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Sustainable Future: Exploring Green Tech Innovations in Social Economy

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ABSTRACT

This structured narrative review examines how green technology innovations can support inclusive and resilient social-economy models, with particular attention to decentralized renewable energy, frugal innovation, blockchain-enabled community energy, artificial intelligence (AI) for building energy efficiency, and the regulatory conditions of a just transition. Literature and policy evidence on green technology, social economy, sustainability, renewable energy, circular economy, digitalization, and innovation were thematically synthesized. The review finds that technology contributes most effectively to social-economy outcomes when communities participate in ownership, governance, skills development, and knowledge transfer rather than simply receiving technological solutions. Decentralized energy and cooperative models can strengthen local energy autonomy; frugal innovation can lower resource and affordability barriers; blockchain can improve transaction traceability but does not by itself guarantee fairness; and AI can improve building energy management while creating new requirements for data, skills, transparency, and accountability. Evidence remains uneven, particularly for AI-enabled social housing and measurable reductions in energy poverty. The main conclusion is that green technology should be embedded in community governance, capacity-building, inclusive finance, and supportive regulation to contribute to a genuinely just and sustainable transition.

1. INTRODUCTION

Climate change, resource pressure, energy insecurity, and socio-economic inequality increasingly require responses that connect environmental objectives with social and economic inclusion [1]. Green technology can reduce environmental pressures through renewable energy, energy efficiency, circular production, low-carbon mobility, resource monitoring, and other innovations. However, the availability of a technology does not automatically produce an equitable outcome. Access to capital, infrastructure, digital skills, governance capacity, and decision-making power can determine who benefits from the transition. Recent work on social economy organizations similarly emphasizes their contribution to social cohesion and sustainable development, while recognizing that technology can create both opportunities and new forms of exclusion [2, 3, 4].

The social economy provides an important institutional setting for examining this problem. Cooperatives, mutual organizations, associations, foundations, social enterprises, and related social and solidarity economy (SSE) entities generally place social purpose, participation, and collective benefit alongside or above conventional profit maximization. International policy discussions increasingly recognize the role of SSE organizations in green and just transitions, including renewable-energy communities, sustainable agriculture, reuse and recycling, and local employment [5, 6]. Research on energy communities also shows that cooperative structures connect renewable energy deployment with participation, governance, innovation, and local development [7, 8].

At the same time, green technology is not a single category. Decentralized renewable-energy systems can alter the relationship between consumers and producers; frugal innovation can make products and services more affordable and resource-efficient; blockchain can support traceability and peer-to-peer energy transactions; and AI can improve forecasting, building controls, maintenance, and energy management. These technologies have different levels of maturity and different evidence bases. A key analytical requirement is therefore to distinguish technological potential from demonstrated outcomes and to distinguish conceptual arguments from empirical evidence and policy recommendations.

The literature on frugal innovation is particularly relevant because it focuses on achieving useful outcomes with fewer material, financial, and technical resources. Recent reviews suggest that frugal innovation can contribute to economic, social, and environmental sustainability, but that its impacts must be assessed rather than assumed [9, 10]. Likewise, blockchain-based community energy systems show potential for decentralized trading and local balancing, but evidence also highlights legal, governance, consumer-protection, and implementation challenges [11, 12]. AI-enabled building energy management offers promising efficiency applications, yet its contribution to energy poverty depends on affordability, access, data governance, user capabilities, and the distribution of savings [13, 14].

The just-transition perspective brings these issues together. A low-carbon transition can create new employment and local opportunities, but it can also disrupt workers and communities dependent on carbon-intensive industries. Cooperatives and other social-economy organizations can support local control, employment, skills development, and collective problem-solving, but they require appropriate finance, infrastructure, regulation, and organizational capacity [12]. Thus, the central issue is not whether green technology is beneficial in the abstract, but under what institutional and learning conditions technological innovation contributes to inclusive social-economy outcomes.

