Journal of Environmental Economics & Chemical Processes (JEECP)

https://doi.org/10.22034/jeecp.2026.2088255.1019

Journal Homepage: WWW.JEECPJournal.com

Journal of Environmental Economics & Chemical Processes (JEECP)

ORIGINAL RESEARCH PAPER

# Financing Green Technology Pathways: A Financeability Typology for Capital Allocation and Greenwashing Risk

Abdolhossein Zameni (Pejman) *; Mahdi Khazaei

*Department of Management, UNF Faculty, University of Niagara Falls Canada, Niagara Falls, Canada.*

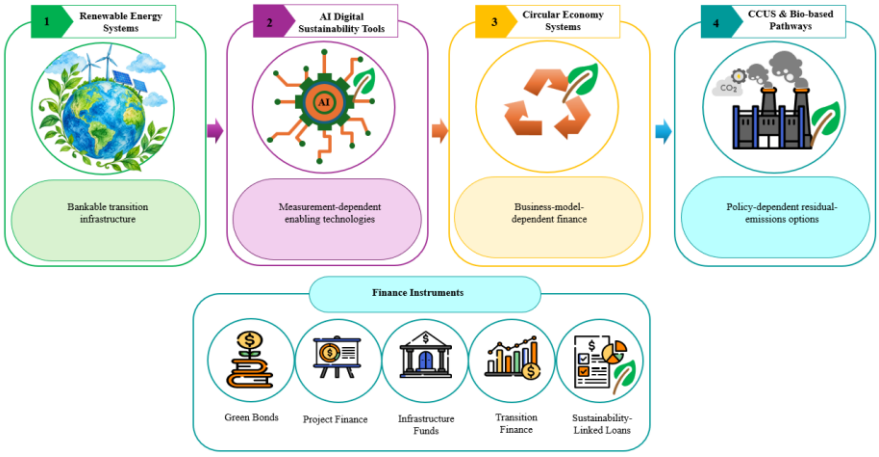
*P A P E R  I N F O*

***Paper history:***
Received: 06/09/2026
Revised: 09/07/2026
Accepted in revised form: 09/30/2026
Published: 03/30/2027

***Keywords:***
Sustainable Finance;
Green Bonds;
Capital Allocation;
ESG Lending;
Circular Economy Finance;
Transition Finance;
Greenwashing Risk.

*A B S T R A C T*

This paper develops a critical thematic review of green technology pathways from a sustainable finance perspective. Rather than treating green technologies as a single investable category, it asks how investors, banks, public finance institutions, and standard setters should allocate capital across pathways that differ in maturity, capital intensity, revenue certainty, system dependence, measurement difficulty, and greenwashing exposure. The analysis focuses on four analytically distinct archetypes: renewable energy systems as bankable transition infrastructure; artificial-intelligence-enabled digital sustainability tools as measurement-dependent enabling technologies; circular economy systems as business-model-dependent finance; and carbon capture, utilization, and storage (CCUS) and selected bio-based pathways as policy-dependent residual-emissions options. Drawing on peer-reviewed research in sustainable finance, climate finance, energy economics, sustainability transitions, industrial ecology, and environmental economics, the paper argues that financeability cannot be inferred from an environmental label alone. Its central contribution is a financeability typology that links technology characteristics to suitable instruments including green bonds, project finance, infrastructure funds, venture capital, private equity, blended finance, transition finance, and sustainability-linked loans and to the verification safeguards each pathway requires. The paper further shows that greenwashing risk varies across pathways because environmental outcomes differ in measurability, additionality, permanence, and disclosure burden. The central implication is that sustainable finance should aim not only to increase the volume of green capital, but to improve the quality and credibility of capital allocation across transition pathways.




## 1. Introduction

Sustainable finance has become one of the central mechanisms through which governments, investors, lenders, and firms seek to accelerate climate mitigation, resource efficiency, and broader sustainability transitions[1]. Its rapid expansion, however, has created a capital allocation problem. Financial markets increasingly label assets, securities, funds, and corporate strategies as green, yet the underlying technologies differ sharply in technological maturity, investment risk, revenue certainty, environmental measurability, and dependence on public policy. A mature solar or wind project backed by a long-term power-purchase agreement is not

* Corresponding Author: Abdolhossein Zameni (Pejman)
E-mail address: pejman.zameni@unfc.ca
ISSN: 3116-0050
URL: https://www.jeecpjournal.com/article_736318.html

Please cite this article as: A. H. Zameni, *Journal of Enviromental Economics & Chemical Processes (JEECP)*, 2027, *4*(1), 1-7. https://doi.org/10.22034/jeecp.2026.2088255.1019

/© 2027 The Author(s). Published by Power of New Vision Movement Institute.

financially equivalent to an early-stage carbon-removal venture, a circular product-as-a-service model, or an artificial-intelligence-enabled efficiency platform. This distinction matters because sustainable investing theory shows that investor preferences, risk perceptions, and climate beliefs can affect expected returns and asset prices, while empirical climate finance research shows that carbon exposure and environmental externalities can be reflected in the cost of capital, option prices, and equity return premia [2-6]. The existing green technology literature offers valuable evidence on decarbonization potential, energy-system integration, circular material flows, artificial-intelligence-enabled optimization, and carbon management. Sustainability transitions research has further shown that technologies do not diffuse in isolation but through socio-technical systems shaped by infrastructure, institutions, user practices, and incumbent resistance [7-10]. Much of this work evaluates technology pathways through environmental performance, policy relevance, or governance conditions. Sustainable finance research, by contrast, tends to focus on asset pricing, ESG performance, green bonds, investor preferences, climate risk, disclosure quality, and greenwashing [11-16]. The two streams are rarely integrated in a way that explains how technology characteristics become financing conditions. This separation matters because investors do not allocate capital to technologies simply because they are environmentally promising; they assess cash-flow stability, policy risk, construction risk, measurement and verification burdens, disclosure credibility, and exit potential. When these financial dimensions are neglected, sustainable capital may flow toward visible or easily labelled assets while underfunding system-critical infrastructure or overfunding technologies with weak environmental verification. Recent work on financing sustainability also emphasizes impact investing, green bonds, public-private partnerships, measurement standards, and public support as mechanisms for aligning environmental goals with investment decisions [17].

This paper addresses that gap by reframing green technology pathways as financeable or conditionally financeable transition assets. The core research question is: how can sustainable finance actors evaluate and allocate capital across green technology pathways that differ in maturity, capital intensity, revenue certainty, policy dependence, measurability, and greenwashing risk? This question moves the review beyond the general claim that green technologies support sustainability and asks instead how finance supports, constrains, prices, evaluates, and sometimes misallocates capital across pathways. The four pathways examined here are not offered as an exhaustive map of green technology. They are selected as analytically distinct archetypes of financeability: bankable infrastructure, enabling digital systems, circular business models, and policy-dependent residual-emissions technologies. This framing allows the paper to compare pathways without treating them as technologically equivalent or assuming that a green label conveys the same financial and environmental meaning across contexts. The paper contributes to sustainable finance research by developing a financeability typology of green technology pathways.

