positive ideal and D_i^- is the distance from the negative ideal. Alternatives were ranked in descending order of CC. No separate formal sensitivity analysis was conducted.

The qualitative phase generated six conceptual dimensions. During operationalization, financial structuring capacity was treated as the framework's design/output layer rather than as an input risk criterion. Infrastructure dependence, initially nested within capital intensity, and market adoption risk, initially nested within revenue certainty, were elevated because expert feedback indicated that each could independently alter instrument suitability. Investor risk tolerance remained a supporting boundary condition but was retained as a separate low-weight criterion to ensure that the proposed package was compatible with capital-provider preferences. The final MCDA hierarchy therefore comprised five core risk dimensions technology maturity, capital intensity, revenue certainty, environmental verification, and policy dependence plus three operational criteria: infrastructure dependence, market adoption risk, and investor risk tolerance.

Several procedures were used to enhance the quality of the study. In the qualitative phase, credibility was strengthened through expert triangulation, member checking, and direct comparison between interview data and literature-based categories. Dependability was supported by documenting all coding decisions, category development, and framework revisions. Confirmability was improved by maintaining an audit trail and by using expert feedback to reduce researcher bias. In the Delphi phase, content validity was supported by repeated expert evaluation of the extracted dimensions and indicators. In the fuzzy multi-criteria phase, reliability was addressed by using a structured questionnaire, consistent linguistic scales, and aggregation of expert judgments.

Participation was voluntary. All participants received information about the study's purpose, data use, confidentiality protections, and right to withdraw, and written informed consent was obtained before interviews or questionnaire completion. Transcripts and questionnaires were anonymized, and no personal or organizational identifiers were reported. The formal ethics review or exemption status is reported in the declaration section and must be completed from the authors' institutional records before submission.

3. Results and Discussion

The results are presented in the order of the research questions and methodological phases. The qualitative phase identified the conceptual dimensions and candidate criteria relevant to RQ1. Delphi validation refined the hierarchy, and fuzzy TOPSIS prioritized the decision criteria and ranked financing alternatives for RQ2 and RQ3. The structured applications then examined how the framework operated across the four selected technologies for RQ4. The findings showed that the financing of low-carbon chemical and energy-intensive processes could not be explained by a single green finance instrument. Rather, the results supported a differentiated financial engineering approach in which each technology required a specific combination of risk-sharing, policy support, environmental verification, and revenue-stabilizing mechanisms.

Table 1. Profile of expert participants

Expert group	Qualitative interviews	Delphi panel	Fuzzy MCDA questionnaires
Financial engineering and capital markets	6	5	10
Environmental economics and climate finance	5	4	8
Chemical/process engineering	5	4	9
Banking and project finance	4	3	7
Sustainability policy and regulation	4	3	8
Total	24	19	42

Source: Research Findings

As shown in Table 1, the largest expert group in the qualitative phase consisted of specialists in financial engineering and capital market instruments. Chemical and process engineering experts were also strongly represented, which was important because the study focused not only on finance but also on the technological characteristics of low-carbon industrial processes. In the fuzzy-MCDA phase, 42 valid questionnaires were analyzed. This number was considered sufficient because the analysis was based on expert judgment rather than population-leve l statistical generalization.

3.1. Qualitative dimensions of the framework

The interview data were analyzed through open coding, category development, and thematic integration. The coding process produced 286 initial codes. After removing repetitions and merging similar codes, 52 final concepts were retained. These concepts were grouped into 15 subcategories and 6 main dimensions. The main dimensions are reported in Table 2.

Table 2. Qualitative dimensions and key indicators of the framework

Main dimension	Key indicators	Interpretation
Technology maturity	Technology readiness level; scale-up risk; operational reliability; demonstration history	Financing suitability depended strongly on whether the technology was commercially proven or still at demonstration stage.
Capital intensity	Initial investment size; payback period; cost-overrun risk; infrastructure requirement (later operationalized separately as infrastructure dependence)	High-capital technologies required stronger risk-sharing and longer-term finance.
Revenue certainty	Product-market demand; green premium; offtake security; price volatility; market acceptance (later operationalized separately as market adoption risk)	Stable revenue was necessary for debt-based instruments and project finance.
Environmental verification	Life-cycle emissions; carbon intensity; circularity; additionality; monitoring quality	Financial credibility depended on measurable and verifiable environmental outcomes.
Policy dependence	Carbon pricing; tax incentives; procurement policy; subsidies; regulatory stability	Policy support reduced risk but also created exposure to policy uncertainty.
Financial structuring capacity (design/output layer)	Guarantees; blended finance; transition bonds; green bonds; sustainability-linked loans; contracts for difference	This dimension represented the framework's response layer—the capacity to assemble an instrument package—rather than an input criterion in the final fuzzy ranking.