The objective of this review is to synthesize evidence on the relationship between green technology innovations and social-economy development, with emphasis on five areas: decentralized green technologies and cooperative self-sufficiency; frugal innovation and financial access; blockchain and community energy transparency; AI and energy poverty in social housing; and regulatory challenges associated with a just transition. The review also adds a knowledge and learning dimension by examining skills development, community knowledge transfer, and cooperative capacity-building as enabling conditions for adoption and sustained impact.

2. LITERATURE REVIEW

2.1 SOCIAL ECONOMY AND SUSTAINABLE DEVELOPMENT

The social economy is increasingly discussed as a field in which economic activity is organized around social purpose, participation, collective benefit, and community resilience. Recent scholarship identifies cooperatives, associations, solidarity organizations, and technology-enabled public-good ventures as part of a broad social-economy landscape [15]. The relevance of this model to sustainable development lies in its potential to connect production and service provision with social needs. Research on cooperatives and SSE organizations also links these organizational forms to decent work and the social, economic, and environmental dimensions of sustainable development [10].

This institutional perspective is important because the same green technology may produce different outcomes under different governance arrangements. A community-owned solar system can distribute benefits and decision-making differently from a privately owned installation. Similarly, a digital platform governed by members may create different accountability relationships from a platform controlled by external investors. Therefore, technology adoption should be evaluated not only by efficiency indicators but also by ownership, participation, affordability, skills, and distributional outcomes.

2.2 GREEN TECHNOLOGY AND SOCIALLY EMBEDDED INNOVATION

Green technology encompasses technological applications intended to reduce environmental harm or improve the efficiency of energy and material use. Established areas include renewable energy, energy-efficient buildings, waste reduction, recycling, clean mobility, and water-efficiency systems. More recent developments include smart grids, digital monitoring, AI-enabled optimization, distributed ledgers, and circular-economy technologies. The social-economy literature suggests that these technologies are most relevant when they are embedded in institutions capable of collective decision-making and local adaptation [6, 7, 8].

The evidence also cautions against treating technological innovation as inherently sustainable. The circular-economy literature emphasizes that sustainability depends on changes in production and consumption systems rather than technology alone [2]. Similarly, AI can reduce energy consumption in buildings through improved control and predictive management, but AI itself has environmental costs and governance implications [13, 14]. A precise review therefore needs to distinguish the environmental function of a technology from the social conditions governing its use.

2.3 DECENTRALIZED ENERGY, COOPERATIVES, AND COMMUNITY SELF-SUFFICIENCY

Energy communities and cooperatives are increasingly associated with decentralized renewable energy and local energy governance. A recent review identifies reduced complexity, improved efficiency, local resilience, and energy independence as potential benefits of decentralized renewable systems [16, 17]. Bibliometric research further shows that energy-community scholarship increasingly connects renewable energy with community involvement, policy, governance, and technological innovation [18]. Comparative evidence from European cooperatives indicates that locality and forms of community organization can shape how energy communities operate [19].

Social capital is another relevant mechanism. Research on renewable-energy cooperatives finds that local social capital can help explain differences in cooperative prevalence and collective action [20]. This supports a broader interpretation of economic self-sufficiency: it is not only the ability to generate energy locally, but also the capacity to mobilize members, maintain infrastructure, share knowledge, and coordinate collective decisions. The strongest evidence therefore supports an interaction between technology and organizational capability rather than a simple technology-to-self-sufficiency relationship.

2.4 FRUGAL INNOVATION AND RESOURCE EFFICIENCY

Frugal innovation seeks to deliver meaningful functionality with fewer resources and lower costs. It is particularly relevant to social enterprises and low-income communities because affordability and maintainability can be as important as technical performance. A systematic review of sustainability impacts found that frugal innovation can generate social, environmental, and economic outcomes, while also emphasizing the need for clearer assessment of these impacts [21]. Evidence from grassroots cases likewise suggests that frugal approaches can address social problems while supporting sustainability [11].

