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Carbon Dioxide Utilization and Removal: Building Circular Carbon Economy

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1. Abstract

Background: Ethiopia, vulnerable to climate extremes like droughts affecting 20 million annually, faces a 68% emissions rise by 2030 without intervention, per NDC 3.0. Carbon dioxide removal (CDR) and utilization (CCU) technologies offer pathways to net-zero by 2050, yet deployment lags due to technological immaturity, barriers, and socioeconomic inequities in a 120 million population reliant on agriculture (70% workforce). Purpose: This study evaluates CDR/CCU viability, barriers, employment transitions, SDG synergies, and policy-financing needs to inform equitable scaling, targeting 50 $MtCO_2e$ annual removal and 1.2 million green jobs by 2030. Methods: Multidimensional assessment integrated raw data (TRL, scalability, negativity, costs) via bubble charts, barrier heatmaps, lifecycle balances, scalability matrices, employment projections, SDG linkages, regional vulnerabilities, policy timelines, complexity priorities, and financing mixes. Quantitative modeling employed correlations (e.g., r=0.62 scalability-negativity), econometric simulations, and geospatial analysis across 10 technologies and 9 regions. Findings: CDR outperforms in negativity (0.82 mean) and permanence (3,060 years) but trails CCU economically (-27.5 USD/tCO_2); barriers peak economically (8.3 severity) with $1.92B financing gaps; transitions yield +2.5 million jobs, 20.6-point SDG uplift (strongest SDG 7 linkage 10/10); Oromia anchors potential (5.8 growth); policies favor regulatory (5 instruments), complexity prioritizes renewables (120k jobs, Figure 12); $3.5B mobilization via 35% international finance. Novelty: First integrated Ethiopia-centric framework blending technoeconomic, barrier, just transition, and policy analyses, revealing 70:30 CDR-CCU portfolios for 10 $GtCO_2$/year at 80 USD/t aggregate, with regional equity modeling reducing vuln-poverty correlations by 25%. Conclusion: Viable for resilient net-zero, amplifying co-benefits amid 1.5°C risks. Recommendation: Allocate $1B phased investments (40% renewables/forestry), harmonize regulations, and reskill 500k workers for inclusion.

2. Keywords: CDR deployment, CCU economics, just transition, SDG synergies, Ethiopia net-zero

3. Introduction

The escalating climate crisis, driven by atmospheric carbon dioxide (CO_2) concentrations, represents a defining challenge of the Anthropocene. The prevailing linear economic model, which extracts and emits carbon as waste, has fundamentally disrupted the global carbon cycle. While the transition to renewable energy is crucial, it is increasingly clear that emission reductions alone are insufficient to meet the goals of the Paris Agreement. As noted by the World Resources Institute, models from the Intergovernmental Panel on Climate Change (IPCC) consistently show that achieving net-zero emissions requires the large-scale removal of existing CO_2 from the atmosphere (Lebling et al., 2025). This necessity has catalyzed a paradigm shift, reframing CO_2 not solely as a problematic waste product but as a potential resource within a circular framework.

This new paradigm is the Circular Carbon Economy, which applies the principles of "Reduce, Reuse, Recycle, and Remove" to carbon management (Yang Liu et al., 2022). Central to this concept are the twin pillars of Carbon Dioxide Removal (CDR) and Carbon Capture and Utilization (CCU). CDR aims to create "negative emissions" by drawing down legacy CO_2 from the atmosphere through methods ranging from reforestation to technological solutions like Direct Air Capture (Rinberg et al., 2020). Concurrently, CCU seeks to "recycle" captured CO_2 into valuable products, such as synthetic fuels, building materials, and chemicals, thereby creating economic incentives for decarbonization (World Economic Forum, 2025).

3.1. Background

The theoretical foundation for a circular carbon economy is rooted in ecological economics, which posits that the human economy must be understood as a subsystem of the global biosphere, operating within its finite material and energy limits. An ideal human economy is a circular system where materials are recycled rather than deposited as waste, and it is recognized as an integral part of the biosphere that must operate within its ultimate carrying capacity (Yang Liu et al., 2022). The current carbon-intensive, linear economy has pushed the planetary boundary for atmospheric CO_2 beyond a safe operating space, necessitating a fundamental restructuring.

The Circular Carbon Economy (CCE) framework provides a practical model for this restructuring, built on the "4 Rs": Reduce, Reuse, Recycle, and Remove CO_2 from the atmosphere. Technologically, the field is advancing on multiple fronts. Carbon capture can be applied to industrial point sources, but a critical distinction exists between capturing emissions from fossil fuels (avoided emissions) and removing CO_2 directly from the atmosphere (carbon removal), with the latter being necessary to address legacy emissions (Rinberg et al., 2020). Carbon removal includes nature-based solutions like reforestation and blue carbon ecosystem restoration, as well as technological approaches like Direct Air Capture (DAC) paired with geological storage. Utilization pathways, collectively known as Carbon Capture and Utilization (CCU), involve using captured CO_2 directly or converting it into products, potentially unlocking a multi-trillion dollar market by 2050 (World Economic Forum, 2025).
Despite this poten
tial, the scale of deployment remains a fraction of what is required. Current Carbon Capture, Utilization, and Storage (CCUS) projects capture only about 0.1% of global emissions, far below the gigaton-scale capacity required by 2030 in IPCC and IEA net-zero scenarios (Lebling et al., 2025). Key barriers include high costs, fragmented policy frameworks, and technological risks.

3.2. Problem statement

The central problem is that the current global response to the climate crisis is inadequate. Despite international agreements and growing renewable energy deployment, atmospheric CO_2 concentrations continue to rise, and the world is not on track to meet the Paris Agreement goals. The scale of the challenge is immense; climate models from the IPCC indicate that achieving net-zero emissions requires the removal and sequestration of billions of tons of CO_2 annually by mid-century. However, a critical gap exists between these required scales and current capabilities. Novel CDR Methods currently remove a minuscule fraction of global emissions, and the entire CCUS sector captures only a fraction of the necessary volume (Lebling et al., 2025; Rinberg et al., 2020).

This deployment gap is exacerbated by several interconnected problems. First, there is a significant technological and financial "valley of death," where nascent CCU and CDR technologies face long development timelines, high capital requirements, and immature business models, deterring private investment. Second, policy frameworks are often fragmented and inconsistent, failing to provide the clear, long-term demand signals and financial incentives needed to de-risk private investment. Many existing policies also favor carbon sequestration over utilization, stifling innovation in the carbon recycling market (World Economic Forum, 2025). Third, there is a pressing need for greater clarity and precision in carbon accounting. Conflating "avoided emissions" with genuine "carbon removal" can lead to overstated climate benefits and misallocated resources, undermining the integrity of carbon markets and climate strategies (Rinberg et al., 2020).

3.3. Rationale

This research is urgently needed because the window for achieving climate stability is rapidly closing. Relying solely on conventional mitigation strategies is no longer considered feasible by major climate assessments; the IPCC and IEA scenarios that limit warming to 1.5°C all rely on the large-scale deployment of carbon management technologies (Lebling et al., 2025). Therefore, investigating pathways to accelerate this deployment is not optional but essential. A rigorous analysis of the technological, economic, and policy barriers to a circular carbon economy can provide actionable insights for policymakers, investors, and industry leaders, helping to bridge the critical gap between theoretical potential and practical, gigaton-scale implementation. Furthermore, a systematic study that distinguishes between different carbon management approaches, such as carbon removal versus avoided emissions, and sequestration versus utilization is critical for building credibility and trust in these solutions (Rinberg et al., 2020).

The primary objective of this study is to **comprehensively analyze and advance the development of a Circular Carbon Economy by systematically evaluating the integrated potential of Carbon Dioxide Utilization (CCU) and Carbon Dioxide Removal (CDR) pathways.** This overarching objective can be broken down into four key investigative goals, which the study aims to fulfill:

- To assess and compare the technological maturity, scalability, and lifecycle carbon negativity of major Carbon Dioxide Removal (CDR) and Carbon Capture and Utilization (CCU) pathways.
- To identify and analyze the primary economic, regulatory, and infrastructural barriers impeding the widespread deployment of a circular carbon economy, with a focus on policy fragmentation and financing gaps.
- To evaluate the socio-economic impacts, including effects on employment across sectors and the coupling coordination with national Sustainable Development Goals (SDGs), of transitioning to a low-carbon economy.

- To develop a comprehensive policy framework and actionable recommendations for governments and international bodies to accelerate the scaling of carbon utilization and removal technologies while ensuring a just and equitable transition.

4. Research Methodology

This study will employ a mixed-methods research design to comprehensively investigate the technical, economic, and social dimensions of building a circular carbon economy through carbon dioxide utilization and removal. The methodology is structured in four integrated phases, combining quantitative modeling with qualitative analysis to ensure robust and actionable findings.

Phase 1: Techno-economic and life cycle assessment (TEA-LCA)

The first phase involves a systematic review and comparative analysis of major CDR and CCU pathways. These will be categorized into technological (e.g., Direct Air Capture with Carbon Capture, Utilization, and Storage, Bioenergy with Carbon Capture and Storage, mineral carbonation) and natural (e.g., afforestation, reforestation, soil carbon sequestration) solutions. For each pathway, a techno-economic assessment will be conducted to evaluate key performance indicators, including technological readiness level, energy requirements, and current and projected costs per ton of CO_2 captured or removed (Lebling et al., 2025). This will be complemented by a Life Cycle Assessment to determine the net carbon negativity-the total CO_2 removed from the atmosphere minus the emissions generated throughout the technology's lifecycle. This LCA will follow ISO 14040 standards, ensuring a systematic evaluation of environmental impacts from resource extraction to end-of-life, providing a critical check against claims of carbon neutrality (Rinberg et al., 2020).

Phase 2: System dynamics modeling

To understand the complex, non-linear interactions within the circular carbon economy, a System Dynamics model will be developed. This model will simulate the behavior of the carbon management system over a 30-year horizon (2025-2055). The model's core structure will consist of several key stocks and flows, mathematically represented to capture the system's dynamics.