The typology links technology maturity, capital intensity, revenue certainty, system dependence, policy dependence, and measurement difficulty to suitable financing instruments and verification safeguards. In doing so, it extends sustainable finance research beyond the binary classification of green and brown assets and shows how capital allocation should differ across bankable, enabling, business-model-dependent, and policy-dependent transition pathways. The paper also contributes to the greenwashing literature by arguing that greenwashing is not only a communication problem but also a capital allocation problem. When technologies with weak measurability receive the same label treatment as technologies with measurable outputs, capital markets may misprice environmental credibility and reward claims that are not matched by verifiable transition outcomes.

### *1.2. Theoretical foundation: sustainability transitions and sustainable finance*

The primary theoretical lens of this paper is sustainability transitions theory, and in particular the multi-level perspective. This lens is appropriate because green technologies differ not only in technical performance but also in the extent to which they require complementary infrastructure, regulatory reform, user adoption, organizational capabilities, and institutional support. The multi-level perspective explains transitions as interactions between niche innovations, socio-technical regimes, and broader landscape pressures, which makes it well suited to comparing mature renewable energy systems, emerging AI tools, circular economy models, and CCUS pathways [7-9]. Transition theory also explains why the same technology can produce different sustainability and financial outcomes across jurisdictions. A renewable project may be financially attractive in a market with stable auctions and grid access but risky in a market with curtailment, weak transmission planning, or volatile offtake rules. Circular economy models may thrive where extended producer responsibility and secondary markets exist yet remain difficult to finance where reverse logistics and residual-value markets are weak.

The supporting theoretical lens is sustainable finance and climate risk pricing, which explains how environmental performance, carbon exposure, investor preferences, and disclosure quality influence valuation and capital allocation. Chava [3] shows that firms with environmental externalities can face a higher cost of capital, and Bolton and Kacperczyk [2] document a carbon premium in equity returns. Krueger et al. [14] find that institutional investors treat climate risks as financially material, and Ilhan et al. [5] demonstrate that carbon exposure affects downside risk in options markets. Pástor et al. [6] further show that green assets may carry lower expected returns in equilibrium when investors value their environmental characteristics and climate-hedging properties. Markets, however, do not always price these risks efficiently: Hong et al. [18] find that equity prices can underreact to slow-moving climate signals, which implies that credible environmental information and verification are needed for prices to reflect transition risk. Taken together, these findings imply that green technology pathways should be assessed as financial assets whose value depends jointly on expected cash flows and environmental risk characteristics. A third element is signalling theory.

Green bonds, ESG labels, taxonomy alignment, transition plans, and sustainability-linked finance all communicate information to investors. The credibility of those signals depends on measurable use of proceeds, third-party verification, transparent reporting, and alignment between stated environmental claims and actual capital expenditure. Flammer [13] shows that corporate green bond issuance can be associated with improved environmental performance and a positive investor response, and Tang and Zhang [15] find favourable shareholder reactions to green bond announcements. At the same time, research on ESG rating disagreement and greenwashing shows that sustainability signals can be noisy, inconsistent, or strategically selective [11, 12, 19]. Recent work on sustainability-linked lending reinforces this concern. Kim et al. [20] show empirically that transparent borrowers use sustainability-linked loans to certify pre-existing commitments while opaque borrowers exhibit deteriorating performance after issuance, and Xia et al. [21] develop a signalling model in which only sufficiently ambitious sustainability performance targets can separate credible borrowers from those using labels with limited underlying change.

Together, these perspectives explain how technology characteristics become financing conditions. Sustainability transitions theory explains why green technologies differ in system dependence, infrastructure needs, and regime resistance. Climate finance theory explains how these differences affect expected cash flows, risk premia, debt capacity, and the cost of capital. Signalling theory explains why measurement difficulty, disclosure quality, and verification design shape investor confidence and greenwashing exposure. The framework therefore links technology features to capital allocation outcomes and treats green finance instruments not as neutral conduits of capital, but as governance mechanisms that can either reduce or amplify information asymmetry.

## 2. Method

### *2.1. Methodology*

This article adopts a structured thematic review design rather than a full systematic review or meta-analysis. A thematic review is appropriate because the paper compares heterogeneous technology domains that differ in units of analysis, evidence types, financing mechanisms, and policy settings. The aim is not to estimate average effect sizes across comparable empirical studies, but to synthesize how technology characteristics shape financeability and sustainable capital allocation. Structured thematic reviews are well suited to such integrative questions when the search logic, source boundaries, inclusion criteria, and synthesis dimensions are made transparent [22]. Because the goal is conceptual integration rather than exhaustive evidence mapping, the review prioritizes theoretical relevance, cross-pathway comparability, and finance-related explanatory power over numerical completeness.

The review draws on peer-reviewed research across sustainable finance, climate finance, energy economics, sustainability transitions, industrial ecology, AI sustainability, circular economy research, and carbon management. The literature search was conducted in Scopus, Web of Science, and Google Scholar and was completed in May 2026. It covered English-language peer-reviewed journal articles published primarily between 2010 and May 2026, while retaining foundational earlier studies that shaped the theoretical framing. The search logic combined technology-pathway terms, including renewable energy, wind, solar, artificial intelligence, digital sustainability, circular economy, product-as-a-service, carbon capture, CCUS, BECCS, and bio-based fuels, with finance-related terms, including sustainable finance, green bonds, ESG investing, ESG lending, project finance, infrastructure finance, transition finance, blended finance, cost of capital, climate risk, carbon risk, taxonomy, disclosure, sustainability-linked loans, and greenwashing. The search and synthesis were concept-driven rather than PRISMA-based, and the paper should therefore be read as a critical thematic review rather than an exhaustive systematic review. The main inclusion criteria were publication in a peer-reviewed journal; relevance to one of the four pathway archetypes; clear implications for environmental performance, system dependence, financing

conditions, investor risk, or verification burden; and a contribution to theory, empirical evidence, or analytical framework development.

Purely technical engineering studies were excluded where they lacked finance, governance, or sustainability-transition relevance. Non-academic reports, websites, consultancy papers, and policy documents were avoided except where needed to interpret institutional terminology. The final synthesis gives priority to articles that connect environmental claims to capital allocation, risk pricing, financial instruments, disclosure quality, or credible sustainability outcomes. Table 1 summarizes the review design and screening logic.

**Table 1.** Review design and screening logic.

| Item | Application in this paper |
|---|---|
| Review type | Structured critical thematic review focused on finance-oriented synthesis rather than effect-size aggregation or PRISMA-style enumeration. |
| Purpose | To compare green technology pathways as financeability archetypes and identify suitable instruments and safeguards. |
| Source fields | Sustainable finance, climate finance, energy economics, sustainability transitions, industrial ecology, circular economy research, AI sustainability, and carbon management. |
| Publication boundary | Peer-reviewed academic journal articles, with priority given to 2010–May 2026 scholarship and foundational earlier studies where theoretically necessary. |
| Search logic | Technology terms combined with sustainable finance terms such as green bonds, ESG investing, ESG lending, project finance, transition finance, cost of capital, climate risk, disclosure, sustainability-linked loans, taxonomy, and greenwashing. |
| Inclusion criteria | Articles with clear relevance to technology-pathway performance, system dependence, environmental credibility, capital allocation, investor risk, verification burden, or finance-mechanism suitability. |
| Exclusion criteria | Purely technical engineering studies with no finance or governance relevance; non-peer-reviewed commentary; consulting reports; websites; duplicated or low-relevance conceptual material. |
| Synthesis procedure | Studies coded by pathway, technology maturity, capital intensity, revenue certainty, system dependence, policy dependence, measurement difficulty, greenwashing exposure, and suitable financing mechanism. |

Source: Research Findings

The four pathways were prioritized because, together, they span contrasting financeability profiles from mature, bankable infrastructure to measurement-dependent enabling tools, business-model-dependent systems, and highly policy-dependent transition technologies rather than because they constitute an exhaustive map of green technology. Renewable energy is a mature, infrastructure-intensive decarbonization pathway with established green bond and project finance markets. AI and digital sustainability tools represent an enabling pathway whose environmental benefits are often indirect and difficult to verify. Circular economy systems represent a business-model and material-flow pathway that challenges conventional asset ownership, collateral, and lending structures. CCUS and selected bio-based pathways represent policy-dependent residual-emissions options with high capital intensity, complex verification, and long-term liability concerns. Other pathways including hydrogen, nuclear power, green buildings, sustainable agriculture, climate fintech, biodiversity finance, and green supply-chain finance are important but are set aside here to preserve analytical depth; they are revisited in the future research agenda.