Source: Research Findings

As shown in Table 2, technology maturity and revenue certainty were the most frequently emphasized conceptual dimensions. Across interviews, first-of-a-kind performance uncertainty was associated with the absence of an operating history on which lenders could rely; offtake certainty was treated as the mechanism that converts technical feasibility into bankable cash flow; policy instability was viewed as a source of unpriceable revenue risk; and life-cycle verification was considered necessary to distinguish genuine emissions reduction from relabeling. These recurring patterns explain why infrastructure dependence and market adoption risk were later separated from their parent dimensions for decision analysis. [Author action required: insert two or three authentic, anonymized interview quotations here—preferably on first-of-a-kind risk, offtake certainty, policy instability, and/or life-cycle verification. Verbatim quotations cannot be reconstructed from the manuscript file alone.]

3.2. Delphi validation of the framework

After the qualitative framework was developed, a 19-member Delphi panel evaluated it in two rounds. Round-1 feedback focused on overlap between capital intensity and infrastructure dependence, revenue certainty and market adoption, and financial structuring capacity and investor risk tolerance. Definitions were clarified, duplicative indicators were merged, and the distinction between conceptual dimensions, operational criteria, and the design/output layer was made explicit before round 2. All panel members completed both rounds. Table 3 reports the final round-2 ratings.

Table 3. Delphi validation of framework dimensions

Dimension	Mean relevance score	Interquartile range	Agreement level	Decision
Technology maturity	4.72	0.50	Very high	Retained
Capital intensity	4.61	0.50	Very high	Retained
Revenue certainty	4.66	0.50	Very high	Retained
Environmental verification	4.58	0.75	High	Retained
Policy dependence	4.49	0.75	High	Retained
Financial structuring capacity	4.70	0.50	Very high	Validated as design/output layer
Infrastructure dependence	4.43	0.75	High	Retained
Investor risk tolerance	4.36	1.00	Acceptable	Retained as supporting criterion

Source: Research Findings

As Table 3 shows, all reported dimensions or supporting elements received mean relevance scores above 4.30. Technology maturity, financial structuring capacity, revenue certainty, and capital intensity received the highest scores. Consensus was very high when the IQR was 0.50, high when the IQR was 0.75, and acceptable when the IQR was 1.00. Kendall's W increased from 0.61 in round 1 to 0.78 in round 2, and both coefficients were statistically significant ($p < .001$), indicating strong convergence. Investor risk tolerance showed the greatest dispersion and was therefore retained as a supporting criterion rather than a core conceptual dimension. Financial structuring capacity was validated as the response/output layer and was not included as an input criterion in Table 4. Note on hierarchy: Market adoption risk was operationalized following the Delphi panel's recommendation to separate demand formation from cash-flow predictability. It therefore appears as an independent criterion in the fuzzy TOPSIS hierarchy (Table 4), while financial structuring capacity remains the output layer that assembles the financing package.

3.3. Prioritization of finance–technology matching criteria

In the fuzzy TOPSIS phase, experts evaluated the relative importance of the eight final criteria and the suitability of financial alternatives for each technology profile. Aggregated triangular fuzzy judgments were normalized, weighted, and defuzzified as described in the Methodology. Table 4 reports the normalized criterion weights, which sum to 1.00.

Table 4. Fuzzy weights of *finance–technology* matching criteria

Criterion	Normalized weight	Rank
Technology maturity	0.174	1
Revenue certainty	0.158	2
Capital intensity	0.146	3
Environmental verification	0.133	4
Policy dependence	0.126	5
Infrastructure dependence	0.108	6
Market adoption risk	0.095	7
Investor risk tolerance	0.060	8

Source: Research Findings

As indicated in Table 4, technology maturity was the most influential criterion, followed by revenue certainty and capital intensity. Environmental verification ranked fourth, confirming that instrument credibility depended on measurable emissions or circularity outcomes. Investor risk tolerance received the smallest weight, which is consistent with its status as a supporting boundary criterion rather than a core technological or market risk dimension.

