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Synergy between Carbon Capture and Storage (CCS) and Geothermal Energy in Kenya: A Pathway to Climate Innovation

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ABSTRACT

As the global push for net-zero intensifies, the intersection of CCS with geothermal energy presents an innovative pathway for climate mitigation. Kenya, a global frontrunner in geothermal energy, is well-positioned to drive sustainable energy innovation through the integration of CCS within its extensive geothermal infrastructure. The country's Rift Valley, characterized by basaltic formations, offers a promising opportunity for permanent CO_2 mineralization enabling safe CO_2 sequestration as shown by recent geoscientific studies.

Significantly, the Paris Agreement's Article 6 recognizes carbon removals, including CCS, as eligible for international carbon markets. This development creates both a policy foundation and financial incentive for countries like Kenya to scale CCS in tandem with geothermal growth.

Kenya is at the forefront of this innovation through Cella's pilot project, the first geological CO_2 storage initiative in Africa. This project demonstrates how geothermal regions can anchor carbon removal technologies and create climate-smart energy systems.

This paper explores the technical and economic feasibility of synergizing CCS with geothermal energy and the potential and early progress within the sector. It discusses how existing geothermal infrastructure, including non-productive wells, can be repurposed for CO_2 storage. Additionally, by utilizing geothermal plants' excess heat and infrastructure, CO_2 can be captured and stored in volcanic rocks. These synergies enable efficient land use, shared infrastructure, and reduced deployment costs, key enablers for scaling decarbonization in emerging economies. I will demonstrate that coupling CCS with geothermal systems offers technical, economic and policy advantages as well as shared infrastructure, co-location benefits, leveraged technical expertise, and an accelerated route to deploy permanent carbon removal while strengthening energy resilience. The paper outlines geo-energy nexus between CCS and geothermal energy, mechanisms for integration, opportunities and challenges and policy/finance recommendations to unlock scalable climate innovation in Kenya.

1 INTRODUCTION

Climate action now requires both rapid decarbonization and the development of durable carbon removal solutions. Carbon Capture and Storage (CCS) involves extracting CO_2 from industrial sources or ambient air and securing it in geological formations to avoid release into the atmosphere. In Kenya, a unique opportunity exists in the Great Rift Valley, where volcanic geology supports both geothermal energy production and CO_2 mineralization. With an estimated geothermal potential of 10 GW and current capacity nearing 1 GW, primarily in the Olkaria fields, Kenya can leverage renewable geothermal energy to power CCS operations, particularly mineralization in Rift Valley basalts. These basalts are chemically reactive, enabling CO_2 to transform into stable carbonate minerals hence ensuring long-term storage.

This synergy not only reduces the carbon footprint of energy production as the country industrializes, but also enables permanent CO2 sequestration via in-situ mineralization, aligning with Kenya's Nationally Determined Contributions (NDCs) targets of 32% emissions reduction by 2030, under the Paris Agreement. Additionally the country has a mature geothermal industry with skilled personnel, drilling capacity and supportive infrastructure that further strengthens this potential.

Integrating CCS with geothermal systems allows for the use of residual heat and steam in carbon capture processes and injecting of CO2 into basalts for mineralization and permanent storage. This dual-use model not only accelerates carbon removal deployment but also enhances efficiency, spurs technological advancement,

lowers operational costs, and creates new value chains and green jobs. It positions Kenya to evolve from a regional geothermal leader to a global CCS innovator.