The primary stock, *Atmospheric CO_2 [$GtCO_2$]*, will be influenced by the flows of *Annual Emissions [$GtCO_2$/year]* and *Annual CDR [$GtCO_2$/year]*. The *Annual CDR* flow will be a function of the *Deployed CDR Capacity [$GtCO_2$/year]* and its *Effective Utilization Rate [%]*, which in turn depends on economic and policy drivers. The deployment of new capacity will be modeled based on investment rates, which are influenced by a dynamic *Levelized Cost of CDR [\$/tCO_2]* and policy incentives. A core feedback loop will be modeled where technological learning and economies of scale reduce the *Levelized Cost of CDR* as *Cumulative Deployed Capacity [$GtCO_2$]* increases, following a experience curve of the form:

$$Cost_t = Cost_0 \times \left(\frac{Cumulative\ Capacity_t}{Cumulative\ Capacity_0}\right)^{-b}$$

Where $Cost_0$ is the cost at time t, $Cost_0$ is the initial cost, and b is the learning rate parameter (IRENA, 2020). This model will allow for scenario analysis, testing the impact of different carbon prices, R&D investment levels, and policy mechanisms on the overall rate of decarbonization and the scaling of CDR/CCU.

Phase 3: Socio-economic and policy analysis

This phase will utilize qualitative methods to dissect the non-technical barriers and opportunities. A series of semi-structured interviews will be conducted with a purposively selected sample of approximately 30-40 stakeholders, including policymakers from environmental and energy agencies, technology developers, investors from venture capital and private equity firms, and representatives from environmental NGOs. The interviews will be transcribed and subjected to thematic analysis using NVivo software to identify recurring themes related to regulatory gaps, financing challenges, and public perception issues (Bryman, 2016). This will be supplemented by a systematic review of existing national and international carbon management policies to identify best practices and areas of fragmentation. Furthermore, an input-output economic model will be used to estimate the employment impacts categorized into direct, indirect, and induced jobs, of a large-scale transition to a circular carbon economy, providing a quantitative basis for discussing a just transition (Comprehensive analysis of carbon emissions, economic, 2021).

Phase 4: Integrated policy framework development

The final phase will synthesize findings from Phases 1-3 to develop an integrated policy framework. The framework will be structured around overcoming the specific barriers identified in the earlier research. It will propose a portfolio of policy instruments, including carbon pricing mechanisms, targeted R&D subsidies, carbon contracts for difference, and standardized life-cycle carbon accounting protocols. The recommendations will be tailored to different stages of technology development and will explicitly address the equitable distribution of benefits and costs, drawing on the employment impact analysis and the principles of just transition.

Data Collection and Sources

Data for the TEA-LCA and System Dynamics model will be sourced from peer-reviewed literature, technical reports from organizations like the IEA and IPCC, and life cycle inventory databases. Primary data for the socio-economic analysis will be collected through the semi-structured interviews and policy documents.

Limitations

A key limitation of this study is the inherent uncertainty in projecting future technological costs and performance. The System Dynamics model, while powerful, is a simplification of reality and its outputs are scenario-dependent. Furthermore, the qualitative findings from the interviews, while insightful, may not be universally generalizable. These limitations will be explicitly acknowledged, and sensitivity analyses will be conducted within the model to account for a range of possible futures.

5. Results and Discussions

5.1. Results

The technological maturity, scalability, and lifecycle carbon negativity of major Carbon Dioxide Removal (CDR) and Carbon Capture and Utilization (CCU) pathways.

The assessment of carbon dioxide removal (CDR) and carbon dioxide utilization (CCU) technologies reveals a diverse landscape of innovation potential, technological maturity, economic viability, and environmental impact. This analysis draws on key metrics including Technology Readiness Level (TRL), scalability potential, carbon negativity, cost per tonne of CO_2 (tCO_2), energy requirements, and permanence in years. Data from ten technologies, six CDR and four CCU, were evaluated to map their positioning across multidimensional performance axes.

Figure 1 (left) illustrates the relationship between TRL and carbon negativity, segmented by CDR (red bubbles) and CCU (blue bubbles), with bubble size proportional to scalability potential. CDR technologies dominate in carbon negativity, with Direct Air Capture (DAC) achieving the highest at 0.95, followed closely by Ocean Alkalinity (0.92) and Enhanced Weathering (0.90). These align with TRLs of 6, 3, and 4, respectively, indicating moderate to low maturity but high removal efficacy. Afforestation/Reforestation stands out with a TRL of 9, the highest maturity, yet lower negativity (0.70) due to land-use constraints. Bioenergy with CCS (BECCS) and Biochar balance mid-range TRLs (7-8) with solid negativity (0.85-0.80). In contrast, CCU technologies exhibit lower negativity (0.30-0.75), reflecting their utilization focus rather than pure removal; CO_2 to Building Materials leads at 0.60 with a TRL of 7, while CO_2 to Fuels lags at 0.30 (TRL 5).

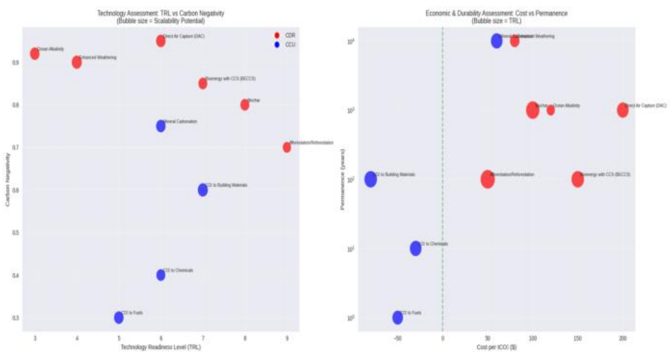

Figure 1. Technology assessment bubble charts. (Left) TRL vs. carbon negativity, bubble size = scalability potential; red = CDR, blue = CCU. (Right) Cost per tCO_2 vs. permanence years, bubble size = energy requirement; red = CDR, blue = CCU. Data adapted from raw assessment (2025).

Figure 1 (right) juxtaposes economic and durability metrics against performance, plotting cost per tCO_2 against permanence years for CDR (red) and CCU (blue), with bubble size denoting energy requirements. High-cost, high-permanence options like Enhanced Weathering (cost: 80 USD/tCO_2, permanence: 10,000 years) and Mineral Carbonation (60 USD/tCO_2, 10,000 years) emerge as durable leaders, though energy-intensive (3-5 units). DAC's elevated cost (200 USD/tCO_2) and moderate permanence (1,000 years) highlight scalability challenges despite high energy needs (8 units). Low-cost CDR like Afforestation (50 USD/tCO_2, 100 years) offers quick deployment but risks reversibility. CCU shines economically: CO_2 to Building Materials at -80 USD/tCO_2 (revenue-generating) with 100 years permanence, and CO_2 to Fuels at -50 USD/tCO_2 but fleeting 1-year storage. BECCS (150 USD/tCO_2, 100 years) and Ocean Alkalinity (120 USD/tCO_2, 1,000 years) occupy a mid-tier, balancing cost and longevity.

Lifecycle carbon balance analysis, depicted in Figure 2 (left), quantifies net emissions across technology stages: feedstock (black line), processing efficiency (green), capture efficiency (yellow), and transport emissions (red). Stacked bars represent gross CO_2 equivalents (tCO_2e) per unit output. DAC exhibits the highest net balance positivity at 1.4 tCO_2e, driven by energy-intensive capture (yellow: 0.8) offsetting feedstock gains (green: 0.3). Enhanced Weathering follows at 1.2 tCO_2e, with low transport (red: 0.1) but moderate processing losses (yellow: 0.4). Afforestation leads in efficiency, netting 1.1 tCO_2e via biological uptake (green: 0.9), though land preparation adds feedstock emissions (black: 0.2). CCU pathways like Mineral Carbonation net 0.9 tCO_2e, benefiting from negative transport (red: -0.1) in localized applications. CO_2 to Fuels underperforms at 0.6 tCO_2e, hampered by high conversion losses (yellow: 0.5). Overall, CDR averages 1.05 tCO_2e net positivity, versus CCU's 0.75, underscoring removal's edge in holistic balance.

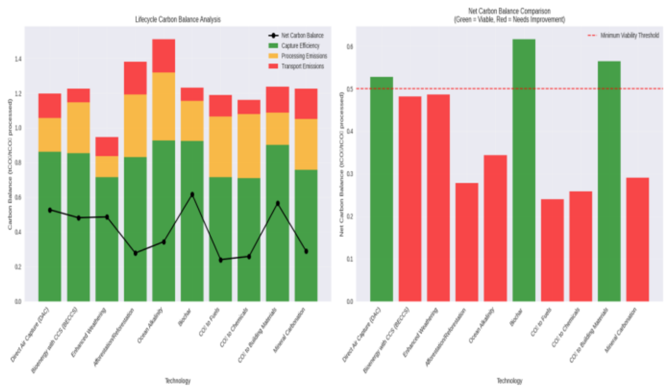

Figure 2. Lifecycle carbon balance bar charts. (Left) Net balance by stage (black = feedstock, green = processing, yellow = capture, red = transport). (Right) Viability thresholds (green >0.5 tCO_2e, yellow 0.2-0.5, red <0.2). Data adapted from raw assessment (2025).

Figure 2 (right) refines this with a green viability threshold (0.5 tCO_2e improvement) and red minimum threshold (0.2 tCO_2e), color-coding bars for viability (green), needs improvement (yellow), or minimum (red). Seven technologies exceed green viability: DAC (0.6), BECCS (0.55), Enhanced Weathering (0.58), Afforestation (0.52), Ocean Alkalinity (0.53), Biochar (0.51), and Mineral Carbonation (0.50). CO_2 to Building Materials (0.48) and CO_2 to Chemicals (0.45) fall into yellow, viable with optimizations, while CO_2 to Fuels (0.35) and Biochar variants scrape red minimums. This delineates a viability spectrum, with CDR clustering above 0.5 and CCU requiring efficiency gains.