3.4. Ranking of financial engineering instruments

The next step ranked the suitability of ten financial engineering alternatives. Table 5 presents an aggregate screening result obtained across the four technology-profile evaluations; it is not a universal ranking for every project, country, or stage of technological development. The alternatives were green bonds, transition bonds, sustainability-linked loans, blended finance, public guarantees or credit enhancement, carbon contracts for difference, offtake-backed project finance, carbon-credit monetization, concessional loans, and insurance-based risk-transfer instruments.

Table 5. Overall ranking of financial engineering instruments

Financial engineering instrument	Closeness coefficient	Overall rank
Blended finance	0.812	1
Public guarantees and credit enhancement	0.786	2
Offtake-backed project finance	0.751	3
Carbon contracts for difference	0.724	4
Transition bonds	0.697	5
Sustainability-linked loans	0.664	6
Green bonds	0.621	7
Concessional loans	0.603	8
Carbon-credit monetization	0.574	9
Insurance-based risk-transfer instruments	0.548	10

Source: Research Findings

As shown in Table 5, blended finance received the highest aggregate closeness coefficient, followed by public guarantees or credit enhancement, offtake-backed project finance, and carbon contracts for difference. These instruments ranked highly because they address different sources of non-bankability—scale-up risk, credit risk, demand uncertainty, and policy-linked revenue volatility. The aggregate ranking should therefore be interpreted as a cross-profile screening result, not as evidence that blended finance is universally superior. Mature, verifiable, and revenue-stable projects may still be better served by green bonds or sustainability-linked loans.

3.5. Case-based finance–technology matching results

The framework was then applied to four structured technology profiles. Information for each profile was assembled from the cited technical and transition-finance literature and from the standardized expert assessments. All 42 fuzzy TOPSIS respondents rated the financing alternatives for each technology profile separately. The instrument packages summarized in Table 6 reflect the dominant risk profile, normalized criterion weights, and the leading technology-specific suitability judgments. These applications were plausibility assessments rather than conventional empirical case studies: no company-level financial statements, confidential project data, or transaction-level valuations

were used, and case-specific numerical matrices are not presented in the main text.

Table 6. Finance-technology matching results by technology case

Technology case	Dominant risk profile	Most suitable financial instruments	Matching interpretation
Green ammonia	High capital intensity; hydrogen price risk; infrastructure dependence	Blended finance; public guarantees; offtake-backed project finance; transition bonds	Financing required risk-sharing because project viability depended on hydrogen cost, renewable electricity access, and long-term demand.
Renewable methanol	Feedstock uncertainty; carbon-source risk; market adoption risk	Carbon contracts for difference; offtake agreements; transition bonds; sustainability-linked loans	Revenue stabilization and carbon-price support were necessary to make the business model bankable.
Carbon capture and utilization	Technology integration risk; uncertain carbon value; verification complexity	Blended finance; carbon contracts for difference; public guarantees; carbon-credit monetization	Public support and carbon-value mechanisms were required because commercial returns depended on avoided emissions and carbon utilization markets.
Circular plastics or advanced recycling	Feedstock quality risk; circularity verification; product-market uncertainty	Sustainability-linked loans; green bonds; offtake-backed finance; insurance instruments	Mature recycling projects could use green bonds, but advanced recycling required stronger verification and market-risk management.

Source: Research Findings

Table 6 shows that green ammonia and carbon capture and utilization (CCU) required the strongest de-risking structures because of their capital intensity, infrastructure dependence, policy exposure, and verification requirements. Renewable methanol was particularly sensitive to revenue stabilization and carbon-source credibility. Circular plastics and advanced recycling had a more heterogeneous profile: commercially mature mechanical recycling could access conventional green finance more readily, whereas advanced recycling required stronger market-risk controls and life-cycle verification.

3.6. Cross-case comparison and final framework

A cross-case comparison was conducted to identify general patterns across the four technology cases. Table 7 presents the main cross-case results.