Pioneering projects like Cella's mineralization initiatives at the rift and Octavia Carbon's Direct Air Capture (DAC) powered by geothermal steam demonstrate cost-effective pathways for scaling negative emissions and highlights practical integration with the geothermal sector

2 BACKGROUND: GEOTHERMAL RESOURCES AND CCS POTENTIAL IN KENYA

2.1 Kenya's geothermal resources

Kenya is globally recognized as a leader in geothermal energy development, with vast untapped resources concentrated along the East African Rift System (EARS), where tectonic activity creates ideal conditions for harnessing underground heat. It is the sixth largest geothermal producer globally and Africa's leader in the sector. The country's potential is estimated at 10 GW, derived from high temperature geothermal fields with steam at depths of 1,000–2,500 meters, extending from Lake Magadi in the south to Lake Turkana in the north. The most developed of these fields is Olkaria, located within the Hell's Gate National Park, where Kenya Electricity Generating Company (KenGen) and other independent power producers have harnessed over 980 MW of installed capacity. Other promising prospects include Menengai, Eburru, Baringo-Silali, Longonot, Suswa, and Akiira, each representing strategic sites for future geothermal expansion.

Geothermal energy utilizes steam from deep wells to generate reliable, low-carbon baseload power and contributes about 47% to Kenya's electricity mix, supporting energy security and reducing reliance on imported fuels amid growing demand. This resource is bolstered by advanced technologies like binary cycle systems, which enhance efficiency and minimize environmental impacts in sensitive ecosystems like Hell's Gate National Park. The untapped potential of Kenya's geothermal resources is immense, representing less than 10% utilization of available reserves along the Rift Valley. Future expansions, aim to add over 2,000 MW by 2030, aligning with national goals for 100% renewable energy. This growth could prevent millions of tons of CO2 emissions annually, create thousands of jobs in drilling and maintenance, and position Kenya as a regional exporter of geothermal expertise to neighboring Rift countries. Supportive policies, such as feed-in tariffs and public-private partnerships, are driving this momentum, fostering economic diversification and sustainable development in a climate-vulnerable nation.

The sector has an experienced workforce, an established supply chain for drilling and well services, and existing wells and infrastructure that can be leveraged for storage demonstration projects in nearby basalts.

2.2 CCS potential in Kenya

Kenya presents a unique and promising opportunity for Carbon Capture and Storage (CCS) due to its favorable geology, growing industrial base, and strong national commitment to climate action. The Kenyan Rift Valley hosts vast potential for permanent CO_2 storage within its extensive basaltic and volcanic formations (Figure1), geologies that combine high mineral reactivity, permeability, and injectivity with the co-location of abundant renewable energy. According to Okoko and Olaka (2021), Kenya's basalts have the potential to store hundreds of gigatons of CO_2, yet this capacity remains largely untapped due to the absence of large-scale demonstration projects. CCS efforts in Kenya focuses on mineralization, a process where captured CO_2 reacts with basaltic rocks to form stable carbonate minerals such as calcite, ensuring long-term and leakage-free sequestration.