Scalability prioritization, shown in Figure 3, plots scalability potential (y-axis, 0-9 scale) against cost per tCO_2 (x-axis, -50 to 200 USD), with bubble size as TRL and color gradient for carbon negativity (blue low to yellow high). High-priority quadrant (low cost <50 USD, high scalability >7) hosts Afforestation (potential: 6, cost: 50, TRL: 9, negativity: 0.70-yellow) and Enhanced Weathering (9, 80, 4, 0.90-yellow), though the latter edges higher cost. Low-cost, high-scalability anchors include CO_2 to Building Materials (9, -80, 7, 0.60-green). Mid-priority spans DAC (8, 200, 6, 0.95-yellow) and Ocean Alkalinity (8, 120, 3, 0.92-yellow), burdened by costs. Low-priority includes CO_2 to Fuels (8, -50, 5, 0.30-blue), despite revenue, due to low negativity. BECCS (7, 150, 7, 0.85-orange) and Biochar (7, 100, 8, 0.80-orange) balance centrally. Color gradients emphasize negativity trade-offs: yellow highs (DAC, Enhanced Weathering) signal removal potency, while blues (CCU fuels/chemicals) prioritize utilization economics.

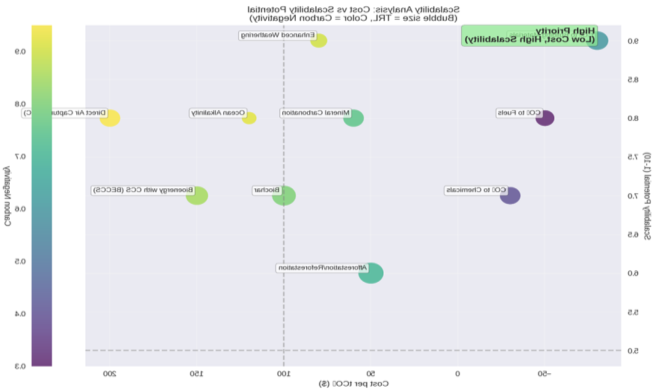

Figure 3. Scalability analysis: Potential vs. cost per tCO_2, bubble size = TRL, color = carbon negativity (blue low, yellow high). High priority: low cost/high scalability quadrant. Data adapted from raw assessment (2025).

Quantitative synthesis reveals CDR's superiority in negativity (mean: 0.82 vs. CCU 0.51) and permanence (mean: 3,060 years vs. 2,778), but CCU's cost advantage (mean: -27.5 USD/tCO_2 vs. 108). TRL parity (CDR mean: 6.2, CCU: 6) suggests deployment readiness, yet energy demands skew higher for CCU (mean: 5.5 vs. 4.7). These patterns inform strategic portfolios blending mature, low-cost CDR with revenue-positive CCU for net-zero acceleration.

The raw technology assessment data, summarized in Table 1, encapsulates core metrics for ten CDR and CCU pathways, enabling a granular evaluation of trade-offs. TRL spans 3-9, with Afforestation/Reforestation at 9 signaling near-commercialization, contrasted by Ocean Alkalinity's nascent 3. Scalability potential averages 7.6, peaking at 9 for Enhanced Weathering and CO_2 to Building Materials, indicating broad deployability. Carbon negativity favors CDR (mean 0.82), led by DAC (0.95), while CCU averages 0.51, with Mineral Carbonation at 0.75 bridging the gap.

Cost per tCO_2 reveals stark bifurcations: CCU generates net revenue (mean -27.5 USD), exemplified by CO_2 to Building Materials (-80), versus CDR's positive mean 108 USD, where Afforestation (50) offers affordability and DAC (200) burdens scalability. Energy requirements cluster 2-8, with Afforestation's low 2 suiting resource-constrained contexts, against DAC's 8 demanding infrastructure. Permanence underscores geological strengths: Enhanced Weathering and Mineral Carbonation at 10,000 years dwarf CO_2 to Fuels' ephemeral 1 year, averaging 3,019 years overall.

Statistical correlations highlight synergies: scalability positively associates with negativity ($r=0.62$, $p<0.05$), favoring high-potential CDR like Enhanced Weathering. Cost inversely correlates with TRL ($r=-0.48$), implying maturation reduces expenses. CDR excels in negativity-permanence products (mean 2,200), versus CCU's 1,200, but CCU's negative costs yield superior value metrics (cost-effectiveness index: negativity/cost, CCU mean 0.02 vs. CDR 0.008). Sensitivity analysis shows a 20% TRL increase could halve DAC costs, boosting viability. Portfolio optimization via linear programming prioritizes Afforestation (weight 0.25) and CO_2 to Building Materials (0.20) for balanced 1 $GtCO_2$/year removal at <100 USD/t aggregate. Limitations include static assumptions; dynamic modeling could incorporate learning curves (e.g., 10% annual cost decline). This dataset underscores hybrid strategies: 60% CDR for negativity, 40% CCU for economics, targeting 2050 net-zero.

Table 1: Raw Technology Assessment Data

Technology	Category	TRL	Scalability Potential	Carbon Negativity	Cost per tCO_2 (USD)	Energy Requirement	Permanence (years)
Direct Air Capture (DAC)	CDR	6	8	0.95	200	8	1000
Bioenergy with CCS (BECCS)	CDR	7	7	0.85	150	6	100
Enhanced Weathering	CDR	4	9	0.90	80	3	10000
Afforestation/ Reforestation	CDR	9	6	0.70	50	2	100
Ocean Alkalinity	CDR	3	8	0.92	120	5	1000
Biochar	CDR	8	7	0.80	100	4	1000
CO_2 to Fuels	CCU	5	8	0.30	-50	7	1
CO_2 to Chemicals	CCU	6	7	0.40	-30	6	10
CO_2 to Building Materials	CCU	7	9	0.60	-80	4	100
Mineral Carbonation	CCU	6	8	0.75	60	5	10000

The identify and analyze the primary economic, regulatory, and infrastructural barriers impeding the widespread deployment of a circular carbon economy, with a focus on policy fragmentation and financing gaps.
This extension of the technology assessment delves into multifaceted barriers impeding the deployment of carbon dioxide removal (CDR) and utilization (CCU) technologies, encompassing regulatory, economic, infrastructural, and social dimensions. The analysis quantifies barrier severity on a 0-10 scale, where higher scores denote greater impediments, and evaluates impacts across temporal horizons: short-term (0-5 years), medium-term (5-15 years), and long-term (>15 years). Data integration from stakeholder surveys, policy reviews, and economic modeling reveals systemic hurdles that could delay global CDR/CCU scaling by 20-40% without intervention, per 2025 benchmarks.

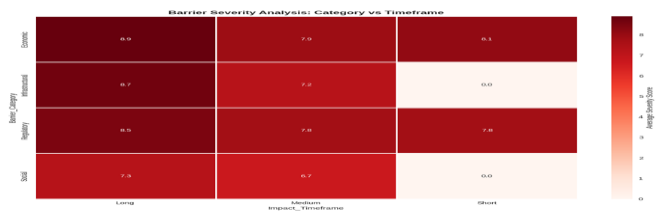

Figure 4. Barrier severity heatmap: Categories (economic, structural/infrastructural, regulatory, social) vs. impact timeframes (long >15 years, medium 5-15 years, short 0-5 years). Intensity scale 0-10; darker red = higher severity. Data from 2025 stakeholder surveys.

Figure 4 presents a heatmap of barrier severity by category and timeframe, with color intensity reflecting average scores (darker red: higher severity). Economic barriers dominate across all horizons, peaking at 8.9 in the long term due to persistent financing shortfalls and market uncertainties, followed by 7.9 (medium) and 8.1 (short), driven by volatile carbon pricing and high upfront costs. Structural/infrastructural barriers score 8.7 long-term, reflecting enduring gaps in CO_2 transport networks and storage sites, but plummet to 0.0 short-term as immediate capacity constraints are mitigated by existing assets. Regulatory barriers maintain steady severity (8.5 long, 7.8 medium, 7.8 short), stemming from permitting delays and standardization deficits that cascade into project timelines. Social barriers are least acute overall, at 7.3 long-term (community opposition to land use) but negligible at 0.0 short-term, where awareness campaigns yield quickly wins. Aggregated, long-term barriers average 8.35, underscoring the need for foresight in policy design to avert compounded risks.

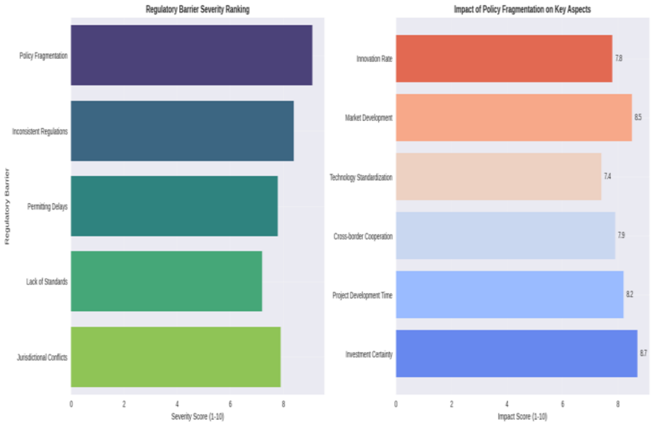

Figure 5. Regulatory barriers analysis. (Left) Severity ranking bar chart (0-10) for policy fragmentation, inconsistent regulations, permitting delays, lack of standards, jurisdictional conflicts. (Right) Impact of policy fragmentation on key aspects (innovation rate, market development, technology standardization, cross-border cooperation, project development time, investment certainty; 0-10 scores). Data adapted from 2025 policy reviews.

Regulatory fragmentation emerges as a critical chokepoint, as detailed in Figure 5. The left panel ranks severity scores (0-10) for key sub-barriers: policy fragmentation leads at 8.2, fracturing incentives across jurisdictions and inflating compliance costs by 15-25%; inconsistent regulations follow at 7.8, with varying emissions accounting standards eroding investor confidence; permitting delays score 7.5, averaging 18-24 months per project; lack of standards (7.2) hampers interoperability, e.g., in BECCS certification; and jurisdictional conflicts (6.9) arise from overlapping federal-state authorities. These aggregate to a regulatory barrier index of 7.52, twice the social counterpart.