Table 7. Cross-case patterns in finance–technology matching

Cross-case pattern	Evidence from cases	Implication for financial engineering
Greater technological uncertainty required stronger public risk sharing.	Green ammonia and CCU ranked highest in need for blended finance and guarantees.	Public capital should absorb early-stage or scale-up risks before private capital enters.
Revenue uncertainty required offtake and carbon-price mechanisms.	Renewable methanol and green ammonia require offtake-backed finance.	Demand creation should be integrated into financial design.
Environmental verification determined instrument credibility.	Circular plastics and CCU require life-cycle verification and monitoring.	Green or transition labels should be tied to measurable environmental outcomes.
Mature projects could access market-based instruments more easily.	Circular plastics received stronger suitability scores for green bonds and sustainability-linked loans.	Instrument selection should reflect technology readiness and cash-flow stability.
Policy dependence increased the need for contractual stabilization.	Carbon contracts for difference were important for CCU and renewable methanol.	Policy uncertainty should be converted into contractually manageable risk.

Source: Research Findings

As shown in Table 7, the strongest cross-case pattern was that financing instruments had to correspond to the dominant risk of each technology. Technologies with high technological uncertainty required public guarantees and blended finance. Technologies with high revenue uncertainty required offtake arrangements and contracts for difference. Technologies with high environmental verification complexity required monitoring-based instruments and performance-linked finance. Mature projects with stable cash flows were better suited to green bonds and sustainability-linked loans.

Table 8. Final finance–technology matching framework

Framework component	Main function	Main output
Technology classification	Identified readiness level, capital intensity, process integration, and infrastructure dependence	Technology-risk profile
Risk diagnosis	Assessed revenue risk, policy risk, market risk, scale-up risk, and verification risk	Dominant financing barrier
Environmental verification	Evaluated life-cycle emissions, carbon intensity, circularity, and additionality	Credibility of green or transition claim
Financial engineering selection	Matched instruments to risk profile and technology maturity	Financing package
Policy alignment	Connected finance design with carbon pricing, procurement, guarantees, and disclosure	Bankability and transition credibility

Source: Research Findings

As Table 8 indicates, the framework did not recommend a universal financing instrument for all green industrial technologies. Instead, it provided a structured decision process. First, the technology was classified. Second, the dominant risks were diagnosed. Third, the environmental value of the project was verified. Fourth, suitable financial engineering instruments were selected. Fifth, policy alignment mechanisms were added to improve bankability and credibility.

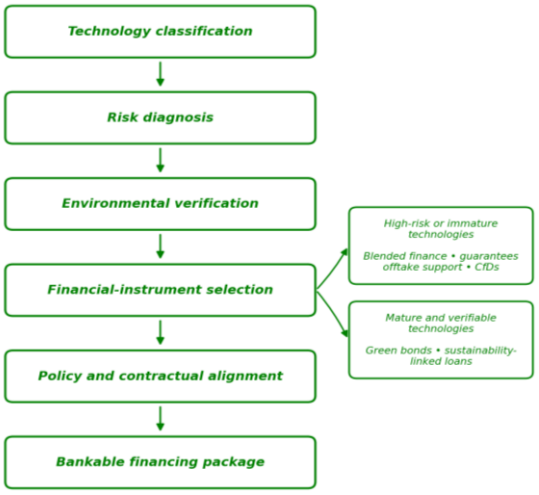


Figure 1. Sequential finance–technology matching pathway and conditional instrument families.

Source: Research Findings

Figure 1 emphasizes that instrument selection occurs only after technology classification, risk diagnosis, and environmental verification. High-risk or immature profiles tend toward public risk-sharing and revenue-stabilization instruments, whereas mature and verifiable profiles tend toward market-based green or performance-linked finance. Policy and contractual alignment then converts the selected instruments into a bankable financing package.

4. Conclusions

The findings indicate that financial engineering is not a peripheral support function in green industrial transition, but a core design mechanism that determines whether low-carbon chemical and energy-intensive process technologies can become bankable. This is consistent with the wider climate-finance literature, which argues that the transition requires not only larger volumes of capital but also risk-sensitive allocation of capital across technologies and sectors [5,6,24]. The results showed that generic green finance instruments are insufficient for hard-to-abate sectors because the dominant constraints are not limited to capital availability. Rather, they include scale-up risk, weak demand signals, uncertain carbon value, feedstock dependency, infrastructure gaps, and environmental verification complexity.

