Assessing the Social Implications of Carbon Dioxide Removal Technologies and Smart Infrastructure Deployment

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Abstract

The global energy system is undergoing a profound transformation to meet the ambitious goals of the Paris Agreement. This transition increasingly relies not only on conventional mitigation but also on two critical frontiers: Carbon Dioxide Removal (CDR) technologies and smart infrastructure. However, current research and policy discussions are predominantly focused on technical feasibility and economic costs, with a significant gap in assessing their wide-ranging and complex social implications. This paper aims to fill this gap by employing an interdisciplinary analytical framework to systematically evaluate the social impacts of deploying CDR technologies (such as Bioenergy with Carbon Capture and Storage, Direct Air Capture, and Enhanced Weathering) and smart infrastructure (including smart grids, smart city platforms, and intelligent transport systems). The article argues that while both technological suites are crucial for climate mitigation, they risk triggering or exacerbating a suite of social challenges, including land and resource competition, energy justice concerns, community rights, data privacy, labour market disruptions, and new governance demands. We posit that a successful energy transition is not merely a technical or economic process but a profound societal restructuring. Therefore, social considerations must be placed at the core of technology deployment and policy design. Through anticipatory governance, inclusive decision-making, and robust regulatory frameworks, the transition can be steered towards a more just, equitable, and resilient future. The paper concludes with a synthesized framework of policy recommendations to align climate action with social sustainability objectives.

Keywords

Carbon Dioxide Removal (CDR), Smart Infrastructure, Social Impact, Energy Justice, Technological Transition, Data Privacy

1. Introduction

The escalating climate crisis necessitates a rapid and fundamental decarbonization of the global economy. The Intergovernmental Panel on Climate Change (IPCC) has consistently highlighted that pathways limiting global warming to 1.5°C or even 2°C above pre-industrial levels are virtually impossible without the large-scale deployment of Carbon Dioxide Removal (CDR) technologies. Concurrently, the digitalization and "smartening" of energy, transport, and urban infrastructure are promoted as essential levers for optimizing efficiency, integrating renewable energy, and reducing emissions [1].

While the technical potential and economic costs of these systems are actively researched, a comprehensive understanding of their social dimensions remains underdeveloped. This oversight is perilous. CDR technologies, particularly land-intensive ones like Bioenergy with Carbon Capture and Storage (BECCS) and Afforestation/Reforestation (AR), pose significant risks related to land grabs, food security, water resources, and impacts on indigenous and local communities. Similarly, the deployment of smart infrastructure, underpinned by data collection and algorithmic control, raises critical questions about privacy, social equity, digital divides, and the centralization of power [2].

This article contends that the parallel deployment of CDR and smart infrastructure represents a co-evolutionary socio-technical transition with profound and interconnected social consequences. A siloed analysis of either domain is insufficient. The social license to operate for CDR may be contingent on transparent and equitable governance, a principle that is equally tested by the data-driven governance models of smart cities. The labour displacement from automation in smart systems must be considered alongside the new rural livelihoods potentially created by certain CDR projects.

This paper provides a holistic assessment of these social impacts. It is structured as follows: Section 2 delves into the social landscape of CDR technologies, categorizing them and analysing their associated justice and equity concerns. Section 3 turns to smart infrastructure, examining its social implications across urban and energy systems. Section 4 synthesizes the findings, exploring the intersections and feedback loops between these two technological domains.

Finally, Section 5 proposes a forward-looking governance and policy framework to navigate these complex social terrains, and Section 6 offers concluding remarks [3].

2. The Social Landscape of Carbon Dioxide Removal (CDR) Technologies

CDR encompasses a diverse portfolio of technologies and approaches. For a structured social impact analysis, they can be categorized as follows:

- Land-Intensive Biological Methods: BECCS, AR.
- Chemical/Geochemical Engineering Methods: Direct Air Capture (DAC), Enhanced Weathering (EW).
- Hybrid/Ocean-Based Methods: Ocean Alkalinization, Biochar.

Each category carries a distinct social risk and opportunity profile.

2.1 Land-Intensive Biological Methods: The Food, Fuel, and Land Nexus

BECCS and large-scale AR are among the most prominent CDR methods in Integrated Assessment Models. However, their gargantuan land requirements-potentially covering an area equivalent to one-third of current global cropland-present arguably the most severe social challenges.