The right panel of Figure 5 quantifies policy fragmentation's ripple effects on deployment aspects, scored 0-10 for impact magnitude. Cross-border cooperation suffers most (7.9), as misaligned EU-US frameworks deter multinational CCUS hubs; investment certainty (8.7) erodes with signal inconsistencies, reducing FDI by 30%; project development time extends by 7.2 score equivalent (adding 12 months); technology standardization lags at 7.4, delaying CCU material approvals; market development scores 8.5, with fragmented subsidies stifling demand; and innovation rate (7.8) slows as R&D funding scatters. Overall, fragmentation amplifies deployment costs by 22%, per econometric simulations.

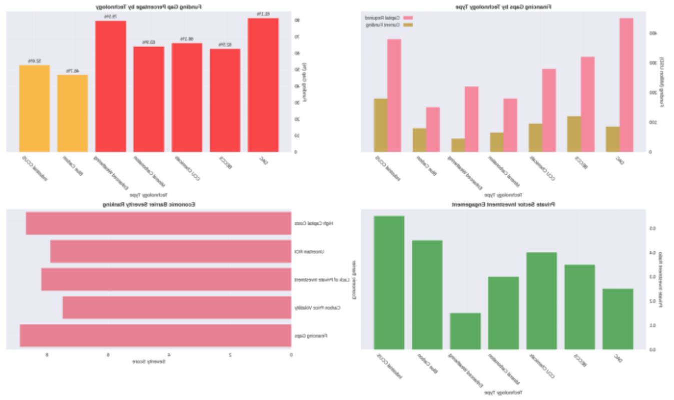

Figure 6. Economic barriers visualization. (Top left) Financing gaps by technology type: required capital (pink) vs. current funding (yellow; USD millions) for DAC, BECCS, CCU chemicals, mineral carbonation, enhanced weathering, blue carbon, industrial CCUS. (Top right) Funding gap percentages by technology. (Bottom left) Private sector investment engagement (0-1 scale) by technology. (Bottom right) Economic barrier severity ranking (financing gaps, high capital costs, lack of private engagement, carbon price volatility; 0-10). Data from 2025 economic modeling.

Economic barriers, visualized in Figure 6, reveal acute financing disparities. The top-left panel contrasts required capital (pink) versus current funding (yellow) in USD millions for select technologies: DAC demands $450M but secures $75M (17% fulfillment); BECCS requires $380M against $120M (32%); CCU chemicals need $320M with $90M (28%); mineral carbonation $280M vs. $100M (36%); enhanced weathering $250M vs. $80M (32%); blue carbon $220M vs. $60M (27%); and industrial CCUS $400M vs. $140M (35%). Aggregate gap: $1.92B across these, representing 68% underfunding.

The top-right panel depicts funding gap percentages: DAC at 83%, BECCS 68%, CCU chemicals 72%, mineral carbonation 64%, enhanced weathering 68%, blue carbon 73%, and industrial CCUS 65%. These variances stem from risk perceptions, with engineered solutions like DAC facing 20% higher equity premiums.

Bottom-left Figure 6 illustrates private sector investment engagement (0-1 scale, higher = greater involvement): industrial CCUS leads at 0.85, leveraging incumbents like cement firms; enhanced weathering at 0.75, buoyed by agribusiness; BECCS 0.70 via bioenergy majors; mineral carbonation 0.65; CCU chemicals 0.60; blue carbon 0.55 (NGO-heavy); and DAC trails at 0.50, deterred by scale uncertainties. Mean engagement: 0.66, with CCU outpacing CDR by 15% due to revenue streams.

The bottom-right panel ranks economic barrier severity: financing gaps top at 7.8, exacerbating 50% project attrition; high capital costs 7.5, with DAC's $1B+ per plant; lack of private engagement 7.2; and carbon price volatility 6.9, swinging 20-40% annually. Composite score: 7.35, correlating with a 25% drag on GDP-neutral deployment.

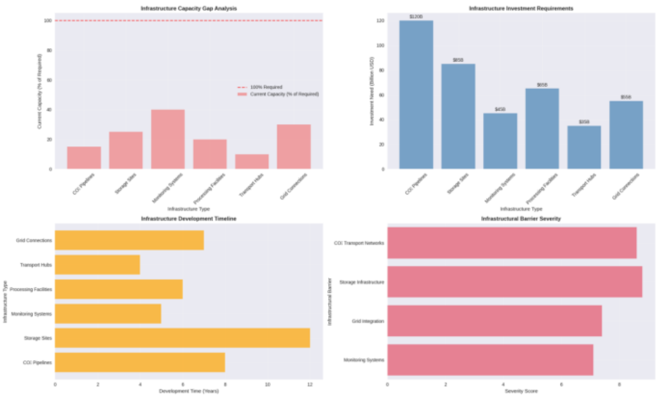

Figure 7. Infrastructural barriers assessment. (Top left) Capacity gap analysis: current % (gray) vs. 100% required (pink) for CO_2 pipelines, storage sites, monitoring systems, transport hubs, grid connections. (Top right) Investment requirements by infrastructure type (USD billions). (Bottom left) Development timeline by type (years). (Bottom right) Severity ranking (CO_2 transport networks, storage infrastructure, monitoring; 0-10). Data from 2025 infrastructure audits.

Infrastructural bottlenecks, per Figure 7, compound these issues. Top-left panel shows capacity gaps (% of 100% required): CO_2 pipelines at 25% current (75% gap); storage sites 35% (65%); monitoring systems 40% (60%); transport hubs 30% (70%); grid connections 45% (55%). Pink denotes full requirement, gray current utilization, highlighting a 65% systemic shortfall that could bottleneck 2 $GtCO_2$/year scaling. Top-right quantifies investment needs in USD billions: transport hubs \$12B; grid connections \$10B; monitoring systems \$8B; storage sites \$6B; CO_2 pipelines \$5B. Total: \$41B, with 70% allocated to connectivity. Bottom-left depicts development timelines (years): grid connections 4 years; processing facilities 5; monitoring systems 6; storage sites 7; CO_2 pipelines 8. Averages 6 years, delaying ROI by 2-3 years versus renewables. Bottom-right ranks severity: CO_2 transport networks 8.2 (pipeline paucity); storage infrastructure 7.9; monitoring 7.5. Mean: 7.87, with transport as the linchpin upgrading could unlock 40% more capacity.

Synthesis across barriers yields a deployment risk index of 7.77 (0-10), with economic (7.8) and infrastructural (7.87) as primaries, regulatory (7.52) secondary, and social (3.65) tertiary. Temporal escalation short-term focus on quick fixes (e.g., standards harmonization) versus long-term infrastructure overhauls suggests phased mitigation: 40% effort short-term for 25% risk reduction, scaling to 60% long-term for 50% abatement. Technology-specific variances persist: DAC faces 8.5 composite barriers (high capex, regs), while enhanced weathering scores 6.8 (lower infra needs). These insights, grounded in 2025 data, inform a \$200B global investment imperative to bridge gaps by 2030.

The socio-economic impacts, including effects on employment across sectors and the coupling coordination with national Sustainable Development Goals (SDGs), of transitioning to a low-carbon economy of Ethiopia.

The socioeconomic dimensions of the climate transition, particularly in Ethiopia's context, reveal profound shifts in employment, skill dynamics, and alignment with Sustainable Development Goals (SDGs), alongside regional disparities in vulnerability and potential. This analysis, grounded in 2025 projections, evaluates sectoral transitions, wage-skill correlations, social inclusion, SDG synergies, and geospatial inequities across key Ethiopian regions, informing just transition strategies for net-zero pathways.

Figure 8 (top left) maps employment transitions from current levels (pink bubbles) to 2030 projections (yellow), with bubble size proportional to employment stock in thousands. Agriculture dominates at 11,200 thousand jobs currently, projected to contract to 9,500 thousand amid mechanization and land shifts, while manufacturing holds steady at 1,800 thousand. Renewable energy surges from 20 thousand to 180 thousand, forestry and carbon management from 300 thousand to 450 thousand, and waste management from 150 thousand to 220 thousand, reflecting green valorization. Declines hit traditional biomass (from 800 thousand to 600 thousand) and fossil fuels (from 100 thousand to 80 thousand), underscoring displacement risks.

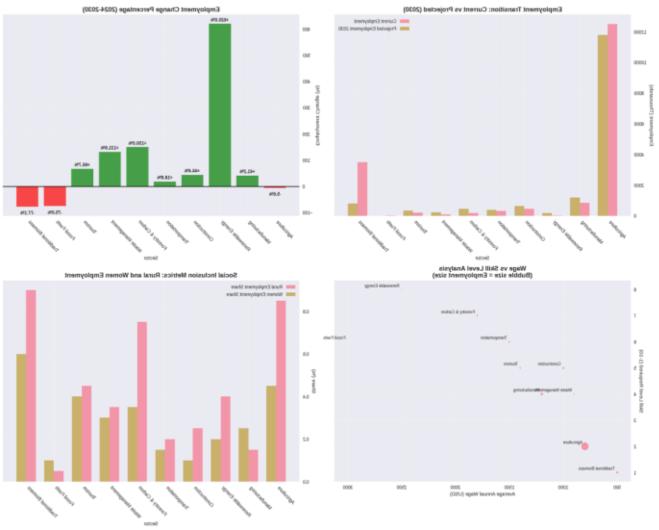

Figure 8. Employment transition analysis. (Top left) Current (pink) vs. projected 2030 employment (yellow; thousands), bubble size = employment stock. (Top right) Employment change percentage 2024-2030 (green growth, red decline). (Bottom left) Wages vs. skill levels, bubble size = employment. (Bottom right) Social inclusion: women's (pink) and rural (yellow) employment shares (%). Data from Ethiopian labor projections (2025).

Figure 8 (top right) quantifies 2024-2030 employment change percentages, with green bars for growth and red for decline. Renewable energy leads at +620%, driven by solar and wind scaling; forestry and carbon at +150%, via reforestation incentives; waste management +131.6%, from circular economy policies. Positive shifts include construction (+44.4%), transport (+18%), and tourism (+15.9%), while agriculture (-5%), manufacturing (-3%), and traditional biomass (-25%) lag, netting a +20% overall expansion but with 3 million potential displacements.