The analytical framework extends the technology-centred lens of sustainability transitions research into a finance-centred one. It retains attention to sustainability function, system dependence, and governance intensity, but adds capital intensity, revenue certainty, cost-of-capital implications, measurement difficulty, disclosure burden, and greenwashing exposure. This extension is necessary because a pathway may be environmentally important yet financially difficult to scale; conversely, a pathway may be financially attractive because it produces stable cash flows and recognizable green labels while leaving broader system bottlenecks underfunded. Figure 1 adds a sequential perspective by showing how each stage conditions the next, from technology characteristics through financing risks, instrument choice, and verification safeguards to capital-allocation quality; Table 2, by contrast, defines each analytical criterion and its finance relevance.

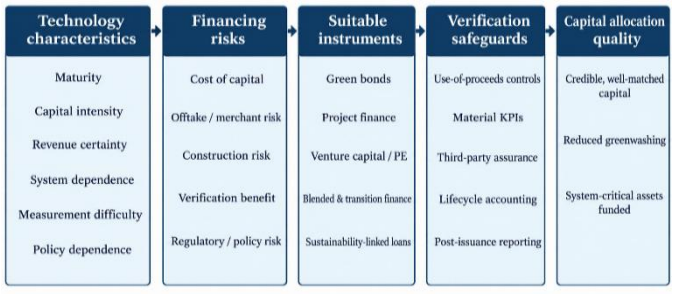



**Figure 1.** Financeability pathway logic.

Source: Research Findings

Note: The framework links technology characteristics to financing risks, suitable instruments, verification safeguards, and capital allocation quality. Each stage conditions the next, so that the credibility of capital allocation depends on whether instruments and safeguards are matched to a pathway's underlying technology and measurement characteristics.

**Table 2.** Finance-oriented analytical framework.

| Criterion | Interpretation | Finance relevance |
|---|---|---|
| Primary sustainability function | The environmental problem the pathway addresses, such as mitigation, circularity, monitoring, or residual-emissions abatement. | Clarifies whether capital supports emissions reduction, resource productivity, environmental information, or carbon removal. |
| Technology maturity | The extent of technical and commercial readiness. | Determines whether debt, equity, venture capital, infrastructure finance, or public risk-sharing is most suitable. |
| Capital intensity | The scale and timing of upfront investment required. | Shapes bankability, financing structure, leverage capacity, and the need for concessional or blended capital. |
| Revenue certainty | The stability and predictability of cash flows. | Affects cost of capital, debt capacity, offtake risk, and investor type. |
| System dependence | Need for complementary infrastructure, regulation, markets, and user practices. | Identifies whether financiers must fund standalone assets or coordinated systems. |
| Measurement difficulty | Difficulty of proving environmental outcomes. | Affects disclosure burden, verification cost, ESG rating disagreement, and investor confidence. |
| Policy dependence | Reliance on subsidies, taxonomies, mandates, carbon prices, or public guarantees. | Raises regulatory risk and determines whether public finance or transition finance is needed. |
| Greenwashing exposure | Risk that labels or claims exceed measurable environmental performance. | Determines the need for verification, use-of-proceeds controls, KPIs, external assurance, and post-issuance reporting. |

Source: Research Findings

## 3. Results and Discussion

### *3.1. Renewable energy systems as bankable transition infrastructure*

Renewable energy systems represent the most mature pathway in the sustainable finance portfolio. Wind and solar electricity have achieved substantial cost reductions and have become core assets in green bond markets, infrastructure portfolios, and project finance pipelines. Their environmental function is clear: they displace fossil-based electricity and enable wider electrification. The investment case, however, does not rest on technological maturity alone. It also depends on stable offtake arrangements, grid access, planning systems, permitting rules, and financing conditions. Energy economics research shows that the market value of variable renewable electricity can decline as penetration increases when flexibility and transmission are insufficient [23]. Renewable energy studies also show that storage, interconnection, demand response, sector coupling, and firm low-carbon resources become essential as systems move toward deep decarbonization [24-28].

From a finance perspective, renewable energy projects are increasingly bankable but not risk-free. Project finance has been especially important because it allows lenders and sponsors to evaluate project-specific cash flows, contract structures, construction risk, offtake risk, and regulatory stability [29,30]. Egli et al. [31] show that financing conditions for renewables have improved as investors and lenders have gained experience, although cost-of-capital differences still shape deployment trajectories. Mazzucato and Semieniuk [32] emphasize that public and private actors finance different parts of the renewable energy transition, which challenges the assumption that private capital alone can fund system transformation. The dependence of deployment on financing design rather than technology alone is well illustrated by solar photovoltaics: Creutzig et al. [33] show that energy-system models have repeatedly underestimated photovoltaic deployment and argue that its future contribution depends less on further cost declines than on adequate financing instruments and the management of system integration. The financeability of renewables is therefore strongest where project cash flows are supported by auctions, feed-in mechanisms, corporate power-purchase agreements, or regulated revenue models, and it weakens where projects face merchant price risk, curtailment, grid congestion, permitting delays, or unstable policy regimes. Green bonds have become a central channel for renewable energy finance because renewable projects often satisfy the use-of-proceeds logic of labelled debt markets. Flammer [13] finds that corporate green bonds are associated with positive environmental outcomes and investor attention; Tang and Zhang [15] report favourable shareholder responses to green bond announcements; and Zerbib [16] documents a green bond premium, suggesting that pro-environmental preferences can affect bond prices. These findings are important, but they also underline the need for credible reporting. A green bond issued for renewable generation has relatively measurable environmental outputs, yet its full sustainability value depends on whether the capital also addresses grid flexibility, storage, and integration. If finance flows only to generation assets

while underfunding transmission and balancing infrastructure, the system may experience curtailment and declining marginal value. Recent evidence from the Journal of Environmental Economics & Chemical Processes similarly reports a positive association between green financing and bank investment in clean energy projects in green startup contexts, which supports the view that financial intermediaries shape the pipeline of bankable renewable and clean-technology assets [34].