The first major finding was that technology maturity had the highest weight among the *finance–technology* matching criteria. This result is theoretically important because it shows that financing decisions in green chemical transition are strongly path-dependent. Mature technologies can be evaluated using conventional credit-risk and project-finance tools, while demonstration-stage technologies require public risk absorption, concessional finance, guarantees, or blended structures. This supports the view that low-carbon industrial technologies move through financing stages: early innovation finance, demonstration finance, scale-up finance, commercial debt, and capital-market refinancing. The findings also explain why green bonds, although important in

sustainable finance markets [32-35], ranked below blended finance and guarantees for high-risk chemical technologies.

The second major finding was that revenue certainty ranked above environmental verification and policy dependence, although all three were highly important. This suggests that investors and lenders require more than proof of emission reduction; they also require credible cash-flow mechanisms. In chemical and energy-intensive processes, revenue certainty can be created through offtake agreements, green public procurement, long-term supply contracts, carbon contracts for difference, and policy-backed price stabilization. This finding is consistent with transition finance frameworks that emphasize credible implementation plans and measurable transition pathways [12-14]. It also extends those frameworks by showing how credibility must be translated into project-level revenue design.

The third major finding concerned instrument architecture rather than a universally superior product. The highest-ranked aggregate instruments shared a common function: they converted risks that private financiers could not price confidently into risks that could be allocated contractually. Blended finance and guarantees absorbed scale-up or credit risk, offtake arrangements stabilized demand, and carbon contracts for difference stabilized policy-linked revenue. Their relative suitability nevertheless remained conditional on the technology profile and institutional setting.

The fourth finding concerns environmental verification. Experts emphasized that financial credibility depends on measurable and verifiable environmental outcomes. This is especially important in chemical processes because emission reductions may be affected by electricity source, hydrogen pathway, carbon feedstock, recycling quality, displacement assumptions, and end-of-life impacts [15-21]. Therefore, the green or transition label of a financial instrument should not be attached merely to a technology name. It should be tied to life-cycle carbon intensity, additionality, circularity, and monitoring procedures. This finding responds to concerns about greenwashing and transition-washing in sustainable finance and suggests that chemical process knowledge must be embedded into financial instrument design.

The cross-technology applications showed that the same instrument may be suitable for different reasons and at different stages. A guarantee may protect lenders against scale-up risk in an immature plant but reduce counterparty risk in a mature infrastructure project; similarly, an offtake agreement may support demand creation in one market and price stabilization in another. Table 6 should therefore be read as a set of conditional financing packages rather than a fixed instrument-to-technology lookup table.

These findings contribute to environmental economics by clarifying the relationship between policy uncertainty, market formation, and capital mobilization. In traditional environmental economics, policy instruments such as carbon pricing, subsidies, and regulation are often treated as incentives that shift firms' cost-benefit calculations. The present study shows that these policies also shape the financial architecture of investment. Stable policies reduce financing risk, while unstable policies raise the cost of capital and discourage long-term investment. Therefore, policy design should be integrated with financial instrument design. Carbon pricing, green procurement, public guarantees, and disclosure rules should be treated as components of bankability rather than as separate policy tools.

The study also contributes to research on chemical process transitions. Many process-level decarbonization studies focus on technical feasibility, energy efficiency, life-cycle emissions, or techno-economic performance. The present framework adds a financial layer to this analysis. It shows that technology selection and process design should be evaluated together with capital structure, risk allocation, revenue model, and verification requirements. A technically promising process may fail to scale if its risk profile does not fit available financing instruments. Conversely, financial engineering can accelerate deployment by converting uncertain risks into contractually manageable and verifiable obligations. The framework advances five theoretical propositions. First, technology maturity constrains the feasible capital structure because demonstration and scale-up risks cannot be financed on the same terms as proven operations. Second, policy mechanisms such as guarantees, procurement commitments, and carbon-price contracts are components of project bankability, not merely external incentives. Third, environmental verification is part of financial contract design because performance metrics determine eligibility, pricing, covenants, and the continuation of support. Fourth, revenue stabilization functions as a financing mechanism by converting uncertain market or carbon value into contractible cash flow. Fifth, finance–technology compatibility is a multidimensional matching problem in which technological, commercial, policy, infrastructure, verification, and investor constraints interact rather than operate independently.