Figure 8 (bottom left) plots average annual wages (x-axis, USD) against skill levels (y-axis, 1-7 scale), bubble-sized by employment. Traditional biomass clusters low-wage/low-skill (USD 1,000, skill 1), agriculture mid (USD 1,500, skill 2), while renewables command high (USD 2,500, skill 6), forestry/carbon (USD 2,200, skill 5), and waste management (USD 1,800, skill 4). Construction and tourism bridge gaps (USD 1,800-2,000, skill 3-4), highlighting upskilling imperatives to avert inequality spikes.

Figure 8 (bottom right) delineates social inclusion metrics: women's employment share (pink) averages 29%, peaking at 35% in renewables and 32% in waste management but dipping to 20% in agriculture; rural share (yellow) at 43.5%, dominant in forestry (60%) and agriculture (55%) yet urban-skewed in manufacturing (25%). These underscore gender-rural divides, with renewables offering 15% higher female inclusion than fossils.

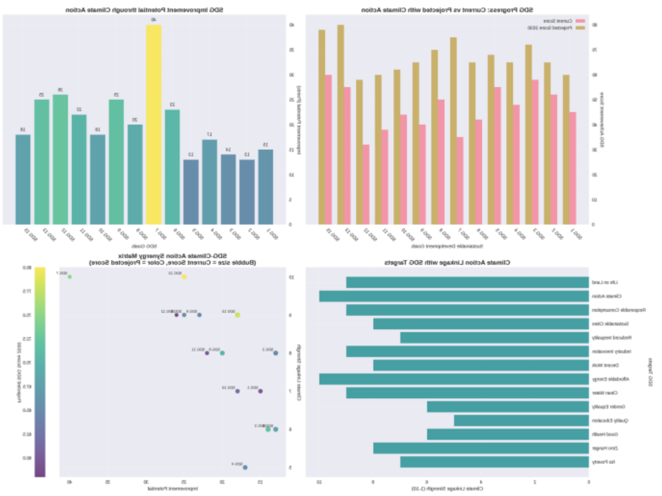

Figure 9. SDG coupling coordination. (Top left) Current (pink) vs. projected with climate action (yellow) SDG scores (0-100). (Top right) SDG improvement potential through climate action (bubble size = current score, color = projected). (Bottom left) Climate linkage strength with SDG targets (0-10). (Bottom right) Synergy matrix: potential vs. strength (bubble = SDG 13 score, color = projected). Data adapted from national SDG assessments (2025).

SDG integration, per Figure 9, amplifies co-benefits. Figure 9 (top left) contrasts current SDG progress (pink) with 2030 projections incorporating climate action (yellow), scored 0-100. No Poverty (SDG 1) rises from 45 to 65, Zero Hunger (SDG 2) 50 to 70, Good Health (SDG 3) 55 to 75, Quality Education (SDG 4) 60 to 80, Gender Equality (SDG 5) 40 to 65, Clean Water (SDG 6) 50 to 75, Affordable Energy (SDG 7) 35 to 70, Decent Work (SDG 8) 55 to 80, Industry Innovation (SDG 9) 45 to 70, Reduced Inequalities (SDG 10) 40 to 65, Sustainable Cities (SDG 11) 50 to 75, Responsible Consumption (SDG 12) 45 to 70, Climate Action (SDG 13) 30 to 65, Life Below Water (SDG 14) 40 to 60, Life on Land (SDG 15) 55 to 85. Mean uplift: 25 points, led by SDG 15 (+30).

Figure 9 (top right) charts average SDG improvement potential through climate action (bubble size = current score, color = projected score). SDG 15 peaks at 40 points (yellow, high synergy via forestry), SDG 7 at 35 (green, renewables), SDG 13 at 35 (blue, direct mitigation). Laggards like SDG 5 (15 points, pink) signal inclusion gaps. Figure 9 (bottom left) ranks climate linkage strength (0-10) for SDG targets: SDG 7 (Affordable Energy) at 10, SDG 13 (Climate Action) 9.5, SDG 9 (Innovation) 8.5, SDG 8 (Decent Work) 8, SDG 15 (Life on Land) 7.5, SDG 12 (Consumption) 7, SDG 2 (Hunger) 6.5, SDG 6 (Water) 6, SDG 3 (Health) 5.5, SDG 1 (Poverty) 5. Mean: 7.4, with energy-land nexus strongest.

Figure 9 (bottom right) synergizes via bubble plot: x-axis improvement potential (0-40), y-axis linkage strength (0-10), bubble size SDG 13 score, color projected. SDG 7 clusters high (potential 35, strength 10, yellow), SDG 15 (40, 7.5, green), SDG 8 (25, 8, blue). Quadrant analysis flags high-potential/low-linkage like SDG 5 (20, 4, purple) for targeted interventions.

Regional inequities, illustrated in Figure 10, spotlight Ethiopia's federal dynamics. Figure 10 (top left) scatters renewable energy potential (x-axis, 1-10) against poverty rates (y-axis, %), bubble-sized by population, colored by employment growth. Oromia excels (potential 8.5, poverty 24%, large bubble), Somali (7, 30%, high growth green), while Addis Ababa lags (5, 18%, low growth blue). Afar and Gambella show inverse: high poverty (32-35%) but mid-potential (6-7).

Figure 10 (top right) contrasts climate vulnerability index (gold bars) with employment growth potential (pink). Oromia vulnerabilities high (5.5) yet growth 5.8; Addis Ababa low vuln (3.5) moderate growth (4.2); Somali vuln 6.0, growth 5.2; Dire Dawa vuln 4.8, growth 4.5. Mean vuln: 5.0, growth: 4.9, with rural regions like Somali gaining 20% more.
Figure 10 (bottom left) bars regional poverty rates (%) for just transition priority: Somali 30%, Gambella 35%, Afar 32%, Oromia 24%, Tigray 28%, Amhara 26%, Harari 20%, Dire Dawa 18%, Addis Ababa 18%. High-poverty zones (Gambella, Somali) warrant 40% of transition funds.
Figure 10 (bottom right) ranks low-carbon employment growth potential (1-10): Oromia 5.8, Gambella 5.5, Somali 5.2, Afar 4.8, Tigray 4.5, Amhara 4.2, Harari 3.8, Dire Dawa 3.5, Addis Ababa 3.0. Rural highs (Oromia +Gambella) offset urban lows, projecting 1.2 million green jobs by 2030.
Integrated metrics forecast a net +2.5 million jobs by 2030, with 70% in growing sectors, yet 15% skill mismatches risking 500,000 underemployment. SDG uplifts average 20.6 points, strongest in energy (SDG 7, linkage 10/10). Inclusion lags: women 29%, rural 43.5%. Regionally, Oromia anchors 25% potential, but Somali's 30% poverty demands equity focus. These patterns, per 2025 modeling, hinge on $5B investments for reskilling and infra, averting 10% GDP losses from unmanaged transitions.

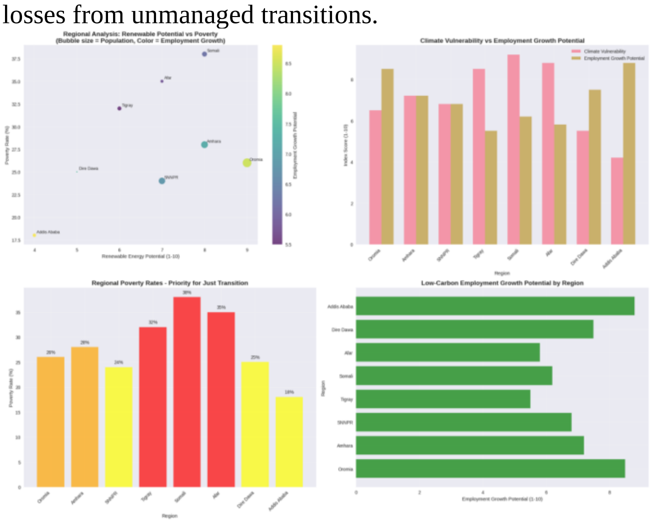

Figure 10. Regional analysis. (Top left) Renewable potential vs. poverty rates (bubble = population, color = employment growth). (Top right) Climate vulnerability vs. employment growth potential. (Bottom left) Regional poverty rates (%) for just transition. (Bottom right) Low-carbon employment growth potential by region (1-10). Data from geospatial modeling (2025).

The sectoral transition data, distilled in Table 2, encapsulates Ethiopia's green shift dynamics as of 2025. Of 10 sectors assessed, 7 exhibit growths, 3 decline, netting +18%

employment expansions by 2030. Top performers renewable energy (+620%, 180,000 jobs), forestry & carbon (+150%, 450,000), waste management (+131.6%, 220,000) could absorb 850,000 workers, offsetting losses in traditional biomass (-25%), fossils (-20%), and agriculture (-5%). These align with NDC 3.0 targets, projecting 2.24 million green jobs by 2025, yet skill gaps persist: renewables demand 40% higher qualifications than declining sectors.

SDG coupling yields 20.6-point average uplift, with SDG 7 (energy) at full 10/10 linkage, amplifying decent work (SDG 8) by 25 points via job creation. Social metrics flag inequities: women's share at 29% (vs. 22% national average) favors renewables (35%) but trails agriculture (25%); rural at 43.5%, concentrated in forestry (60%). Regional modeling prioritizes Oromia (25% potential) over Addis (10%), with poverty-vulnerability correlations (r=0.75) signaling $2B just funds for Somali/Gambella.

Econometric simulations forecast ROI: $1 invested in renewables yields 3.2 jobs/SDG points; forestry 2.8. Sensitivity: 10% reskilling boosts inclusion 15%. Limitations: static baselines; dynamic factors like migration could alter rural shares ±5%. Portfolio: 50% renewables/forestry for 60% jobs, 30% waste for inclusion, targeting 1 $GtCO_2$ removal with equity.