The renewable energy pathway should therefore be classified as high maturity, high capital intensity, medium measurement difficulty, and medium policy dependence. The best-fit financing mechanisms include green bonds, project finance, infrastructure funds, yield-oriented vehicles, and public or blended finance for grid infrastructure. The central sustainable finance challenge is no longer whether renewable energy is green, but how to finance the wider infrastructure architecture needed to make high-renewable systems reliable, affordable, and environmentally credible. For investors, lenders, and assurance providers, the key due-diligence question is not only whether proceeds fund renewable capacity, but whether the financing structure accounts for offtake quality, curtailment risk, grid integration, and long-term system value.

### *3.2. AI and digital sustainability tools as measurement-dependent enabling finance*

Artificial intelligence and digital sustainability tools occupy a different position from renewable energy. They rarely function as direct decarbonization assets; instead, they are enabling technologies that improve forecasting, optimization, monitoring, and decision-making across energy, transport, industry, agriculture, and environmental management. Vinuesa et al. [35] show that AI may support many Sustainable Development Goal targets while impeding others, which means that its sustainability status is inherently conditional. Kaack et al. [36] provide a useful framework that separates the computing-related impacts of AI, the immediate effects of AI applications, and wider system-level consequences. Cowls et al. [37] similarly argue that AI can support climate action only when deployment is governed by accountability, transparency, and evidence of net environmental value.

The finance problem in this domain is measurement. AI-based sustainability claims often promise efficiency gains, lower emissions, better monitoring, or more accurate risk assessment. Yet investors may find it difficult to verify whether these tools produce additional environmental benefits or merely shift burdens to digital infrastructure. Data centres, servers, semiconductor supply chains, cooling systems, and electricity procurement create material and energy demands that must enter any credible sustainability assessment. Belkhir and Elmeligi [38] estimate that information and communication technology can carry a significant global emissions footprint. Masanet et al. [39] show that data centre energy use must be interpreted in relation to efficiency improvements and workload growth. Dhar [40] and Kaack et al. [36] warn that AI's climate value depends on aligning computing growth with clean energy and high-value mitigation uses. Recent evidence on AI servers reinforces this point. Xiao et al. [41] estimate that rapid expansion of AI server infrastructure in the United States could add substantial annual carbon emissions and water use through 2030. Their estimates also indicate that the industry is unlikely to meet net-zero aspirations without credible siting, efficiency, grid-decarbonization, and offset strategies.

These issues have direct implications for sustainable finance instruments. AI sustainability platforms may attract venture capital or growth equity because of their scalability and software-like margins. Data-centre infrastructure may instead be financed through corporate debt, infrastructure finance, green leases, power-purchase agreements, or sustainability-linked loans. Each instrument requires careful key performance indicator (KPI) design. A sustainability-linked loan may be tied to data-centre energy intensity, renewable electricity procurement, water-use efficiency, or verified downstream emissions reductions. Such metrics create useful incentives only when they are material, externally assured, and difficult to manipulate. ESG investors also face disclosure risk because digital firms may report downstream efficiency benefits while omitting Scope 2 electricity demand, hardware replacement cycles, water use, or rebound effects. The ESG rating disagreement documented by Berg et al. [12] is particularly relevant here. Measurement choices can produce conflicting assessments of whether digitalization is environmentally beneficial. Evidence on ESG lending further suggests that transparency is not cosmetic: low-transparency sustainability-linked borrowers may retain labels without maintaining environmental performance [20]. The digital-finance literature adds another layer to this problem. Fintech, blockchain, and platform-based financial systems can improve traceability and access to capital only when governance, screening, and accountability are clearly designed [42].

The AI and digital sustainability pathway should therefore be classified as medium maturity, medium-to-high capital intensity, high measurement difficulty, and medium-to-high greenwashing exposure. Best-fit mechanisms include venture capital for early-stage climate software, corporate finance for mature technology firms, and sustainability-linked loans for operational performance. Data-centre infrastructure finance is appropriate only where credible renewable procurement, siting, water, and efficiency controls exist. The central sustainable finance principle is selectivity. AI should receive sustainability-aligned capital when it produces measurable net environmental gains in hard-to-manage systems, not simply because the technology is digital, scalable, or marketed as innovative.

### *3.3. Circular economy systems as business-model-dependent finance*

Circular economy systems broaden the sustainable finance agenda beyond carbon by focusing on material throughput, product longevity, reuse, repair, remanufacturing, and regenerative value creation. This shift is conceptually important because many sustainability problems are rooted not only in energy sources but also in extraction, consumption, disposal, and product-system design. The literature shows that circular economy strategies can be organized around closing, slowing, narrowing, and regenerating resource loops, but it also warns that the concept has become broad enough to invite ambiguity and symbolic use [43-47]. Figge et al. [48] argue that circularity must remain central to the concept if it is to avoid becoming a generic sustainability label, and Nobre and Tavares [49] show that the persistent lack of a shared definition creates room for misuse and greenwashing. This warning bears directly on sustainable finance, because vague circularity claims can attract labelled capital without measurable reductions in virgin material demand.

Circular economy finance differs from renewable energy finance because the value proposition is often embedded in business models rather than standalone infrastructure assets. Product-as-a-service models, leasing arrangements, repair networks, take-back systems, reverse logistics, secondary material markets, and remanufacturing platforms change the timing and location of cash flows. A firm that retains product ownership and earns service revenue may require more working capital and balance-sheet capacity than a firm that sells products outright. Investors must therefore evaluate residual-value risk, asset utilization, customer retention, repair cost, secondary-market liquidity, and the credibility of material-flow metrics. De Kwant et al. [50] show that product design is closely linked to circular business model viability, and Pomponi and Moncaster [51] show that circularity in the built environment requires coordination across design, supply chains, and use phases. Recent circular economy finance research reaches the same conclusion from a financial standpoint: circular business models often require new financing sources, risk-sharing arrangements, residual-value estimation, and stronger integration between financial actors and circular ecosystems [52, 53].

The literature also highlights a tension between circular rhetoric and measured circular outcomes. Circular strategies may reduce waste and extend product life, but they can also generate rebound effects if lower costs stimulate higher consumption or if recycling substitutes for deeper design changes. Suárez-Eiroa et al. [54] therefore stress the importance of operational principles that link circular economy theory to sustainability outcomes, and D'Amato et al. [55] show that the circular economy overlaps with green and bioeconomy approaches but does not automatically guarantee social or ecological improvement. This matters for lenders and investors because circularity may be difficult to capture in conventional ESG datasets. Circular performance requires evidence on product durability, material recovery rates, avoided virgin inputs, repairability, utilization intensity, and end-of-life recovery. Without these metrics, circular finance is exposed to the same information problems that undermine ESG credibility more broadly [11, 12].

The circular economy pathway should therefore be classified as medium maturity, medium capital intensity, high measurement difficulty, and high dependence on business-model and policy support. Suitable financing mechanisms include private equity for scaling circular platforms, asset-based lending for leasing models, working-capital finance for reverse logistics, public finance for recycling infrastructure, and sustainability-linked loans tied to verified material metrics. Green bonds may be appropriate where proceeds fund clearly defined recycling, remanufacturing, or waste-reduction infrastructure, but they are less suitable for vague circularity strategies that lack measurable material outcomes. A circular finance claim should be judged by material-flow evidence, residual-value logic, and business-model credibility rather than by circular terminology alone.