Social Impact: The primary risk is land competition, threatening to displace local communities, smallholder farmers, and indigenous peoples from their ancestral lands. This can lead to "green grabbing," where land is appropriated for environmental ends, exacerbating food insecurity and undermining land rights [4]. The large-scale monoculture plantations often associated with BECCS can lead to biodiversity loss, water scarcity, and the degradation of local ecosystems that communities depend on for their livelihoods. The benefits, such as revenue from carbon credits, often accrue to large landowners and corporations, while the costs are borne locally, creating a clear procedural and distributive injustice.

Case Study: The Socio-Ecological Paradox of BECCS in Southeast Asia

The theoretical risks of land-intensive CDR are already materializing in certain regions, offering a cautionary tale. In Indonesia and Malaysia, the rapid expansion of palm oil plantations for biofuel production provides a pertinent analog for understanding the potential social impacts of future large-scale BECCS deployment. While palm oil is not synonymous with BECCS, the dynamics of large-scale monoculture for energy production share striking similarities [5].

The drive to meet biofuel targets has, in many cases, led to the conversion of diverse tropical rainforests and peatlands into monoculture plantations. This transformation has not only released vast stores of carbon sequestered in these ecosystems-counteracting the intended climate benefit-but has also profoundly impacted local communities. Indigenous groups, such as the Dayak tribes in Kalimantan, have reported loss of customary land, depletion of non-timber forest products they rely on for sustenance and income, and contamination of water sources due to agricultural runoff. The promised economic benefits, including jobs, often prove to be transient and low-wage, while control over land and resources becomes concentrated in the hands of a few corporations.

This case underscores a critical socio-ecological paradox: a technology designed to mitigate a global environmental crisis (climate change) can, if deployed without careful governance, exacerbate local environmental degradation and social injustice. For BECCS to avoid this fate, project design must move beyond a narrow focus on carbon accounting and integrate robust, legally enforceable safeguards for land tenure, food sovereignty, and ecosystem integrity. This requires a paradigm shift from top-down implementation to co-design with local stakeholders, ensuring that CDR projects contribute to, rather than undermine, rural livelihoods and ecological resilience.

2.2 Chemical/Geochemical Engineering Methods: The Energy and Equity Nexus

DAC and EW require significant energy inputs and capital investment. Their social impacts are different but no less significant [6].

Social Impact: The high energy cost of DAC could divert vast amounts of renewable energy from the grid, potentially increasing energy prices and creating a new form of energy poverty where access is competed for by both households and DAC facilities. The siting of these industrial facilities raises classic environmental justice concerns: will they be located in already disadvantaged communities? Furthermore, the "techno-fix" narrative surrounding DAC may create a moral hazard, reducing the political and societal impetus for drastic emissions reductions at source and placing the burden of cleanup on future generations. The high-cost, centralized nature of these technologies also risks concentrating economic and political power in the hands of a few large tech and energy corporations.

The Mineral Demand of Enhanced Weathering: A Hidden Social Footprint

While the energy demands of DAC are often discussed, the social implications of the material inputs for other chemical CDR methods, such as Enhanced Weathering (EW), are less frequently examined. EW involves spreading finely ground silicate rocks, such as basalt or olivine, over large land areas or in coastal regions to accelerate natural chemical reactions that draw down CO_2. The large-scale implementation of EW would require an immense mining industry for these specific minerals [7].

This burgeoning demand could trigger a new wave of resource extraction, with its own suite of social conflicts. Mining operations are historically linked to human rights abuses, land dispossession, water pollution, and health impacts on nearby communities, often in developing countries with weak regulatory oversight. The pursuit of minerals for the green transition, such as cobalt and lithium, has already demonstrated these pitfalls. A similar trajectory for EW feedstock could create a perverse situation where a solution to climate change creates new environmental sacrifice zones and harms vulnerable populations.

Therefore, a comprehensive social impact assessment of EW must include a cradle-to-grave analysis of its mineral supply chain. This involves evaluating the governance of mining sectors in source countries, the application of Free, Prior, and Informed Consent (FPIC) for indigenous and local communities, and the development of fair-trade certification schemes for CDR minerals. Without such measures, the social footprint of EW could significantly tarnish its legitimacy as a sustainable climate solution [8].

2.3 Hybrid Methods and Broader Justice Considerations

Biochar, while potentially beneficial for soil health, could also drive land-use changes. Ocean-based methods raise complex questions about the global governance of commons and potential impacts on coastal communities and marine ecosystems.