The framework also has boundary conditions. Its implementation requires credible project preparation, contract enforcement, technical due diligence, life-cycle measurement capacity, and institutions capable of administering guarantees or performance-linked support. Advanced economies may rely more heavily on deep capital markets, stable carbon-policy regimes, and investment-grade counterparties. Emerging economies may require a larger concessional or sovereign-risk layer, currency-risk mitigation, multilateral participation, and stronger project-development facilities. Accordingly, the criterion weights and instrument rankings should be recalibrated when policy regimes, capital costs, or market institutions differ materially from those represented in the expert panel. From a practical perspective, firms should develop a finance–technology profile before approaching lenders or investors. The profile should document technology readiness, capital requirements, emission-reduction logic, revenue model, offtake strategy, infrastructure dependencies, verification plan, and policy exposure. Financiers can then use the framework as a screening and structuring sequence rather than treating a green label as sufficient evidence of bankability.

For policymakers, the findings imply that instrument design and institutional capacity must develop together. Taxonomies and transition-finance guidance require credible verification systems; guarantees require transparent eligibility and fiscal-risk controls; procurement or carbon contracts require durable counterparties and budget commitments; and blended-finance facilities require project pipelines and clear additionality rules. Without these capacities, nominally suitable instruments may fail to mobilize private capital or may create greenwashing, moral hazard, or contingent liability risks. This study developed and validated a financial engineering framework for green industrial transition in chemical and energy-intensive processes. The framework was based on the premise that low-carbon technologies require financing arrangements that correspond to their technological maturity, capital intensity, revenue certainty, environmental verification requirements, policy dependence, and infrastructure needs. By combining qualitative expert interviews, Delphi validation, fuzzy multi-criteria prioritization, and multi-case plausibility probing, the study provided a structured approach for matching financial instruments with low-carbon industrial technologies.

The main conclusion is that industrial decarbonization financing should be treated as a conditional matching problem rather than a search for one universally superior green instrument. The feasible package depends on how technological maturity, capital intensity, revenue formation, infrastructure, policy exposure, environmental verification, and investor tolerance combine in a specific project and institutional setting. Aggregate rankings are useful for screening, but final structuring must remain technology- and context-specific.

The study also concluded that environmental verification is essential for the credibility of green and transition finance. In chemical processes, environmental performance must be evaluated through life-cycle emissions, carbon intensity, circularity, additionality, and monitoring quality. Financial instruments should therefore include environmental performance triggers and reporting requirements. This is necessary to avoid greenwashing and to ensure that capital mobilization leads to measurable emission reductions.

The framework provides a common decision language for firms, investors, lenders, engineers, and policymakers. It can support project screening, identify the risk that prevents bankability, specify the environmental evidence required for financing, and clarify which public or contractual mechanism is needed before private capital can enter. Its principal value is therefore procedural: it links process characteristics to risk allocation and converts transition credibility into a financing design.

The study has several limitations. The findings rely on purposive expert sampling and may reflect expert-selection bias, disciplinary framing, or geographic concentration. Complete sectoral and national distributions were not available in the source manuscript, which limits assessment of panel diversity and transferability. The study did not use transaction-level financial data, completed-project default records, or observed changes in cost of capital. The four technology applications were structured as plausibility assessments rather than company-level empirical cases, and the ranking may be sensitive to policy regimes, market conditions, currency risk, and the maturity of local financial institutions. Instrument suitability will also change as technologies move from demonstration to commercial operation. No formal sensitivity analysis was conducted, and the framework was not directly validated by project developers, institutional investment committees, or lending and credit committees. Future research should test the framework with real project portfolios, country-specific decision matrices, longitudinal technology updates, and stakeholder groups responsible for final investment and credit decisions.

Author Contributions

The author was solely responsible for the conception, preparation, and writing of this manuscript.

Conflict of Interest

The author, while observing publication ethics in the referencing, declares the absence of any conflict of interest.

Acknowledgement

The authors gratefully acknowledges the support provided by the Islamic Azad University in conducting this research.

AI-Assisted

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