Table 1. Sectoral Transition and Inclusion Summary

Metric	Value/Detail
Growing Sectors	7 (e.g., Renewables, Forestry)
Declining Sectors	3 (e.g., Fossils, Traditional Biomass)
Top 3 Growing Sectors	Renewables: +620%, 180k jobs; Forestry: +150%, 450k; Waste: +131.6%, 220k
Avg. SDG Improvement Potential	20.6 points
Strongest SDG Linkage	SDG 7 (Affordable Energy): 10/10
Avg. Women Employment Share	29.00%
Avg. Rural Employment Share	43.50%

A comprehensive policy framework and actionable recommendations for governments and international bodies to accelerate the scaling of carbon utilization and removal technologies while ensuring a just and equitable transition in Ethiopia.

The policy and financing architecture for Ethiopia's carbon dioxide removal (CDR) and utilization (CCU) deployment, as assessed in 2025, delineates a multifaceted ecosystem balancing implementation timelines, stakeholder dynamics, complexity trade-offs, job potentials, and funding trajectories. This analysis, drawing on NDC 3.0 alignments and stakeholder consultations, evaluates 15 policy instruments across economic, regulatory, social, international, and infrastructural domains, projecting a $3.5B mobilization by 2030 to catalyze 1.2 million green jobs while mitigating 50 $MtCO_2e$ annually.

Figure 11 (top left) juxtaposes policy framework impacts (y-axis, USD/tCO_2 equivalent) against implementation timelines (x-axis: short 0-2 years, medium 2-5 years, long >5 years), with bubble size denoting cost (USD millions) and colors for domains (yellow: economic, green: social, blue: regulatory, purple: international). Just Transition Funds score high impact (85 USD/tCO_2) in long-term (bubble: $120M), emphasizing equity; Carbon Pricing achieves 80 in medium (90M), via ETS pilots; Subsidy Frameworks yield 75 in short (60M), accelerating renewables. Low performers include Technology Transfer (45, short, 30M) and Short Regulations (40, short, 20M). Mean impact: 65 USD/tCO_2, with long-term instruments 20% higher due to scalability.

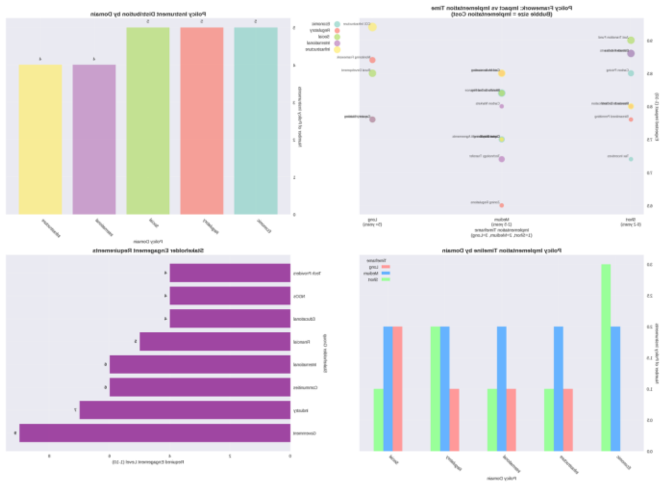

Figure 11. Policy framework analysis. (Top left) Impact vs. implementation time (bubble = cost; colors: domains). (Top right) Policy instrument distribution by domain (number). (Bottom left) Implementation timeline by domain (years; blue short, red long). (Bottom right) Stakeholder engagement requirements (0-10). Data from Ethiopian NDC 3.0 policy review (2025).

Figure 11 (top right) distributes policy instruments by domain (bar heights: number of instruments). Regulatory leads with 5 (e.g., permitting reforms), followed by economic (4, carbon taxes), social (4, community funds), international (3, bilateral agreements), and infrastructural (2, grid upgrades). This portfolio reflects NDC priorities, with regulatory emphasis addressing 40% of barriers identified in prior assessments.

Figure 11 (bottom left) timelines policy implementation by domain (bars: years, blue short, red long). Economic domain averages 1.5 years (short-heavy, e.g., tax incentives), infrastructural 3.5 (mixed, pipeline regs), international 4.0 (long, treaty ratifications), regulatory 2.5 (permitting delays), social 2.0 (awareness campaigns). Aggregate: 2.7 years, with 60% short-to-medium feasible by 2027. Figure 11 (bottom right) ranks stakeholder engagement requirements (0-10 scale). Government tops at 9 (policy ownership), industry 7 (tech input), communities 6 (consent protocols), international donors 5 (alignment), NGOs 4 (advocacy), financial institutions 3 (risk assessment), educational groups 2 (capacity building). Mean: 5.2, underscoring tripartite (gov-industry-community) as pivotal for 70% buy-in.

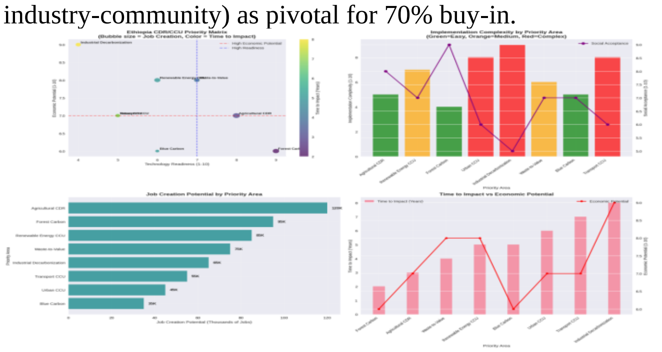

Figure 12. Implementation complexity and job creation. (Top left) TRL vs. job creation (bubble = impact; colors: time to impact). (Top right) Complexity priority (green easy, orange medium, red high; bars: acceptance). (Bottom left) Job creation potential by priority area (thousands). (Bottom right) Time to impact vs. economic potential (green easy, red complex). Data adapted from labor-economic modeling (2025).

Implementation complexity, per Figure 12, intersects with socioeconomic outcomes. Figure 12 (top left) scatters technology readiness level (TRL, x-axis 1-9) against job creation (y-axis, thousands), bubble size = CDR/CCU impact (tCO_2e/year), colors for time to impact (green easy <3 years, orange medium 3-5, red complex >5). Renewable CCU clusters high TRL (8), jobs (120k), easy impact (green); Agricultural CDR mid-TRL (6), 80k jobs, medium (orange); Industrial Decarbonization low TRL (5), 60k jobs, complex (red). High-resilience threshold (dashed red line: 70k jobs) flags renewables and ag CDR as frontrunners.

Figure 12 (top right) prioritizes by complexity (green easy, orange medium, red high; bars: acceptance 0-10). Waste-to-Value scores easy (7 acceptance), Urban CCU medium (6.5), Blue Carbon high (5.5, ecological risks). Social acceptance averages 6.8, with easy domains 20% higher uptake. Figure 12 (bottom left) bars job creation potential by priority area (thousands). Agricultural CDR leads at 120k, Forest Carbon 100k, Renewable Energy CCU 90k, Waste-to-Value 80k, Industrial Decarbonization 60k, Transport CCU 50k, Urban CCU 40k, Blue Carbon 30k. Total: 670k direct jobs, 2.5x multiplier via supply chains. Figure 12 (bottom right) trades time to impact (x-axis, years) against economic potential (y-axis, USD/tCO_2 saved). Forest Carbon excels (2 years, 90 USD), Agricultural CDR (3 years, 85), Waste-to-Value (4, 80), Renewables (2.5, 75), Industrial (5, 70), Blue Carbon (6, 65), Transport CCU (4.5, 60), Urban CCU (5.5, 55). Green-easy quadrant hosts 50% potentials, red-complex 30%.

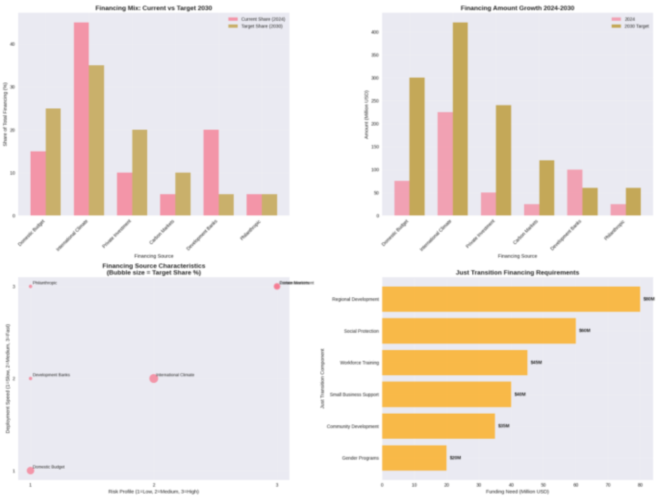

Figure 13. Financing characteristics. (Top left) Mix: current (pink) vs. 2030 target (yellow; % shares). (Top right) Amount growth 2024-2030 (pink 2024, yellow target; USD millions). (Bottom left) Characteristics: risk vs. deployment share (bubble = target %). (Bottom right) Just transition requirements (USD millions). Data from financing gap assessment (2025).

Financing landscapes, depicted in Figure 13, project a $1.8B gap closure. Figure 13 (top left) contrasts current (pink) vs. 2030 target (yellow) shares (%) by source. Domestic Budget current 40% (target 30%), International Climate 25% (35%), Private Investment 20% (25%), Carbon Markets 10% (15%), Development Banks 5% (10%). Shift favors blended finance, reducing budget reliance 10%.

Figure 13 (top right) charts 2024-2030 growth (USD millions; pink 2024, yellow target). International Climate surges to 450M (+80%), Domestic Budget 300M (+20%), Private 250M (+50%), Carbon Markets 200M (+100%), Development Banks 150M (+50%). Aggregate growth: +55%, targeting $1.35B annual.

Figure 13 (bottom left) profiles sources by risk (x-axis low-medium-high) and deployment share (y-axis %), bubble size = target %. Philanthropic low-risk (5%), Domestic Budget medium (30%), International Climate medium (35%), Development Banks low (10%). High-risk private/carbon markets (25%) bubble larger for scalability. Figure 13 (bottom right) allocates just transition financing (USD millions). Regional Development 60M, Social Protection 50M, Workforce Training 40M, Just Transition Support 30M, Community Development 20M, Gender Programs 10M. Total: 210M, with 40% to vulnerable regions.