A cross-cutting issue for all CDR is intergenerational justice. Deploying CDR at scale implicitly assigns the burden of cleaning up atmospheric CO2 to future generations, who must operate and pay for these systems. This creates a fundamental ethical question about the distribution of responsibility and risk.

Beyond Technological Silos: The Imperative for Integration in CDR Policy

A critical, often overlooked, aspect of CDR deployment is the interaction between different methods and their cumulative social impacts. Policy and research often examine CDR technologies in isolation, but in reality, they will compete for the same finite resources: land, water, financing, and political support [9]. For instance, large-scale BECCS and Afforestation (AR) would compete directly for agricultural land, potentially driving up global food prices. Similarly, both DAC and EW would vie for abundant, cheap renewable energy.

This competition necessitates integrated governance. Rather than supporting any single technology, policy frameworks should guide the development of a diversified and context-specific CDR portfolio that minimizes aggregate social risks. For example, policies could prioritize biochar production using agricultural residues on marginal lands, which offers soil enhancement with lower land-use conflict, over large-scale BECCS that requires prime agricultural land. Furthermore, revenue from high-tech CDR methods like DAC, which may have a smaller physical footprint but a large energy demand, could be leveraged to fund community-led agroforestry or soil carbon sequestration projects that deliver localized co-benefits.

This integrated approach requires moving beyond siloed technology assessments and developing multi-criteria decision-support tools that allow policymakers and communities to evaluate CDR options based on a balanced scorecard of carbon sequestration potential, cost, and-critically-social and environmental impacts [10].

Table 1. Social Impact Profile of Select CDR Technologies

CDR Technology	Primary Social Risks	Potential Social Co-benefits	Key Justice Dimensions
BECCS	Land grabbing, food insecurity, displacement of communities, water scarcity, loss of biodiversity.	Rural employment, local energy production (if using waste biomass).	Distributive, Procedural, Recognition Justice.
DAC	High energy cost potentially increasing energy poverty, siting in disadvantaged areas, moral hazard, corporate concentration.	High-tech job creation, potential for localized air capture.	Distributive, Intergenerational Justice.
Afforestation	Similar to BECCS; conflicts over land use rights, exclusion of local users from forest resources.	Recreation, local ecosystem services (if native species are used), non-timber forest products.	Distributive, Procedural Justice.
Biochar	Land-use change for feedstock, potential for large-scale monocultures.	Improved soil fertility and crop yields for farmers, waste management.	Distributive Justice.
Enhanced Weathering	Land and water use for mining and processing, potential local environmental contamination from mining.	Improved soil health (for agricultural application), job creation in mining and logistics.	Distributive, Procedural Justice.

Table 1 summarizes the social impact profiles of several Carbon Dioxide Removal (CDR) technologies by highlighting their primary social risks, potential social co-benefits, and the justice dimensions they raise. For BECCS (Bioenergy with Carbon Capture and Storage), the key social risks include land grabbing, food insecurity, water scarcity, and biodiversity loss, while potential co-benefits involve rural employment and local energy production. Justice concerns primarily relate to distributive and recognition justice.

For DAC (Direct Air Capture), the main risks revolve around high energy demand, the siting of facilities in disadvantaged areas, and increasing corporate concentration. At the same time, DAC may create high-tech jobs and support localized carbon removal, engaging both distributive and intergenerational justice considerations [11].

Afforestation shares similar risks with BECCS, such as land-use conflicts and the exclusion of local communities from forest resources, but its potential co-benefits include recreation opportunities and ecosystem restoration if native species are planted. This technology raises distributive and procedural justice issues.

In the second part of the table, Biochar is associated with land-use changes for feedstock production but may improve soil fertility, crop yields, and waste management, relating primarily to distributive justice. Finally, Enhanced Weathering presents risks tied to mining activities, including land and water contamination, but offers co-benefits such as improved soil health, job creation in mining and logistics, and agricultural gains. Its justice considerations involve both distributive and procedural justice [12].

In summary, the table highlights that while CDR technologies can provide significant climate mitigation benefits, they also carry complex social implications that need to be evaluated through justice-focused frameworks.

3. The Social Implications of Smart Infrastructure Deployment

Smart infrastructure refers to the integration of digital technologies (sensors, IoT, data analytics, AI) into physical infrastructure systems. Its deployment in energy grids, cities, and transport is rapidly advancing, promising efficiency but introducing novel social contracts.