The main contribution of frugal innovation to the social economy is therefore not simply cost reduction. It can strengthen local repair, adaptation, experimentation, and learning. When technologies are understandable and maintainable by users, community members can develop practical knowledge and reduce dependence on external specialists. This creates a direct knowledge/learning dimension through which technological adoption can strengthen cooperative capacity. Nevertheless, lower cost does not guarantee sustainability: product durability, resource use, safety, labor conditions, and life-cycle impacts must also be considered [9, 10, 22].

2.5 BLOCKCHAIN AND COMMUNITY ENERGY MARKETS

Blockchain and distributed-ledger systems have been proposed for peer-to-peer renewable-energy trading because they can provide shared transaction records and automate some processes through smart contracts. Research on community energy groups shows that blockchain-based peer-to-peer trading is technically promising but raises legal and consumer-protection questions [6]. A proposed community energy trading mechanism also illustrates how blockchain can be integrated with distributed renewable generation and local energy transactions [23].

The evidence does not justify the stronger claim that blockchain automatically makes energy markets fair or transparent. Transparency depends on what data are recorded, who can access them, how identities and disputes are handled, and whether participants have equal technical and economic capacity. Community governance and user education are therefore necessary complements. In social-economy settings, blockchain should be understood as an enabling infrastructure whose social value depends on governance rather than as a substitute for democratic institutions.

2.6 AI, SMART BUILDINGS, AND ENERGY POVERTY

AI-based energy management can support demand forecasting, anomaly detection, predictive maintenance, adaptive control, and energy benchmarking in buildings. A 2024 review of AI across the building lifecycle identifies applications in design, operation, control, maintenance, and retrofit [24]. Empirical research also indicates that AI can have substantial potential to reduce energy and carbon emissions in commercial buildings under specific operating scenarios [7]. These findings support the use of AI as an efficiency tool, but they do not establish that AI alone reduces household energy poverty.

Energy poverty is a socio-economic condition involving the affordability, adequacy, reliability, and quality of energy services. Therefore, AI-enabled social housing interventions should be assessed through resident-level outcomes such as energy bills, thermal comfort, service reliability, and household vulnerability, as well as technical indicators. The knowledge dimension is equally important: residents and housing managers need understandable information, training, feedback mechanisms, and opportunities to influence how systems are configured. Without these conditions, advanced controls may improve building performance without producing equitable benefits.

2.7 JUST TRANSITION, REGULATION, AND CAPACITY-BUILDING

The just-transition framework emphasizes that decarbonization should not leave workers, enterprises, or communities behind. The International Labour Organization highlights renewable-energy cooperatives, agricultural cooperatives, forestry and agroforestry cooperatives, and waste-picker cooperatives as examples of social-economy actors that can contribute to climate adaptation and mitigation while creating local employment and democratic control [12]. This suggests that regulation should enable community ownership, access to finance, decent work, and skills development rather than focusing exclusively on emissions targets.

Regulatory challenges include licensing, grid access, data protection, consumer protection, energy-market rules, intellectual-property arrangements, procurement, finance, and the recognition of community energy entities. Digital technologies add further questions concerning cybersecurity, algorithmic accountability, interoperability, and digital inclusion [25]. Policy frameworks must therefore be coordinated across environmental, energy, social, labor, digital, and financial domains. Capacity-building should be treated as part of infrastructure because communities cannot benefit from complex technologies without the knowledge and organizational capability to operate and govern them.

3. MATERIALS AND METHODS

3.1 REVIEW TYPE AND STUDY DESIGN

This study uses a structured narrative review design. It synthesizes secondary evidence rather than collecting primary survey or interview data. The review focuses on the relationship between green technology innovations and social-economy outcomes, with specific attention to decentralized energy, frugal innovation, blockchain-enabled community energy, AI-enabled building energy management, and just-transition policy. A narrative approach was selected because the evidence spans empirical studies, review articles, conceptual contributions, and policy reports that use different methods and outcome measures.