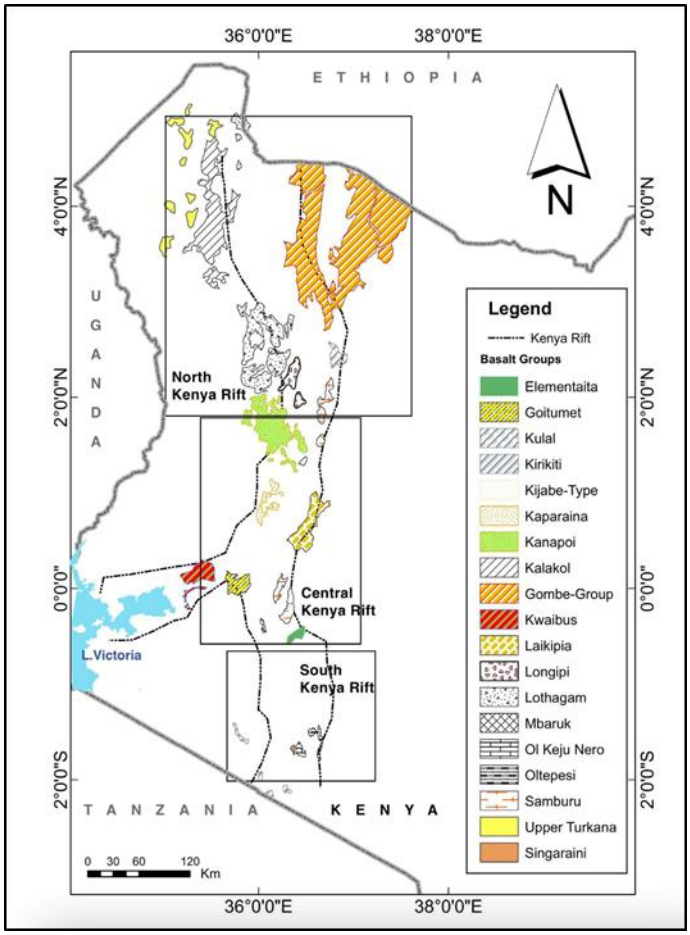


Figure 1. Map of the Kenya rift showing the basaltic formations (Okoko and Olaka, 2021)

Carbon mineralization is a novel method for geologic carbon storage and a pathway to permanent CO_2 removal. It involves injecting captured CO2 into underground volcanic formations like basalts, where carbon is permanently sequestered through natural geochemical reactions (reacts with divalent cations Ca, Mg, Fe) to precipitate stable carbonate minerals. The CO2 can either be dissolved in water or can be injected as pure-phase CO2 (Figure 2). In essence, the process accelerates the Earth's natural carbon cycle, converting gaseous CO_2 into solid, inert mineral forms that are thermodynamically stable. Thus, mineralization offers important advantages compared to other carbon storage options; namely, increased security, verifiability, and no adverse environmental impacts

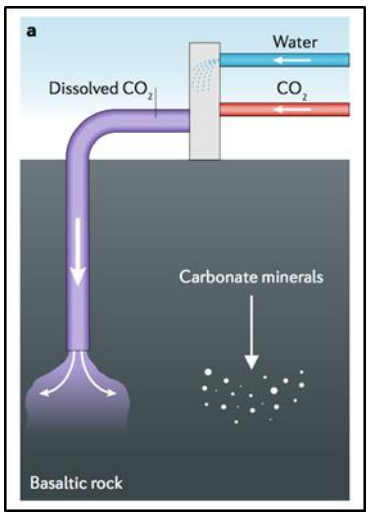


Figure 2. Illustration showing injection of dissolved CO2 (Snaebjornsdottir et al. (2020))

With its rich geological endowment and renewable energy infrastructure, Kenya has the potential to establish itself as a global hub for low-cost, high-integrity carbon mineralization, complementing its Nationally Determined Contributions (NDCs) and attracting green investment as global demand for durable carbon removal and high-quality carbon credits continues to grow. Successful demonstrations (e.g., CarbFix) show that under appropriate conditions mineralization can be rapid and verifiable.

3 THE GEO-ENERGY NEXUS: GEOTHERMAL ENERGY AND CARBON STORAGE FOR KENYA'S LOW-CARBON FUTURE

In the push to cap global warming at 1.5°C, Kenya must balance expanding energy access for its expanding populace with emission reductions. As a nation emitting minimally but highly susceptible to climate effects, Kenya prioritizes eco-friendly strategies. Geothermal energy, plentiful in the East African Rift, delivers steady baseload electricity, while CCS secures emissions from industry and power generation. The "geo-energy nexus" describes their merger, where geothermal assets energize CCS or share facilities for CO_2 injection, creating a looped, low-emission system. By 2025, progress in these areas establishes Kenya as an emerging frontrunner, with initiatives yielding expandable frameworks amid expanding carbon markets and green funding.