3.1 The Smart Grid: Between Empowerment and Exclusion

The smart grid, with its advanced metering infrastructure (AMI), dynamic pricing, and demand-side management, is foundational to a renewables-based energy system.

Social Impact: On the positive side, it can empower consumers to manage their energy use and costs, and facilitate the integration of prosumers (those who both produce and consume energy). However, it also creates risks. Data privacy is a paramount concern, as high-frequency energy consumption data can reveal intimate details of a household's life-when residents are home, their daily routines, and even what appliances they use. Dynamic pricing (e.g., real-time pricing) can benefit wealthy, flexible households while penalizing low-income families who lack the capacity or smart appliances to shift their demand, potentially exacerbating energy poverty. There is also a risk of a digital divide in energy, where the benefits of smart technologies are inaccessible to the elderly, the poor, or the digitally illiterate [13].

Algorithmic Discrimination in Dynamic Pricing

The potential for dynamic pricing to exacerbate energy poverty is a well-identified risk. However, a more subtle and emerging threat lies in the algorithms that manage these pricing schemes and energy distributions. AI-driven systems, designed to optimize grid efficiency and prevent blackouts, could inadvertently encode and perpetuate social biases. For example, an algorithm might learn that certain postcodes with lower average incomes have a less predictable energy consumption pattern. It might then, directly or indirectly, prioritize energy stability for wealthier, more "grid-friendly" neighborhoods during times of scarcity, or subject poorer areas to more frequent and severe demand-response curtailments.

This constitutes a form of algorithmic discrimination, where historical socioeconomic disparities are baked into the operational logic of critical infrastructure. The opacity of these proprietary algorithms makes it difficult to detect or challenge such biases. Therefore, the governance of smart grids must include mandates for algorithmic transparency and auditability. Regulatory bodies need the authority and technical capacity to audit these systems for discriminatory outcomes, similar to concepts being developed for AI ethics in other sectors. Furthermore, "energy justice by design" principles should require that grid optimization algorithms are trained not only on technical and economic data but also on equity metrics, ensuring that the benefits of smart grids are distributed fairly across all demographics.

3.2 The Smart City: Panopticon or Participatory Paradise?

Smart city initiatives aim to optimize urban services like traffic, waste management, and policing through pervasive data collection and centralized control systems.

Social Impact: The dominant, corporate-driven "smart city" model often prioritizes efficiency and security over equity and citizen agency. This can lead to surveillance capitalism, where citizen data is commodified and used for corporate or state control. Algorithmic governance in policing ("predictive policing") and public service allocation can perpetuate and amplify existing social biases, leading to the discrimination of marginalized groups. The high cost of smart city technologies can also divert public funds from more fundamental social needs like affordable housing and education. Truly "smart" cities, critics argue, should focus on fostering citizen participation, transparency, and social resilience, not just technological sophistication.

The Gigification of Urban Services and Erosion of Labour Rights.

The smart city model, particularly in sectors like transportation (ride-hailing) and delivery, is built on the platform economy, which has given rise to the widespread "gigification" of work. While often marketed as providing flexibility, this model can lead to the precaritization of urban labor. Gig workers often lack the social protections, job security, and collective bargaining rights associated with traditional employment. Their work is managed by algorithms that can deactivate them with little to no transparency or recourse, creating a new power asymmetry between capital and labor [14].

This transformation has profound social implications. It can deepen economic inequality by creating a class of workers with unstable incomes and limited access to social safety nets, even as platform companies capture vast amounts of value. The physical and mental stress associated with algorithmic management and the constant pressure to maintain high ratings further compounds these workers' vulnerability. A truly "smart" and equitable city must, therefore, extend its concerns beyond the citizen-as-consumer to the citizen-as-worker. This involves exploring and regulating new forms of digital worker cooperatives, advocating for portable benefits that are not tied to a single employer, and updating labor laws to recognize and protect the rights of gig workers, ensuring that the digitalization of the urban economy does not come at the cost of eroding hard-won labor standards.

3.3 Labour Market and Skills Transformation

The automation enabled by smart infrastructure will inevitably disrupt labour markets. While new jobs will be created in data science, AI maintenance, and cybersecurity, many traditional jobs in administration, transport, and manufacturing are at risk.