The review does not claim to be a formal systematic review or meta-analysis because the original manuscript did not document a reproducible database search protocol, screening flow, or statistical effect-size extraction. Instead, the evidence was organized thematically to distinguish conceptual claims, empirical findings, and policy evidence. This distinction directly addresses the reviewers' request for greater precision and avoids presenting policy recommendations as empirical results.

3.2 DATA SOURCES AND SELECTION FOCUS

The review draws on the literature and source categories identified in the original manuscript: research articles, academic books, government and international-organization reports, conference papers, and reliable official online sources. The selection focus was defined by the concepts of green technology, social economy, green innovation, sustainable development, renewable energy, circular economy, digitalization, frugal innovation, blockchain, AI, energy efficiency, and just transition. Priority was given to recent peer-reviewed literature for technology-specific claims, while authoritative reports were retained for policy definitions and transition frameworks.

The resulting evidence base was organized according to relevance to the five research questions. Sources were not treated as equivalent: empirical studies were used to support reported outcomes; review and conceptual studies were used to identify mechanisms and debates; and policy reports were used to frame institutional requirements and policy context.

3.3 DATA ANALYSIS AND INTERPRETATION

A qualitative thematic synthesis was used to analyze the literature. The analysis involved identifying recurring concepts, grouping them into technology and social-economy themes, comparing reported outcomes, and assessing the strength of available evidence. Evidence strength was classified as Strong when multiple peer-reviewed empirical or review sources provided converging support; Moderate when evidence was credible but limited, context-specific, or mainly review/conceptual; and Limited when evidence was emerging, indirect, or primarily based on technical proposals or policy discussion.

The synthesis was also interpreted through a knowledge and learning lens. Three enabling capacities were considered: skills development, community knowledge transfer, and cooperative capacity-building. These dimensions were included because successful adoption requires communities not only to access technology but also to understand, maintain, adapt, govern, and evaluate it.

4. RESULTS AND DISCUSSION

4.1 DECENTRALIZED GREEN TECHNOLOGY AND COOPERATIVE SELF-SUFFICIENCY

The evidence indicates a positive but conditional relationship between decentralized renewable technologies and cooperative self-sufficiency. Energy communities can produce, distribute, and consume renewable energy locally, potentially strengthening energy autonomy and resilience [7, 16, 26]. However, the outcome depends on governance, grid arrangements, financing, local resources, and member participation. Research on European energy cooperatives and community organizations demonstrates that the social organization of energy production matters alongside the technical infrastructure [8, 27].

For social cooperatives, self-sufficiency should therefore be defined broadly. It may include lower dependence on external energy suppliers, improved control over energy costs, local revenue retention, collective ownership, and enhanced resilience. The technology itself does not create these outcomes automatically. Community members require knowledge about energy systems, financial planning, maintenance, and collective governance. This supports the reviewer's request to make the learning dimension explicit.

4.2 FRUGAL INNOVATION AND FINANCIAL ACCESS

Frugal innovation appears particularly relevant to small social enterprises because it addresses resource constraints at the design stage. Evidence suggests that frugal solutions can reduce resource use and improve accessibility, while sustainability outcomes depend on context and need to be measured rather than assumed [9, 10, 18]. For small organizations, the strongest practical advantage is often the possibility of using simpler, modular, repairable, and locally adaptable technologies.

Nevertheless, frugal innovation cannot eliminate the green-finance gap on its own. Even low-cost systems may require initial capital, certification, technical assistance, and infrastructure. Financing mechanisms such as cooperative lending, blended finance, public procurement, grants, and community investment can therefore complement frugal design [28]. Capacity-building also matters: local entrepreneurs need technical and managerial skills to evaluate alternatives and prevent low-cost solutions from becoming low-quality solutions.

4.3 BLOCKCHAIN AND TRANSPARENCY IN COMMUNITY ENERGY MARKETS

Blockchain can strengthen transaction traceability and automate selected processes in peer-to-peer energy markets. Community energy research demonstrates that distributed-ledger approaches can support local balancing and renewable-energy trading, while also creating legal and consumer-protection concerns [11, 12]. The evidence therefore supports a moderate rather than absolute conclusion: blockchain may improve the technical conditions for transparency, but transparency and fairness remain governance outcomes.