Kenya stands at a pivotal moment in its energy transition journey, one where innovation in clean energy and carbon management will determine the country's role in shaping a resilient and low-carbon future. The intersection of geothermal energy and carbon storage presents a transformative opportunity for Kenya to decarbonize its industries, enhance energy security, and pioneer climate-smart development

3.1 Emerging Opportunities

- Shared Drilling and Well Infrastructure: The presence of well-developed geothermal infrastructure can be adapted for CO_2 injection and monitoring, reducing costs and risks associated with site characterization, drilling, and reservoir management, significantly accelerating the pathway to commercial-scale deployment. Geothermal drilling rigs, casing and cementing equipment, geothermal sector expertise and well completion teams can be mobilized for injection and monitoring wells.
- Shared Power & Site Facilities: Geothermal plants provide on-site renewable electricity and heat for CO_2 compression, Direct Air Capture (DAC), pumps, and monitoring systems, lowering operational emissions and costs for CCS pilots. Existing roads, cranes, and logistics bases reduce project footprints.
- Technical & Human Capital Transfer: Geothermal professionals possess reservoir characterization, drilling oversight and subsurface monitoring experience directly transferable to CO_2 injection, tracer tests, and MRV (Monitoring, Reporting & Verification). Collaborations btween CCS and geothermal industry demonstrate how a geothermal-rich nation can leverage its natural and human capital to build a new climate innovation frontier, one that captures carbon, creates green jobs, and strengthens industrial resilience.
- Hydrogeologic and Geochemical Complementarity: Basalt formations in the Rift Valley are both the target for mineralization and part of geothermal stratigraphy. Integrated site selection optimizes for both heat extraction and reactive mineral availability.
- Risk Reduction via Co-located Pilots: Co-located pilots/projects allow joint simulation of operational scenarios especially pressure management, fluid interactions, and surface safety systems, thus building evidence for regulators and financiers.
- Electricity favorable tarrif: Geothermal's affordable, steady power can fuel CCS, cutting capture energy costs by up to 30%. This makes the projects less costry and encourages the financiers.
- Co-Benefits: In addition to power, geothermal aids applications like farming and thermal uses especially in underprivileged communities. This promotes economic variety and eco-friendly progress in a climate-sensitive country. The geo-energy nexus can catalyze new industries around carbon storage, provide upskilling opportunities for geothermal professionals, and attract international climate finance and partnerships.

- Development of an enabling policy framework for carbon storage as well as development of clear permitting and monitoring standards. As Kenya commits to support early demonstration projects there is an opportunity to leverage on the already existing geothermal permiting regime and expertise to develop CCS permiting regimes.
- Research and development: Kenya could position itself as an R&D hubs especialy at universities for EGS modeling and pilot scaling as well as leveraging Kenya's renewable grid for low-carbon CCS.

3.2 Challenges

- Technical Challenges: Generally, CCS is an energy intensive and water demanding process. In a country that is categorized as a water deficient country, this may pose a huge challenge. To mitigate this challenge of water, it is wise to use recirculated geothermal fluids, brines, or desalination powered by geothermal for purposes of CO2 injection. Additionally, the projects can be co-located near a geothermal plant to utilize cheap electricity or heat for its processes.
- High costs of establishing and running a CCS project.
- Well integrity and pressure management: Completion failures or overpressure risk must be managed via robust well design, staged injection, and pressure monitoring.
- MRV complexity: Demonstrating mineralization requires integrated geochemistry, tracers, geophysics and long-term monitoring.
- Regulatory and Legal Challenges: Kenya needs clear regulations around CO_2 injection, long-term stewardship, and liability transfer. Early engagement with regulators is critical.
- Data transparency & public trust: There is need for clear public engagement and independent verification to build societal license.
- Social & Environmental Risks: Community concerns over safety and land use bust be promptly and urgently addressed. This can be done through early engagement, benefit sharing, local hiring, and establishment of sound grievance mechanisms.

4 BENEFITS FOR KENYA

Kenya's adoption of Carbon Capture and Storage (CCS) technologies offers significant environmental benefits, particularly through the utilization of the Great Rift Valley's unique geological features for permanent CO_2 mineralization. Integrating CCS with Kenya's geothermal resources amplifies energy security and innovation benefits, enabling cost-effective operations powered by abundant, low-carbon geothermal energy. Specifically the benefits include:

- Accelerated Permanent Carbon Removal and support to national climate goals: Mineralization locks away carbon for geologic time, helping Kenya contribute verified removal credits. This process not only helps mitigate global warming by removing CO_2 from the atmosphere but also aligns with Kenya's climate commitments under the Paris Agreement, supporting the country's Nationally Determined Contributions (NDCs) to reduce emissions by 32% by 2030.
- Economic Value Capture: Economically, CCS presents opportunities for job creation and revenue generation in Kenya, transforming the nation into a regional leader in carbon removal. Projects such as those by Cella, Octavia Carbon and Sirona are expected to generate thousands of skilled jobs in engineering, drilling, and monitoring, boosting local economies. By producing verifiable carbon credits, these efforts can attract international investments and create new export markets for carbon offsets, with high value credit that create revenue streams.
- Enhance energy security: By linking CCS with geothermal and other renewables, Kenya can decarbonize its growing energy system without sacrificing industrial growth. CO_2 storage near geothermal sites creates synergies that support clean baseload power and a resilient, low-carbon energy mix.
- Promotes sustainable community development: CCS projects bring infrastructure, training, and local procurement benefits to communities near project sites as well as creating jobs and growth of SME opportunities. Through inclusive engagement and transparent operations, they can improve livelihoods and local resilience.
- Scientific Leadership: Kenya’s scientific and technical leadership stems from its long-standing expertise in geothermal energy development. This success was achieved through local training, international collaboration, and deep scientific research in geothermal development. This established scientific base, provides an ideal foundation for advancing Carbon Capture and Storage (CCS) and

mineralization technologies. The synergy of the geothermal sector and development of CCS projects, position Kenya as a leader in African carbon removal science and standards-setting.

- Attract climate finance and innovation partnerships: As a frontier market for carbon storage, Kenya can attract international investment, grants, and technology partnerships and open markets for African-origin carbon removal credits. This strengthens the country's role in global climate innovation. The county can collaborate internationally with research institutions (e.g., CarbFix in Iceland, Cella, Northwestern University, etc.) to refine techniques and validate results.

5 CONCLUSIONS AND RECCOMENDATIONS

In conclusion, the synergy between Carbon Capture and Storage (CCS) and geothermal energy in Kenya represents a transformative opportunity to advance climate innovation while bolstering energy security and sustainable development. CCS in Kenya is not just about capturing CO2, it's about creating a new climate economy. It blends Kenya's natural geological assets, renewable energy leadership, and human capital into a powerful engine for decarburization, innovation, and sustainable growth. The synergy of CCS and geothermal in Kenya offers a transformative pathway to climate innovation, harnessing natural endowments for sustainable development. By powering capture with geothermal and storing via mineralization, Kenya can achieve negative emissions at scale, bolstering energy security and global leadership.

Early movers such as Cella Mineral Storage and Octavia Carbon are already piloting integrated carbon capture and mineral storage solutions in the Rift Valley, demonstrating local technical capacity and cross-sector collaboration. With continued investment in regulation, monitoring frameworks, and public-private partnerships, Kenya is well-positioned to emerge as Africa's leading hub for CCS innovation, bridging the gap between climate mitigation, industrial decarburization, and sustainable economic growth.

To fully realize this potential, policymakers should prioritize the development of a comprehensive CCS regulatory framework, including incentives like a regulatory sandbox for CCS pilots with clear permitting timelines, tax credits and carbon pricing mechanisms to attract private investment. Continued investment in research, pilot demonstrations, and capacity building should be encouraged to de-risk emerging technologies and attract sustainable financing. Partnerships and collaborations between public institutions, academia, and the private sector should be encouraged so as to strengthen knowledge exchange and innovation. Additionally, integrating CCS into national climate strategies, such as the Kenya Vision 2030 and NDCs, will position the country as a continental leader in carbon removal science and technology. With the right support and governance, Kenya can not only achieve its emission reduction goals but also export carbon management expertise across Africa, anchoring a truly green industrial revolution.

Kenya and Africa at large, should accelerate deployment of pilot projects and consider providing them with incentives that makes CCS projects attractive and economical. This not only meets domestic goals but inspires Africa-wide adoption, proving that resource-rich nations can drive the energy transition.

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