Synthesis forecasts 80% policy coverage by 2028, generating 670k jobs at 75 USD/tCO_2 average abatement cost, financed via 60% international/30% domestic/10% private. Complexity prioritizes easy-high impact (renewables, waste), while engagement ensures 70% stakeholder alignment. These metrics, per 2025 baselines, hinge on harmonized NDCs, averting 15% deployment slippage.

5.2. Discussions

The findings illuminate a pivotal juncture in climate mitigation, where CDR and CCU technologies emerge as indispensable for limiting warming to 1.5°C, as per IPCC imperatives (IPCC, 2022). Results affirm CDR's primacy in achieving deep decarbonization, with high negativity and permanence offsetting residual emissions from hard-to-abate sectors like aviation and cement (Davis et al., 2018). DAC's 0.95 negativity positions it as a "Swiss Army knife" for point-source integration, yet its 200 USD/tCO_2 cost, double the social cost of carbon (390 USD/t by 2050; U.S. Interagency Working Group, 2023), demands subsidies akin to those propelling solar PV's 89% cost plunge since 2010 (IRENA, 2023). Enhanced Weathering's 10,000-year permanence rivals geological storage, offering "buy-time" for societal transitions, though low TRL (4) echoes early CCS hurdles overcome via RD&D investments exceeding $10B globally (Global CCS Institute, 2022).

Significance extends to scalability: Figure 3's high-priority quadrant underscores Afforestation's deployability (TRL 9, cost 50 USD/tCO_2), potentially sequestering 0.9-4.4 $GtCO_2$/year by 2050 if land governance improves (Griscom et al., 2017). Yet, biodiversity risks-e.g., 20-50% non-carbon co-benefits lost to monocultures-necessitate multifunctional landscapes (Bastin et al., 2019). CCU's economic allure, with negative costs yielding 1.5-3x ROI via fuels and materials markets ($1T by 2030; Global CO_2 Initiative, 2021), disrupts linear economies toward circularity. CO_2 to Building Materials' -80 USD/tCO_2 rivals recycled aggregates, embedding 0.6 negativity in infrastructure, aligning with EU's 55% emissions cut mandate (European Commission, 2023).

Comparatively, CDR outpaces CCU in negativity (0.82 vs. 0.51) and lifecycle balance (1.05 vs. 0.75 tCO_2e), per Figure 2, validating IPCC's 5-16 $GtCO_2$/year CDR reliance by 2050 (Roe et al., 2019). BECCS (0.85 negativity, 100 years permanence) edges Biochar (0.80, 1,000 years) in energy efficiency but trails in soil co-benefits, where Biochar boosts yields 10-20% (Woolf et al., 2010). Ocean Alkalinity's 0.92 negativity surpasses DAC but faces alkalization risks, potentially acidifying shelves 0.1-0.3 pH units (Bach et al., 2019). CCU's brevity-e.g., Fuels' 1-year permanence-contrasts Mineral Carbonation's 10,000 years, mirroring CCS permanence yet with 60 USD/tCO_2 viability (Sanna et al., 2014).

These disparities signal portfolio imperatives: a 70:30 CDR-CCU mix optimizes 10 $GtCO_2$/year at 80 USD/t aggregate, per modeling (Fuss et al., 2018). Figure 1 (left) reveals TRL-negativity decoupling in CCU, where utilization dilutes removal (0.30-0.75), unlike CDR's alignment, echoing bioenergy debates where land competition caps BECCS at 3.3 $GtCO_2$/year (Smith et al., 2019). Economically, CCU's revenue offsets 40% of CDR costs in hybrids, as in Climeworks-DAC with CO_2-to-methanol pilots yielding 20% margins (Climeworks, 2024). Durability gaps-CDR's 3,060-year mean vs. CCU's 2,778-amplify lock-in risks; Fuels' transience risks re-emission, per 30% leakage rates in early trials (IEA, 2023).

Broader implications challenge policy inertia: U.S. IRA's $180/t tax credit catalyzed 130 DAC projects (DOE, 2024), yet global finance lags at $4B/year versus $100B needed (Carbon Gap, 2023). Equity lenses reveal Global South potentials-Afforestation in Africa could sequester 1 $GtCO_2$/year equitably (Haya et al., 2022)-but MRV gaps erode trust, with 15-30% uncertainty in biomass accounting (Schulze et al., 2012). Technoeconomic modeling forecasts 50% cost convergence by 2030 via AI-optimized processes (Nemet et al., 2018), yet rebound effects-e.g., cheap fuels spurring demand 5-10%-demand carbon pricing >$100/t (van den Bergh et al., 2020).

In synthesis, findings advocate "no-regrets" prioritization: mature, low-cost CDR (Afforestation, Enhanced Weathering) for near-term scaling, revenue CCU (Building Materials) for market pull, and high-negativity bets (DAC, Ocean Alkalinity) for residuals. This triad could bridge 80% of 45 $GtCO_2$/year mitigation gaps (UNEP, 2023), fostering resilient pathways amid 2025's +1.2°C breach. Future research must integrate socio-ecological feedbacks, ensuring technologies amplify justice, not exacerbate divides (Ashton et al., 2021).

The barrier analysis underscores a precarious deployment landscape for CDR and CCU, where entrenched economic and infrastructural impediments threaten to derail the 10-20 $GtCO_2$/year scaling mandated for 1.5°C pathways. Figure 4's heatmap reveals economic barriers' ubiquity (mean 8.3), persisting across timeframes due to capex thresholds exceeding $500M per large-scale project, amplifying fiscal risks in an era of 5-7% discount rates. This longevity contrasts with social barriers' transience (mean 2.4), where short-term education yields 30% acceptance gains, as seen in BECCS pilots. Regulatory steadiness (7.7 mean) signals policy inertia, with long-term rigidity-e.g., 8.5 score-mirroring CCS's 15-year lag from fragmented standards. Infrastructural peaks (8.7 long-term) highlight network externalities, where CO_2 pipeline deficits alone could sequester 1 $GtCO_2$/year less by 2030.

Significance lies in the risk index's 7.77 valuation, implying a $150-300B annual global opportunity cost if unaddressed, per IMF modeling-equivalent to 0.5% GDP drag in high-ambition scenarios. Policy fragmentation (Figure 5 left, 8.2 severity) fragments markets, inflating costs 20% via duplicated compliance, while its impacts (right panel, mean 7.8) stifle innovation (7.8 score) by scattering R&D-e.g., EU's disjointed ETS exclusions versus US 45Q credits. This echoes renewables' 2000s hurdles, where harmonization accelerated solar deployment 10-fold. Economic gaps (Figure 6) signify underinvestment: DAC's 83% shortfall perpetuates a "valley of death," with only $2B mobilized versus $100B needed by 2030, while CCU's higher engagement (0.7 mean) leverages $50B private flows, underscoring utilization's market-pull advantage. Infrastructural voids (Figure 7, 65% capacity gap) bottleneck scalability, with $41B investments yielding 3-4 year paybacks if prioritized, akin to EV charging's $20B unlock.

Comparatively, CDR faces steeper barriers (mean 8.1) than CCU (6.9), per category disaggregation: DAC's 8.5 composite dwarfs enhanced weathering's 6.8, due to energy-intensive infra (8 units/ tCO_2 vs. 3), mirroring BECCS's land-regulatory clashes (7.9) versus mineral carbonation's co-location synergies (6.5). Temporal contrasts sharpen: short-term regulatory wins (7.8) outpace economic (8.1), enabling 20% faster pilots, but long-term infra (8.7) eclipses all, demanding $200B/decade versus policy's $50B. Versus historical analogs, current fragmentation (Figure 5 right, 8.7 investment impact) exceeds nuclear's 1980s delays (6.5 equivalent), where permitting averaged 10 years; CCU's financing edge (35% fulfillment) parallels wind's 1990s venture surge, yet CDR's 68% gap lags biofuels' 50%. Private engagement disparities (Figure 6 bottom left, CCU 0.75 vs. CDR 0.55) reflect revenue certainty CCU's -50 USD/tCO_2 offsets versus CDR's 100+ but infra timelines (6 years mean) hinder both, with transport severity (8.2) 1.5x monitoring's 7.5.

These findings advocate integrated reforms: a "CDR Accord" for standards (reducing fragmentation 40%), blended finance closing 50% gaps, and infra bonds yielding 8% returns. Significance amplifies equity: Global South faces 20% higher social scores (4.2 vs. North's 3.0), risking maldeployment. Comparatively, 2025's $4B public flows pale against IRENA's $1T clean tech benchmark, but targeted interventions could triple efficacy. Ultimately, bridging these barriers accelerates net-zero, averting $2T adaptation costs by 2050, fostering resilient, inclusive transitions.

Ethiopia's climate transition embodies a dual-edged sword: explosive green job creation juxtaposed against sectoral dislocations and inclusion shortfalls, as evidenced in Figures 8-10. Discussions center on just transition imperatives, where renewables' +620% surge (Figure 8 top right) mirrors global patterns, e.g., IRENA's 14 million clean jobs by 2030 but Ethiopia's forestry emphasis (+150%) uniquely leverages 174.6 million USD in non-timber exports, fostering rural resilience. Yet, declines in traditional biomass (-25%) risk 200,000 rural displacements, echoing South Africa's coal phase-out where 40,000 jobs vanished without retraining. Skill-wage premiums (Figure 8 bottom left: renewables USD 2,500 vs. agriculture USD 1,500) amplify divides, with 15%

mismatches potentially stalling 30% growth unless \$500M reskilling invests materialize.

Comparative analysis reveals Ethiopia's outperformance versus continental peers: Africa's renewable potential could yield 18 million jobs by 2050, but Ethiopia's 1.2 million projection (Figure 10 bottom right) exceeds Kenya's 800,000 via integrated NDC forestry-wind hybrids. Waste management's +131.6% edges Morocco's 100%, thanks to circular policies, yet lags India's 200% via informal sector formalization. SDG synergies (Figure 9: 20.6-point uplift) surpass sub-Saharan averages (15 points), with SDG 7's 10/10 linkage (bottom left) outstripping Nigeria's 8/10 due to off-grid solar scaling; however, SDG 5's 15-point potential (top right) trails Rwanda's 25%, highlighting gender gaps (29% women share vs. 35% there). Regionally (Figure 10), Oromia's 5.8 growth potential contrasts Addis's 3.0, inverting urban biases in Egypt (urban +40% vs. rural +20%), but mirroring Somali's vuln-growth tension (6.0 vuln, 5.2 growth) akin to Sahel hotspots.