### *3.4. CCUS and selected bio-based pathways as policy-dependent transition finance*

CCU, together with selected bio-based pathways, occupies the most policy-dependent position in the reviewed portfolio. Throughout the paper, CCUS is used as the umbrella term; CCS refers specifically to capture and storage, while BECCS denotes bioenergy with carbon capture and storage. Unlike renewable energy, these technologies do not primarily replace fossil electricity generation. Unlike circular economy strategies, they do not primarily reduce material throughput. Their main role is residual-emissions abatement, carbon management, and, in selected cases, carbon removal. This role is strategically important for hard-to-abate sectors such as cement, steel, chemicals, aviation fuels, and some forms of dispatchable industrial energy. Bui et al. [56] show that CCS can play a credible role in climate mitigation. Hepburn et al. [57] show that $CO_2$ utilization and removal pathways vary

significantly in scale, permanence, and economics. Dziejarski et al. [58] further show that CCUS remains uneven globally because technical development coexists with high cost, infrastructure gaps, and weak commercialization conditions.

The financeability of CCUS and selected bio-based pathways depends heavily on policy design. Many projects cannot generate stable private cash flows without carbon prices, tax credits, contracts for difference, regulated asset bases, public guarantees, or long-term offtake arrangements. For this reason, transition finance is a more appropriate category than conventional green finance for many such applications. The objective is not to certify all CCUS activity as green. Instead, it is to finance credible decarbonization in sectors where near-term alternatives are limited, under strict rules that prevent fossil lock-in. A CCUS project attached to an industrial process with few substitutes has a different sustainability profile from one that extends the economic life of avoidable fossil-fuel extraction. Sustainable finance therefore needs sector-specific eligibility rules, lifecycle emissions accounting, monitoring and verification standards, and clear treatment of long-term storage liability.

Bio-based pathways raise a related set of finance and verification problems. Algae-based fuels, biomass energy, bioenergy with carbon capture and storage (BECCS), and other bio-based systems can contribute to decarbonization or carbon removal. Their performance, however, depends on land use, water demand, feedstock sustainability, energy inputs, supply-chain emissions, and permanence. Adeniyi et al. [59] review algae biofuel potential while identifying commercialization barriers. Fajardy and Mac Dowell [60] show that BECCS can deliver negative emissions only under strict resource and sustainability conditions. Fuss et al. [61] and Minx et al. [62] show that negative-emissions pathways carry uncertain costs, potentials, and side effects. These findings create a demanding due-diligence problem for sustainable finance. Carbon credits, transition bonds, and blended finance structures are credible only where additionality, permanence, leakage, monitoring, and lifecycle impacts can be verified.

The CCUS and selected bio-based pathways archetype should therefore be classified as low-to-medium maturity, very high capital intensity, very high measurement difficulty, very high policy dependence, and high greenwashing exposure. The distinction between the measurement and greenwashing ratings is intentional. Measurement difficulty is very high because lifecycle impacts, permanence, and leakage are difficult to verify. Greenwashing exposure is rated high rather than very high because stringent eligibility rules and independent verification can reduce, although not eliminate, the risk. Best-fit financing mechanisms include blended finance, public guarantees, contracts for difference, transition finance, and carbon-credit revenues. Project finance may also be appropriate where long-term policy support creates bankable cash flows. Private capital can play a role, but typically only where public institutions absorb early-stage risk, clarify liability, and impose credible verification. This pathway is selectively financeable, not broaxdly scalable by default.

### *3.5. Cross-pathway synthesis: a financeability typology*

The four pathways differ less in whether they are green than in how their environmental value can be financed, verified, and governed. Renewable energy systems come closest to bankable transition infrastructure because they combine measurable environmental outputs with established financing structures. AI and digital sustainability tools are governance-dependent enabling technologies whose environmental value is often indirect and measurement-intensive. Circular economy systems are business-model-dependent pathways, because their financial viability turns on ownership structures, reverse logistics, residual value, and material-flow accounting. CCUS and selected bio-based pathways are policy-dependent residual-emissions options that require public risk-sharing, carbon accounting, and long-term liability arrangements. This classification is more useful for sustainable finance than a general ranking of technologies, because it links environmental function to the suitability of financing mechanisms. Tables 3 and 4 summarize the resulting financeability profiles and the instruments and safeguards each pathway requires. The typology also clarifies greenwashing risk. Greenwashing is not only a communication problem; it is also a capital allocation problem. When technologies with weak measurability receive the same label treatment as technologies with measurable outputs, investors may overestimate environmental performance. Marquis et al. [19] show that selective disclosure can shape perceptions of environmental responsibility, and Lyon and Montgomery [63] argue that greenwash involves both information asymmetry and strategic communication. ESG rating divergence intensifies the problem, because different measurement models can produce inconsistent sustainability assessments for the same firm or asset [12]. Empirical evidence from ESG lending shows that labelled sustainable debt can distinguish credible commitments from weaker, low-transparency claims when contract details and performance targets are sufficiently observable [20]. Complementing this evidence, Xia et al. [21] develop a signalling model in which sufficiently ambitious sustainability performance targets separate credible borrowers from those relying on labels without comparable underlying change. A financeability typology can reduce this risk by identifying where use-of-proceeds controls, KPI design, third-party verification, taxonomy alignment, and post-issuance reporting must be strongest. Additionality risk also differs across the four archetypes. For renewable energy, the main concern is financial additionality: labelled finance may support already-bankable projects that would have proceeded without it, while system-critical grid and storage investments remain underfunded [32]. For AI and digital tools, additionality depends on whether verified environmental gains exceed baseline efficiency improvements and account for rebound effects [36]. For circular economy systems, finance is additional only when it produces measurable reductions in virgin material use rather than relabelling existing recycling or reuse activity [48, 49]. For CCUS and selected bio-based pathways, additionality requires credible counterfactuals, net lifecycle abatement, and evidence that finance does not prolong avoidable fossil assets [60, 61]. These differences call for pathway-specific baselines, use-of-proceeds controls, KPIs, lifecycle accounting, and ex post verification.

The typology further shows that sustainable finance should avoid a one-instrument-fits-all approach. Green bonds are well suited to assets with clear use of proceeds and measurable outputs, such as renewable energy or recycling infrastructure. Venture capital is more appropriate for early-stage AI sustainability tools and circular platforms with scalable but uncertain business models. Project finance works where project-level cash flows can be isolated, as in renewable energy, storage, and some CCUS infrastructure. Blended finance and public guarantees are needed where environmental value is socially important but private risk–return conditions are weak, as in early CCUS hubs, BECCS, or infrastructure in emerging markets. Transition finance is necessary where high-emitting sectors require credible decarbonization pathways rather than simple exclusion from capital markets.