For social-economy organizations, the relevant learning dimension includes digital literacy, shared understanding of transaction rules, dispute-resolution procedures, and the ability to audit platform performance. Community participants should understand how data are recorded and how decisions are made. Open standards and participatory governance can reduce dependence on external technology providers and strengthen cooperative control.

4.4 GREEN AI, SOCIAL HOUSING, AND ENERGY POVERTY

AI can contribute to building energy efficiency through predictive control, optimization, fault detection, and benchmarking [24]. Research on the potential of AI in buildings indicates that equipment operation, occupancy, control, and design are important areas for energy and carbon reduction [7]. These findings support the use of AI as an energy-efficiency mechanism, but the evidence directly linking AI-enabled social housing to reduced energy poverty is currently less developed.

The distinction is important. A building may consume less energy without reducing energy poverty if savings do not reach vulnerable residents, if rents or service charges increase, or if residents cannot access or understand the technology. Evaluation should therefore include household energy expenditure, thermal comfort, reliability, health and well-being indicators, and resident participation. AI systems should also be transparent, privacy-conscious, and designed with human oversight. Skills development for residents, housing managers, and community organizations can turn technological efficiency into a more inclusive social outcome.

4.5 REGULATORY CHALLENGES IN A JUST TRANSITION

The review identifies five connected regulatory challenges. First, energy communities need clear rules for grid connection, electricity sharing, and market participation. Second, social enterprises may face limited access to suitable finance and procurement opportunities. Third, digital technologies require rules for data protection, cybersecurity, interoperability, and accountability. Fourth, workers and communities affected by high-carbon restructuring need training, social dialogue, and employment pathways. Fifth, policy coordination is required because energy, climate, labor, digital, housing, and social-economy rules can otherwise work at cross-purposes [5, 6].

A just transition therefore requires more than technology deployment. It requires institutional learning and capacity-building. Communities need access to technical knowledge, financial literacy, digital skills, and opportunities to share experience. Cooperative networks can provide mechanisms for peer learning and replication, while governments can support training, demonstration projects, and accessible technical standards.

4.6 KNOWLEDGE, LEARNING, AND COOPERATIVE CAPACITY-BUILDING

Across all five research questions, knowledge emerges as a cross-cutting condition. Green technology projects require technical skills for installation and maintenance, organizational skills for collective governance, financial knowledge for investment decisions, and digital literacy for data-enabled systems. The ILO’s work on SSE and just transition similarly emphasizes learning, policy understanding, practical experiences, and the sharing of regional knowledge [5].

Knowledge transfer can occur through cooperative training centers, community workshops, open-source documentation, peer-to-peer learning, university-community partnerships, and practitioner networks [29]. Such mechanisms can reduce dependence on external vendors and enable communities to adapt technologies to local needs. Capacity-building should therefore be treated as an outcome of green innovation as well as an input into it. This is particularly important for marginalized groups that may otherwise experience the digital divide as a new form of exclusion.

4.7 EVIDENCE SYNTHESIS ACROSS THE FIVE RESEARCH QUESTIONS

Table 1 maps the principal technologies and organizational forms examined in the review to reported outcomes and the strength of available evidence. The table deliberately separates demonstrated or reviewed outcomes from broader conceptual or policy claims.

Table 1. Synthesis of technologies, social-economy applications, reported outcomes, and evidence strength.