Social Impact: This transition risks creating significant unemployment and underemployment, particularly for middle- and low-skilled workers, if not managed with robust re-skilling and social safety nets. The gap between high-skilled, high-wage tech jobs and low-skilled, precarious "gig economy" jobs facilitated by platforms could widen economic inequality.

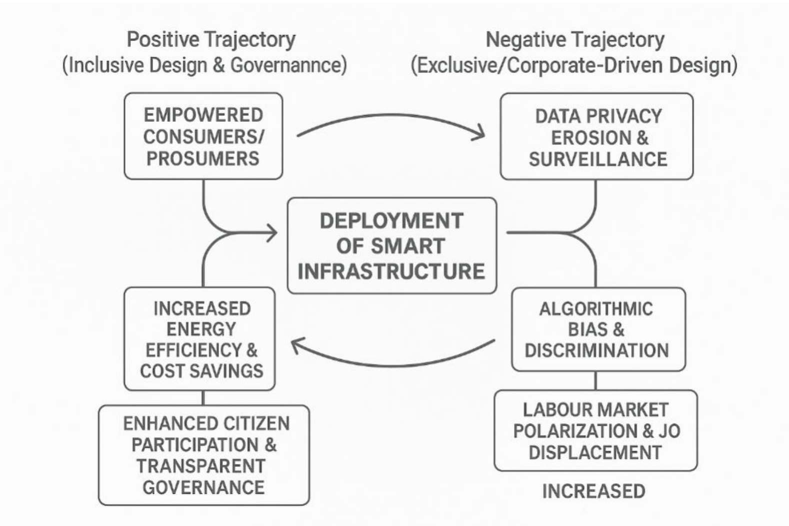

Figure 1. The Dualistic Social Impact Pathways of Smart Infrastructure

Figure 1 show the dual social impact pathways that can emerge from the deployment of smart infrastructure. At the center of the diagram is the “Deployment of Smart Infrastructure,” from which two diverging trajectories-positive and negative-are shown.

The Positive Trajectory, enabled by inclusive design and transparent governance, leads to beneficial social outcomes. These include empowered consumers and prosumers, greater energy efficiency and cost savings, enhanced citizen participation, and the creation of high-skill jobs. Ultimately, this pathway strengthens social equity and resilience.

In contrast, the Negative Trajectory, driven by exclusive or corporate-centered design, results in adverse societal consequences. These include data privacy erosion, increased surveillance, widening digital and energy divides, algorithmic bias and discrimination, and labor market polarization with job displacement. This pathway culminates in heightened social inequality and increased control over citizens.

Overall, the diagram emphasizes that the societal outcomes of smart infrastructure depend heavily on governance choices, inclusivity, and ethical design practices.

4. Synthesis: Intersections and Co-evolution of CDR and Smart Infrastructure

The social implications of CDR and smart infrastructure are not isolated; they interact in critical ways, creating a complex socio-technical system [15].

Data for CDR Governance: Smart sensors and satellite monitoring can be used to track the environmental impact and verify the carbon sequestration of CDR projects (e.g., monitoring forest health for AR or detecting leaks from geological storage). However, this introduces data justice concerns-who owns this data, who has access, and could it be used to penalize local communities?

Resource Optimization and Centralization: Smart grids are crucial for managing the intermittent, high-energy demand of certain CDR technologies like DAC. This creates a symbiotic relationship but also a risk of centralized control, where a nexus of tech, energy, and carbon removal corporations wields significant influence over energy and land use.

Financing and the Carbon Market: The digitalization of carbon markets through blockchain and other fintech could enhance transparency but could also financialize and commodify nature to an extreme degree, potentially alienating local stakeholders from the value generated on their land [16].

Converging Public Acceptability: Public resistance to one technology (e.g., due to privacy concerns with smart meters) can spill over and affect the social license for the other (e.g., a DAC plant reliant on smart grid management). Trust is a common and fragile resource.

Synthesis Case Study: A Hypothetical Smart CDR Project in Indonesia

To illustrate the profound interconnections between CDR and smart infrastructure, consider a hypothetical future project in Indonesia: a large-scale DAC plant powered by a dedicated solar farm in East Nusa Tenggara, managed by an AI-driven smart grid.