**Table 3.** Financeability profile of major green technology pathways

| Technology pathway | Sustainability function | Maturity and capital intensity | Main investor and additionality risk | Measurement and greenwashing exposure |
|---|---|---|---|---|
| Renewable energy systems | Electricity decarbonization and electrification support. | High maturity; high capital intensity. | Grid congestion, curtailment, merchant exposure, permitting delay, and limited financing additionality for already-bankable projects. | Low-to-medium measurement difficulty; medium greenwashing exposure. |
| AI and digital sustainability tools | Optimization, forecasting, monitoring, and decision support. | Medium maturity; medium-to-high capital intensity. | Unverified net impact, weak counterfactual evidence, fast obsolescence, data centre footprint, water use, and rebound effects. | High measurement difficulty; high greenwashing exposure. |
| Circular economy systems | Material throughput reduction, reuse, repair, and product-life extension. | Medium maturity; medium capital intensity. | Residual-value risk, reverse logistics, weak secondary markets, working-capital pressure, and uncertain reductions in virgin material use. | High measurement difficulty; high greenwashing exposure. |
| CCUS and selected bio-based pathways | Residual-emissions abatement, carbon utilization, and selected removals. | Low-to-medium maturity; very high capital intensity. | Policy uncertainty, liability, permanence, infrastructure coordination, feedstock sustainability, weak lifecycle additionality, and fossil lock-in. | Very high measurement difficulty; high greenwashing exposure. |

Source: Research Findings

**Table 4.** Finance-mechanism suitability and safeguards

| Technology pathway | Best-fit finance mechanisms | Policy dependence | Key safeguards |
|---|---|---|---|
| Renewable energy systems | Green bonds; project finance; infrastructure funds; PPAs; blended finance for grids. | Medium: depends on grid rules, auctions, permitting, and market design. | Use-of-proceeds reporting; grid-integration disclosure; curtailment and merchant-risk analysis. |
| AI and digital sustainability tools | Venture capital; corporate finance; sustainability-linked loans; data centre infrastructure finance. | Medium: depends on electricity procurement, disclosure standards, water management, and data governance. | Net-impact evidence; Scope 2 and hardware disclosure; rebound-effect assessment; externally assured KPIs. |
| Circular economy systems | Private equity; leasing finance; asset-based lending; working-capital finance; public recycling infrastructure finance. | High: depends on product standards, right-to-repair rules, secondary markets, and reverse logistics. | Material-flow metrics; residual-value assessment; take-back performance; verified avoided virgin inputs. |
| CCUS and selected bio-based pathways | Blended finance; transition finance; carbon contracts for difference; carbon-credit revenue; public guarantees. | Very high: depends on carbon prices, tax credits, liability rules, and sectoral transition plans. | Lifecycle carbon accounting; permanence and leakage controls; storage liability rules; safeguards against fossil lock-in. |

Source: Research Findings

### *3.6. Implications for sustainable finance research and practice*

For sustainable finance theory, the paper shows that the financeability of green technologies depends on the interaction between technology characteristics and capital-market mechanisms. Sustainable investing models often distinguish between green and brown assets, but real transition portfolios contain assets that are green, enabling, circular, residual, uncertain, or conditionally credible. A finance-oriented typology refines this binary by explaining why some technologies attract debt finance, others require equity, and others need public risk-sharing before private capital can scale. This extension is consistent with climate finance research that emphasizes risk pricing, investor preferences, and financial frictions [1, 3, 5], and with evidence that sustainable investing influences corporate behaviour primarily through capital-allocation and engagement channels rather than through labels alone [64].

For investors, the findings imply that green asset selection should not be driven by labels alone. A credible investment process should ask whether the pathway has measurable environmental outputs, whether revenues are stable, whether policy dependence is understood, whether complementary infrastructure is financed, and whether disclosure is strong enough to prevent selective reporting. Institutional investors increasingly recognize climate risks as financially material [14], but climate-aware investment requires more than divesting from high-emission assets or buying labelled bonds. It requires comparative analysis of which technologies can reduce transition risk, which need patient capital, and which may create new stranded-asset risks if policy or measurement assumptions fail.

For lenders and issuers, the analysis underscores the importance of instrument design. Green bonds are strongest where proceeds can be traced to assets with measurable environmental outputs. Sustainability-linked loans can be useful where use of proceeds cannot easily be ring-fenced, but they require material KPIs, ambitious sustainability performance targets, transparent margins, and credible external assurance. The risk is highest where borrowers can draw on general-purpose proceeds while relying on weak targets or low-disclosure structures. Recent ESG lending evidence shows why this matters: Kim et al. [20] find that high-transparency structures are more likely to certify genuine commitments, while low-transparency structures can support greenwashing with limited performance improvement. Xia et al.'s [21] signalling model complements this evidence by explaining how sufficiently ambitious performance targets can separate credible borrowers from weaker sustainability claims. For policymakers and regulators, the analysis highlights the importance of matching financial instruments to pathway conditions. Taxonomies and disclosure regimes should avoid treating all green claims as equivalent. Mature renewable infrastructure can be evaluated through use-of-proceeds and project-level reporting. AI and digital tools need net-impact disclosure that accounts for data centre energy, water, hardware burdens, and rebound effects. Circular economy finance needs material-flow metrics, durability standards, and disclosure on product ownership and end-of-life recovery. CCUS and selected bio-based pathways require lifecycle carbon accounting, storage-liability rules, permanence standards, and strict eligibility criteria for transition finance. Without such differentiation, sustainable finance frameworks risk either under-supporting difficult but necessary transition assets or over-legitimizing weak claims.

### *3.7. Limitations and future research agenda*

This paper has limitations. It is a structured thematic review rather than a systematic review, bibliometric study, or meta-analysis. Its purpose is conceptual integration across heterogeneous literature, not exhaustive enumeration of all studies in each domain. The four pathways are selected as financeability archetypes rather than as a complete map of green technology, so the typology is best read as an analytical framework that can guide future empirical work rather than as a final ranking of technologies. The review also concentrates on financeability, capital allocation, and greenwashing risk; it does not provide a full lifecycle assessment or policy appraisal of each technology family.

Future research should empirically test the financeability typology developed here. One promising strategy is to build a secondary dataset linking green technology categories to financing instruments, issuance terms, investor types, and post-financing environmental performance. For renewable energy, researchers could examine whether green bond or project finance structures reduce the cost of capital relative to conventional debt, controlling for policy regime, technology type, and offtake contracts. For AI sustainability tools, researchers could compare firms' green claims with data centre energy use, renewable electricity procurement, water use, and verified downstream emissions reductions. For circular economy systems, researchers could test whether product-as-a-service models face different financing constraints from conventional product-sale firms. For CCUS and selected bio-based pathways, researchers could examine how contracts for difference, carbon credits, public guarantees, or storage-liability frameworks affect bankability. A second research direction concerns ESG measurement. The literature on ESG disagreement shows that investors receive inconsistent signals about sustainability performance [11, 12]. Future studies should examine whether disagreement is higher for enabling and measurement-dependent pathways, such as AI and circular economy systems, than for asset-specific pathways, such as renewable energy. A third direction concerns greenwashing risk. Researchers could analyze whether firms using broad green technology language in bond prospectuses, sustainability-linked loan KPIs, or annual reports deliver measurable environmental outcomes after financing. Such work would help connect sustainable finance research with industrial ecology and lifecycle assessment. The scope of future reviews should also extend to pathways excluded here. Hydrogen, nuclear energy, green buildings, sustainable agriculture, climate fintech, biodiversity finance, and green supply-chain finance each have distinctive financeability profiles. Hydrogen raises questions about colour classifications, infrastructure lock-in, and offtake certainty. Nuclear power raises questions about long construction periods, public guarantees, and political risk. Green buildings are highly relevant to green bonds and mortgage finance. Sustainable agriculture creates challenges around smallholder finance, nature risk, and the measurement of biodiversity outcomes. Climate fintech may improve disclosure and monitoring but can also create new data and governance risks. Each of these pathways can extend the financeability framework developed in this paper.