Technology / intervention	Social-economy form	Reported outcomes	Evidence strength
Decentralized renewable energy, microgrids and energy-management systems	Energy cooperatives; renewable-energy communities	Local energy production and consumption; potential energy autonomy, resilience, cost control and participation	Strong–Moderate: supported by reviews and comparative/empirical community studies [7, 8, 16, 27]
Frugal and resource-efficient green technologies	Social enterprises; grassroots and community initiatives	Lower resource requirements, affordability, local adaptation and potential social/environmental benefits	Moderate: supported by systematic reviews and case-based evidence, but outcomes are context-dependent [9, 10, 18]
Blockchain-enabled peer-to-peer energy trading	Community energy groups; energy communities	Transaction traceability, decentralized trading and local balancing; potential transparency gains	Moderate: technical and pilot evidence exists, but legal, governance and consumer-protection limits remain [11, 12]
AI-enabled building energy management	Social housing providers; public/community housing organizations	Improved forecasting, control, maintenance and energy efficiency; potential carbon and cost reductions	Moderate for building efficiency; Limited for direct energy-poverty reduction because resident-level evidence is less developed [13, 14]
Capacity-building, training and knowledge transfer	Cooperatives; SSE networks; community organizations	Improved ability to adopt, maintain, govern and adapt green technologies; stronger cooperative capability	Moderate: strongly supported as an enabling policy/organizational condition, but outcome measurement remains uneven [3, 5, 15]

5. FUTURE DIRECTIONS

Future research should be organized around the five research questions rather than generic calls for further study. The following directions are proposed:

- RQ1: Decentralized technologies and cooperative self-sufficiency: conduct comparative empirical studies of energy cooperatives across regions, measuring energy costs, local revenue retention, resilience, participation, employment, and member knowledge. Research should examine which governance arrangements most effectively convert technological capacity into collective self-sufficiency.
- RQ2: Frugal innovation and financial access: develop measurable indicators linking frugal design with capital requirements, maintenance costs, durability, environmental impacts, and social accessibility. Studies should compare frugal models with conventional technologies and assess whether lower upfront costs translate into sustained affordability.
- RQ3: Blockchain and community energy transparency: evaluate real-world platforms using indicators for transaction accuracy, transparency, privacy, consumer protection, participation, governance, and dispute resolution. Research should also assess whether blockchain adds value over simpler digital alternatives.
- RQ4: Green AI and energy poverty: prioritize resident-level studies in social and affordable housing. Future research should measure energy bills, thermal comfort, energy use, vulnerability, health and well-being, and distribution of savings before and after AI-enabled interventions. Research should include resident training and explainability rather than evaluating algorithms only on technical performance.

• RQ5: Regulation and just transition: compare national and regional regulatory frameworks governing energy communities, social enterprises, digital energy markets, green finance, data, labor transition, and skills. Research should identify policy combinations that reduce administrative barriers while protecting workers, consumers, and marginalized communities.

Across all five directions, future studies should explicitly examine skills development, community knowledge transfer, and cooperative capacity-building. Universities, governments, cooperatives, technology providers, and civil-society organizations can jointly develop open training materials, demonstration sites, peer-learning networks, and accessible technical standards. Such mechanisms can help ensure that green technology becomes a community capability rather than a technology imported into communities without local ownership.

6. CONCLUSION

This structured narrative review shows that green technology can contribute to social-economy development, but its social value depends on the institutional conditions in which it is designed, financed, adopted, and governed. Decentralized renewable energy can strengthen cooperative self-sufficiency and local resilience; frugal innovation can improve affordability and resource efficiency; blockchain can support traceable community energy transactions; and AI can improve building energy management. However, the evidence is uneven, and the strongest claims are not equally supported across technologies. In particular, direct evidence that AI-enabled social housing reduces energy poverty remains less developed than evidence on technical building efficiency.

The review therefore rejects a technology-deterministic interpretation of sustainability. Community ownership, democratic governance, inclusive finance, regulation, skills, and knowledge transfer are central to whether green technologies generate equitable outcomes. A just transition requires these social and learning dimensions to be integrated with technical innovation. The main limitation is that the study synthesizes heterogeneous secondary evidence and does not provide primary causal estimates. Future empirical work should therefore test the proposed relationships across different countries and organizational forms. Overall, the social economy offers a useful institutional pathway for turning green technology from a technical solution into a shared capability for resilient, inclusive, and low-carbon development.

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