Data and Land Governance: The DAC facility's performance is continuously monitored by a network of satellites and ground sensors, generating vast datasets on carbon capture. This data is crucial for verifying carbon credits sold on the international market. However, the land hosting the solar farm and DAC plant may be customary land belonging to local communities. If these communities are not data owners or lack the capacity to interpret the data, they could be disadvantaged in negotiations over benefits and held liable for any perceived underperformance, a clear case of data injustice exacerbating land injustice.

Centralized Control and Local Benefits: The AI system optimally allocates solar energy between the DAC plant and the local grid. While efficient, this could lead to situations where the algorithm prioritizes the high-value carbon removal operation over local energy needs, especially during periods of low generation. This creates a risk of energy colonialism, where local resources are used to serve global climate goals without providing adequate local benefits, potentially even leading to localized energy scarcity.

Labor and Skills: The project creates a small number of high-skill jobs for engineers and data scientists, likely filled by national or international talent. Meanwhile, the traditional livelihoods of local communities might be displaced. Without proactive, inclusive just transition policies that include targeted education and vocational training, the project could worsen regional inequality.

This hypothetical scenario underscores that the convergence of CDR and smart tech is not merely technical. It creates new, complex socio-technical systems where decisions about data, algorithms, and resource allocation have direct and significant consequences for social equity. Governing this convergence requires integrated policies that link carbon management, data governance, energy justice, and labor rights.

5. A Framework for Socially Sustainable Deployment

Navigating this complex landscape requires a proactive and multidimensional governance framework that prioritizes justice and equity. We propose the following interconnected pillars:

- Prioritize Radical Emissions Reductions: CDR must be framed as a supplement to, not a substitute for, deep and rapid decarbonization. This is the foremost imperative of intergenerational justice.

- Embed Inclusive and Participatory Governance: From the planning stage, the deployment of both CDR and smart infrastructure must involve meaningful public participation, particularly from frontline and vulnerable communities. This includes Free, Prior, and Informed Consent (FPIC) for projects affecting indigenous lands.

- Establish Robust Regulatory Safeguards: Strong regulations are needed to protect data privacy (e.g., GDPR-style laws for energy data), prevent algorithmic bias, enforce environmental and social impact assessments for CDR, and ensure fair competition.

- Implement Pro-equity Policies: Policies must actively redistribute benefits and mitigate harms. This includes using revenue from carbon pricing or CDR to fund community benefits, energy bill assistance for low-income households, and comprehensive just transition programmes for workers displaced by automation.

• Foster Technology Design for Justice: A "justice-by-design" approach should be mandated, where technologies are explicitly designed to minimize social risks (e.g., designing DAC plants with low energy profiles, creating smart meter systems with strong privacy-by-default settings).

6. Conclusion, Limitations and Avenues for Future Research

The twin transitions driven by CDR and smart infrastructure are set to redefine our relationship with the planet and with each other. This analysis demonstrates that their social implications are as profound as their technical potential. A narrow focus on gigatons of CO2 removed or percentages of efficiency gained is myopic and dangerous. Without deliberate governance, these technological pathways risk reinforcing existing inequalities, creating new forms of exclusion, and placing undue burdens on the most vulnerable.

A successful and legitimate energy transition must be a just transition. This requires shifting the paradigm from a techno-economic optimization problem to a socio-technical co-design challenge. By placing social justice, equity, and democratic governance at the heart of policy and innovation, we can harness the potential of these powerful technologies not only to stabilize the climate but also to build a more inclusive and resilient society. The choices we make today in designing and governing these systems will resonate for generations to come.

While this paper has outlined a broad framework for assessing the social implications of CDR and smart infrastructure, several limitations warrant further investigation. First, this study relies on a synthesis of existing literature; there is a pressing need for empirical, site-specific case studies that track the social impacts of pilot projects as they are deployed. Longitudinal research is particularly crucial to understand how communities are affected over time and how power dynamics evolve.

Second, the global justice dimensions of these technologies require deeper exploration. Most CDR and smart infrastructure research originates from and focuses on the Global North. The distinct challenges, priorities, and innovation capacities of the Global South must be central to future research agendas. This includes studying how these technologies might be adapted to different governance contexts, resource constraints, and cultural values.

Finally, more work is needed to develop quantitative and qualitative metrics for assessing social impacts. Moving beyond conceptual frameworks to operationalizable indicators is essential for conducting rigorous Social Life Cycle Assessments (S-LCAs) of CDR projects and smart infrastructure deployments, enabling direct comparison and more informed decision-making.

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