## 4. Conclusions

This paper has argued that sustainable finance needs a more differentiated approach to green technology pathways. The four archetypes examined here (renewable energy systems, AI-enabled digital tools, circular economy systems, and the combined CCUS and selected bio-based pathway) all contribute to sustainability debates. However, they differ fundamentally in maturity, capital intensity, revenue certainty, measurement difficulty, policy dependence, and greenwashing exposure. Treating these pathways as equivalent can distort sustainable capital allocation and weaken the credibility of green finance markets.

The review contributes a finance-oriented typology that links technology characteristics to suitable financing mechanisms and verification safeguards. Renewable energy systems are best understood as bankable transition infrastructure, although their long-run value depends on grid integration and system flexibility. AI and digital sustainability tools are measurement-dependent enabling technologies that require net-impact disclosure and careful treatment of data centre burdens. Circular economy systems are business-model-dependent pathways that require finance structures suited to leasing, residual value, reverse logistics, and material-flow metrics. CCUS and selected bio-based pathways are policy-dependent residual-emissions options that require public risk-sharing, strict verification, and safeguards against fossil lock-in.

The central implication is that sustainable finance should aim not only to increase the volume of green capital, but to improve the quality of capital allocation. That requires investors, lenders, policymakers, and standard setters to ask which technologies are bankable now, which require institutional and business-model support, and which need public risk-sharing before private finance can scale credibly. A finance-oriented framework can help sustainable finance move beyond broad green labels toward more disciplined, transparent, and environmentally credible investment decisions.

## Acknowledgments

The author gratefully acknowledges the support provided by University of Niagara Falls Canada in conducting this research.

## Author Contribution

A. Zameni (Pejman) is solely responsible for the conception, preparation and writing of this manuscript.

## Conflict of Interest

A. Zameni (Pejman) as a member of editorial-board, while observing publication ethics in the referencing, declared the absence of interest of conflict.

## AI Use Statement

The author retains full responsibility for the accuracy, originality, integrity, legality, and ethical compliance of all text, data, tables, figures, analyses, references, and conclusions, and have verified all AI-assisted outputs. Any fabrication, falsification, manipulation, plagiarism, copyright infringement, or other misuse of AI remains solely the responsibility of the authors and does not transfer or diminish their accountability for the published work.

## References

[1] S. A. Razavi, M. Nasr Esfahani, *Political Strategic Studies*, 2020, **9(35)**, 101-134. https://doi.org/10.22054/qpss.2020.42777.2320

[2] P. Bolton, M. Kacperczyk, *Journal of Financial Economics*, 2021, **142(2)**, 517-549. https://doi.org/10.1016/j.jfineco.2021.05.008

[3] S. Chava, *Management Science*, 2014, **60(9)**, 2223-2247. https://doi.org/10.1287/mnsc.2013.1863

[4] S. Giglio, B. Kelly, J. Stroebel, *Annual Review of Financial Economics*, 2021, **13**, 15-36. https://doi.org/10.1146/annurev-financial-102620-103311

[5] E. Ilhan, Z. Sautner, G. Vilkov, *The Review of Financial Studies*, 2021, **34(3)**, 1540-1571. https://doi.org/10.1093/rfs/hhaa071

[6] Ľ. Pástor, R. F. Stambaugh, L.A. Taylor, *Journal of Financial Economics*, 2021, **142(2)**, 550-571. https://doi.org/10.1016/j.jfineco.2020.12.011

[7] F. W. Geels, *Environmental Innovation and Societal Transitions*, 2011, **1(1)**, 24-40. https://doi.org/10.1016/j.eist.2011.02.002

[8] F. W. Geels, *Energy Research & Social Science*, 2018, **37**, 224-231. https://doi.org/10.1016/j.erss.2017.10.010

[9] F. W. Geels, *Current Opinion in Environmental Sustainability*, 2019, **39**, 187-201. https://doi.org/10.1016/j.cosust.2019.06.009

[10] J. Markard, R. Raven, B. Truffer, *Research Policy*, 2012, **41(6)**, 955-967. https://doi.org/10.1016/j.respol.2012.02.013

[11] D. Avramov, S. Cheng, A. Lioui, A. Tarelli, *Journal of Financial Economics*, 2022, **145(2)**, 642-664. https://doi.org/10.1016/j.jfineco.2021.09.009

[12] F. Berg, J. F. Kölbel, R. Rigobon, *Review of Finance*, 2022, **26(6)**, 1315-1344. https://doi.org/10.1093/rof/rfac033

[13] C. Flammer, *Journal of Financial Economics*, 2021, **142(2)**, 499-516. https://doi.org/10.1016/j.jfineco.2021.01.010

[14] P. Krueger, Z. Sautner, L. T. Starks, *The Review of Financial Studies*, 2020, **33(3)**, 1067-1111. https://doi.org/10.1093/rfs/hhz137

[15] D. Y. Tang, Y. Zhang, *Journal of Corporate Finance*, 2020, **61**, 101427-101442. https://doi.org/10.1016/j.jcorpfin.2018.12.001

[16] O. D. Zerbib, *Journal of Banking & Finance*, 2019, **98**, 39-60. https://doi.org/10.1016/j.jbankfin.2018.10.012

[17] A. Zameni, *Financing Sustainability: Economic Models and Investment. Green Society, Environmental Strategies and Sustainable Development*. Springer, 2025, pp. 203-228.

[18] H. Hong, F. W. Li, J. Xu, *Journal of Econometrics*, 2019, **208(1)**, 265-281. https://doi.org/10.1016/j.jeconom.2018.09.015

[19] C. Marquis, M. W. Toffel, Y. Zhou, *Organization Science*, 2016, **27(2)**, 483-504. https://doi.org/10.1287/orsc.2015.1039

[20] S. Kim, N. Kumar, J. Lee, J. Oh, *Journal of Financial Economics*, 2025, **173**, 104150-104172. https://doi.org/10.1016/j.jfineco.2025.104150

[21] B. Xia, Q. Ma, Y. J. Pan, *Energy Economics*, 2025, **150**, 108843-108864. https://doi.org/10.1016/j.eneco.2025.108843

[22] H. Snyder, *Journal of Business Research*, 2019, **104**, 333-339. https://doi.org/10.1016/j.jbusres.2019.07.039

[23] L. Hirth, *Energy Economics*, 2013, **38**, 218-236. https://doi.org/10.1016/j.eneco.2013.02.004

[24] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, M. Greiner, *Energy*, 2018, **160**, 720-739. https://doi.org/10.1016/j.energy.2018.06.222

[25] J. D. Jenkins, M. Luke, S. Thernstrom, *Joule*, 2018, **2(12)**, 2498-2510. https://doi.org/10.1016/j.joule.2018.11.013

[26] H. Kondziella, T. Bruckner, *Renewable and Sustainable Energy Reviews*, 2016, **53**, 10-22. https://doi.org/10.1016/j.rser.2015.07.199

[27] P. D. Lund, J. Lindgren, J. Mikkola, J. Salpakari, *Renewable and Sustainable Energy Reviews*, 2015, **45**, 785-807. https://doi.org/10.1016/j.rser.2015.01.057

[28] N. A. Sepulveda, J. D. Jenkins, F. J. de Sisternes, R. K. Lester, *Joule*, 2018, **2(11)**, 2403-2420. https://doi.org/10.1016/j.joule.2018.08.006