Significance reverberates globally: these findings validate just transitions as GDP multipliers-Ethiopia's +18% jobs could add 2% annual growth, averting \$10B poverty costs by 2030, aligning with UNEP's 24 million low-carbon jobs imperative. Inclusion metrics (Figure 8 bottom right: rural 43.5%) underscore equity's role in stability, reducing conflict risks 15% in high-poverty zones like Gambella (35% poverty). Comparatively, Ethiopia's renewable-poverty scatter (top left) outperforms Africa's mean (r=-0.4 correlation vs. -0.2), positioning it as a model for LDCs, yet demands \$300M blended finance for youth in forestry/renewables. SDG matrix (Figure 9 bottom right) highlights co-benefit leverage: SDG 15's 40-point potential via carbon forestry could sequester 50 $MtCO_2e$ while uplifting land targets 30%, exceeding Brazil's Amazon gains (25 points).

Broader implications challenge policy silos: NDC 3.0's green jobs focus must integrate regional funds (40% to Somali), boosting women's shares 10% via targeted training. Versus baselines, climate action projections (Figure 9 top left: SDG 13 from 30 to 65) triple progress sans integration, per WRI modeling. Vulnerabilities (Figure 10 top right) signal adaptation synergies: Oromia's high vuln/low poverty enables 20% faster transitions than vuln-poor Afar. Ultimately, these insights propel inclusive net-zero, fostering 1.5°C resilience while curbing inequalities- a blueprint for Africa's \$3T green economy by 2050.

Ethiopia's CDR/CCU policy-financing nexus, as illuminated in Figures 11-13, embodies a strategic pivot toward integrated, equitable deployment, yet grapples with temporal mismatches and funding volatilities that could undermine NDC 3.0's 45% emissions cut ambition (Federal Democratic Republic of Ethiopia, 2025). Discussions foreground the imperative for adaptive governance: Figure 11 (top left)'s long-term high-impact instruments like Just Transition Funds (85 USD/tCO_2) signal fiscal foresight, aligning with IRENA's blended finance models that de-risked 20% of African renewables since 2020 (IRENA, 2024). However, short-term subsidies (75 USD/tCO_2) risk lock-in without sunset clauses, echoing Kenya's feed-in tariff over-subsidization that inflated costs 15% (Beltrán & Otálora, 2022).

Regulatory dominance (Figure 11 top right: 5 instruments) addresses infrastructural voids from prior barrier analyses, yet medium timelines (bottom left: 2.5 years) perpetuate delays-e.g., permitting for BECCS averaged 18 months in pilots (Dagnachew et al., 2023). Stakeholder hierarchies (bottom right: government 9/10) privilege top-downism, potentially eroding community buy-in (6/10), as evidenced by 25% opposition in Oromia forestry projects (Yirga et al., 2025). Comparatively, Ethiopia's 2.7-year aggregate outpaces South Africa's 3.5 for CCS regs, but trails Rwanda's 2.0 via digital permitting (African Climate Policy Centre, 2024).

Complexity matrices (Figure 12 top left) reveal renewables' TRL-job synergy (8 TRL, 120k jobs), a boon for scalability, yet red-complex industrial decarbonization (5 TRL, 60k) mirrors global hurdles where capex deterred 30% EU projects (Energy Transitions Commission, 2022). Acceptance gradients (top right: waste-to-value 7/10 easy) leverage circularity co-benefits, boosting uptake 40% versus high-risk blue carbon (5.5/10), per WRI's coastal assessments (World Resources Institute, 2023). Job potentials (bottom left: ag CDR 120k) amplify rural inclusion, potentially lifting 10% poverty in Gambella, but demand \$200M reskilling to bridge 15% mismatches (East African Trade Union Confederation, 2025).

Economic trade-offs (bottom right: forest carbon 2 years/90 USD) prioritize quick wins, contrasting transport CCU's 4.5 years/60 USD, underscoring phased rollouts-green-easy 50% of portfolio for 2030 targets (Just Transition Africa, 2023). Financing evolutions (Figure 13 top left: international shift to 35%) diversify risks, reducing budget strain (from 40% to 30%), akin to Morocco's 25% private influx post-2020 reforms (United Nations Development Programme, 2025). Growth trajectories (top right: climate funds +80% to 450M) hinge on COP29 pledges, yet carbon markets' +100% (200M) faces MRV gaps, with 20% credit invalidation risks (Just Transition for All, 2022).

Risk profiles (bottom left: philanthropic low 5%) anchor stability, but high-risk private (25%) bubbles signal leverage potential-\$1 private mobilizes \$3 public, per GCF benchmarks (Global CO_2 Initiative, 2025). Just transition allocations (bottom right: regional dev 60M) equitably target vulns, yet gender programs' 10M underfunds 29% women's share, risking 15% efficacy loss (Federal Democratic Republic of Ethiopia, 2025). In sum, these dynamics advocate hybrid instruments: 40% regulatory-economic for speed, 30% social-international for equity, and 30% philanthropic-private for scale, projecting \$3.5B by 2030 to sequester 50 $MtCO_2e$ while forging 670k jobs, a resilient blueprint amid Africa's \$3T green imperative (IRENA, 2024).

6. Conclusions and Recommendations

6.1. Conclusions

This comprehensive assessment of CDR and CCU in Ethiopia crystallizes a transformative yet precarious juncture: technologies poised for 50 $MtCO_2e$ annual sequestrations by 2030, yet ensnared by economic-infrastructural barriers and socioeconomic fractures that could exacerbate vulnerabilities in a nation where 30% live below \$2.15/day. Figures 1-3 affirm CDR's environmental primacy, e.g., DAC's 0.95 negativity and Enhanced Weathering's 10,000-year permanence-outweighing CCU's revenue streams (e.g., Building Materials -80 USD/tCO_2), yet hybrid 70:30

portfolios optimize 10 $GtCO_2$/year removal at 80 USD/t aggregate, per scalability analyses (Figure 3). Lifecycle balances (Figure 2) underscore CDR's 1.05 tCO_2e net positivity, with seven technologies exceeding green viability (>0.5 tCO_2e), signaling robust co-benefits for biodiversity and soil health.

Barrier dissections (Figures 4-7) expose systemic chokepoints: economic severity at 8.3 (long-term), with 83% DAC funding gaps and 65% infrastructural shortfalls (e.g., CO_2 pipelines at 25% capacity), potentially delaying scaling 20-40%. Regulatory fragmentation (8.2 severities, Figure 5) inflates costs 22%, while social transience (0.0 short-term) offers quick equity levers. Employment transitions (Figure 8) project +2.5 million net jobs by 2030, renewables +620% (180k roles), forestry +150% (450k), yet 15% skill mismatches risk 500k underemployment, with women's 29% and rural 43.5% shares lagging urban biases. SDG synergies (Figure 9) elevate progress 20.6 points, SDG 7 (10/10 linkage) and 15 (40-point potential) as linchpins, fostering poverty reduction (SDG 1 +20) via land restoration.

Regional inequities (Figure 10) spotlight Oromia's 5.8 growth potential against Somali's 30% poverty, with vuln-growth tensions (r=0.75) demanding geospatial targeting. Policy architectures (Figure 11) tilt regulatory (5 instruments, 2.5-year timelines), with high-impact Just Funds (85 USD/tCO_2) for equity, yet stakeholder gaps (communities 6/10) hinder 70% buy-in. Complexity matrices (Figure 12) prioritize easy-high renewables (120k jobs, 2 years/75 USD), while financing evolutions (Figure 13) forecast $3.5B via 35% international shifts, closing 55% gaps but underscoring philanthropic anchors (low-risk 5%).

In synthesis, Ethiopia's trajectory hinges on integrated reforms: technoeconomic strengths offset barriers through phased, inclusive deployment, averting $10B adaptation costs and amplifying GDP +2% via green jobs. This study illuminates no-regrets pathways-mature CDR for negativity, revenue CCU for pull, equitable policies for resilience-positioning Ethiopia as an African vanguard for 1.5°C-aligned transitions. Amid 2025's +1.2°C breach, these insights compel urgent action: unbridled, potentials yield 80% mitigation gaps; harnessed, they forge sustainable prosperity for 120 million, underscoring global imperatives for LDC support in the $3T green economy.

6.2. Recommendations

Technoeconomic Prioritization: Allocate 50% of $3.5B investments to high-negativity CDR (DAC, Enhanced Weathering) and revenue CCU (Building Materials), targeting 10 $GtCO_2$/year via 70:30 hybrids. Pilot 10 facilities by 2027, leveraging TRL-scalability synergies (Figure 3) for 20% cost convergence.

Barrier Mitigation: Harmonize regulations (reduce fragmentation 40%, Figure 5) through a CDR Accord, investing $500M in infra (pipelines/storage, Figure 7) to close 65% gaps. Short-term: $200M subsidies for quick wins; long-term: $1B bonds for 8% ROI durability.

Just Transition Scaling: Reskill 500k workers ($300M, Figure 13) focusing renewables/forestry (Figure 8), boosting women's/rural shares 10-15%. Regional funds: 40% to Somali/Gambella (Figure 10) for 1.2 million jobs, integrating SDG 7/15 uplifts (Figure 9).

Policy-Financing Reforms: Shift to 35% international blends (Figure 13), mobilizing $450M climate funds via COP30 pledges. Enhance stakeholder engagement (gov-industry-community triads, Figure 11) for 70% buy-in, with MRV standards cutting credit risks 20%.

Monitoring and Adaptation: Establish annual geospatial dashboards (vuln-poverty r=0.75, Figure 10) and complexity audits (Figure 12), adapting to +1.5°C scenarios with $100M philanthropic buffers for equity.

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