[29] B. Steffen, *Energy Economics*, 2018, **69**, 280-294. https://doi.org/10.1016/j.eneco.2017.11.006

[30] H. Mofid, M. R. Khosravi-Nikou, S. A. Razavi, M. Mohammadian, *Applied Thermal Engineering*, 2024, **245**, 1228101-17. https://doi.org/10.1016/j.applthermaleng.2024.122810

[31] F. Egli, B. Steffen, T. S. Schmidt, *Nature Energy*, 2018, **3(12)**, 1084-1092. https://doi.org/10.1038/s41560-018-0277-y

[32] M. Mazzucato, G. Semieniuk, *Technological Forecasting and Social Change*, 2018, **127**, 8-22. https://doi.org/10.1016/j.techfore.2017.05.021

[33] F. Creutzig, P. Agoston, J. C. Goldschmidt, G. Luderer, G. F. Nemet, R. C. Pietzcker, *Nature Energy*, 2017, **2**, 17140-17161. https://doi.org/10.1038/nenergy.2017.140

[34] A. Najarzadeh, *Journal of Environmental Economics & Chemical Processes*, 2025, **2(3)**, 72-76. https://doi.org/10.22034/jeecp.2025.735016

[35] R. Vinuesa, H. Azizpour, I. Leite, M. Balaam, V. Dignum, S. Domisch, A. Felländer, S. D. Langhans, M. Tegmark, F. Fuso Nerini, *Nature Communications*, 2020, **11**, 233-268. https://doi.org/10.1038/s41467-019-14108-y

[36] L. H. Kaack, P. L. Donti, E. Strubell, G. Kamiya, F. Creutzig, D. Rolnick, *Nature Climate Change*, 2022, **12(6)**, 518-527. https://doi.org/10.1038/s41558-022-01377-7

[37] J. Cowls, A. Tsamados, M. Taddeo, L. Floridi, *AI & Society*, 2023, **38(1)**, 283-307. https://doi.org/10.1007/s00146-021-01294-x

[38] L. Belkhir, A. Elmeligi. *Journal of Cleaner Production*, 2018, **177**, 448-463. https://doi.org/10.1016/j.jclepro.2017.12.239

[39] E. Masanet, A. Shehabi, N. Lei, S. Smith, J. Koomey, *Science*, 2020, **367(6481)**, 984-986. https://doi.org/10.1126/science.aba3758

[40] P. Dhar, *Nature Machine Intelligence*, 2020, **2(8)**, 423-425. https://doi.org/10.1038/s42256-020-0219-9

[41] T. Xiao, F. Fuso Nerini, H. D. Matthews, M. Tavoni, F. You, *Nature Sustainability*, 2025, **8(12)**, 1541-1553. https://doi.org/10.1038/s41893-025-01681-y

[42] N. Alam, L. Gupta, A. Zameni, *Fintech and Islamic Finance: Digitalization, Development and Disruption*. springer, 2019, pp.1-178. https://doi.org/10.1007/978-3-030-24666-2

[43] N. M. P. Bocken, I. de Pauw, C. Bakker, B. van der Grinten, *Journal of Industrial and Production Engineering*, 2016, **33(5)**, 308-320. https://doi.org/10.1080/21681015.2016.1172124

[44] M. Geissdoerfer, P. Savaget, N. M. P. Bocken, E. J. Hultink, *Journal of Cleaner Production*, 2017, **143**, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

[45] P. Ghisellini, C. Cialani, S. Ulgiati, *Journal of Cleaner Production*, 2016, **114**, 11-32. https://doi.org/10.1016/j.jclepro.2015.09.007

[46] J. Kirchherr, D. Reike, M. Hekkert, *Resources, Conservation and Recycling*, 2017, **127**, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005

[47] J. Korhonen, A. Honkasalo, J. Seppälä, *Ecological Economics*, 2018, **143**, 37-46. https://doi.org/10.1016/j.ecolecon.2017.06.041

[48] F. Figge, A. Stevenson Thorpe, M. Gutberlet, *Ecological Economics*, 2023, **208**, 107823-107832. https://doi.org/10.1016/j.ecolecon.2023.107823

[49] G. C. Nobre, E. Tavares, *Journal of Cleaner Production*, 2021, **314**, 127973-127988. https://doi.org/10.1016/j.jclepro.2021.127973

[50] C. de Kwant, A. F. Rahi, R. Laurenti, *Sustainable Production and Consumption*, 2021, **27**, 1728-1742. https://doi.org/10.1016/j.spc.2021.03.032

[51] F. Pomponi, A. Moncaster, *Journal of Cleaner Production*, 2017, **143**, 710-718. https://doi.org/10.1016/j.jclepro.2016.12.055

[52] S. Fallahi, A.-C. Mellquist, O. Mogren, E. Listo Zec, P. Algurén, L. Hallquist, *Business Strategy and the Environment*, 2023, **32(6)**, 3233-3248. https://doi.org/10.1002/bse.3297

[53] Q. Ma, B. Xu, U. Bititci, *Journal of Environmental Management*, 2025, **384**, 125507-125521. https://doi.org/10.1016/j.jenvman.2025.125507

[54] B. Suárez-Eiroa, E. Fernández, G. Méndez-Martínez, D. Soto-Oñate, *Journal of Cleaner Production*, 2019, **214**, 952-961. https://doi.org/10.1016/j.jclepro.2018.12.271

[55] D. D'Amato, N. Droste, B. Allen, M. Kettunen, K. Lähtinen, J. Korhonen, P. Leskinen, B. D. Matthies, A. Toppinen, *Journal of Cleaner Production*, 2017, **168**, 716-734. https://doi.org/10.1016/j.jclepro.2017.09.053

[56] M. Bui et al., *Energy & Environmental Science*, 2018, **11(5)**, 1062-1176. https://doi.org/10.1039/c7ee02342a

[57] C. Hepburn, E. Adlen, J. Beddington, E. A. Carter, S. Fuss, N. Mac Dowell, J. C. Minx, P. Smith, C. K. Williams, *Nature*, 2019, **575(7781)**, 87-97. https://doi.org/10.1038/s41586-019-1681-6

[58] B. Dziejarski, R. Krzyżyńska, K. Andersson, *Fuel*, 2023, **342**, 127776-127792. https://doi.org/10.1016/j.fuel.2023.127776

[59] O. M. Adeniyi, U. Azimov, A. Burluka, *Renewable and Sustainable Energy Reviews*, 2018, **90**, 316-335. https://doi.org/10.1016/j.rser.2018.03.067

[60] M. Fajardy, N. Mac Dowell, *Energy & Environmental Science*, 2017, **10(6)**, 1389-1426. https://doi.org/10.1039/C7EE00465F

[61] S. Fuss et al., *Environmental Research Letters*, 2018, **13(6)**, 63002-63019. https://doi.org/10.1088/1748-9326/aabf9f

[62] J. C. Minx et al., *Environmental Research Letters*, 2018, **13(6)**, 63001-63016. https://doi.org/10.1088/1748-9326/aabf9b

[63] T. P. Lyon, A. W. Montgomery, *Organization & Environment*, 2015, **28(2)**, 223-249. https://doi.org/10.1177/1086026615575332

[64] J. F. Koelbel, F. Heeb, F. Paetzold, T. Busch, *Organization & Environment*, 2020, **33(4)**, 554-574. https://doi.org/10.1177/1086026620919202