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Unlocking the Potential of Bioenergy with Carbon Capture and Sequestrations in Africa

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Abstract

The Intergovernmental Panel on Climate Change has highlighted the need for technologies that can remove greenhouse gases from the atmosphere to meet the targets of the Paris Agreement. Bioenergy with Carbon Capture and Sequestrations (BECCS) is one such technology for mitigating climate change by enabling negative carbon emissions. Despite Africa's vast bioenergy potential, the continent has yet to fully explore and develop a BECCS market. This review paper provides a comprehensive overview of BECCS technology, the role of BECCS in sustainable development, mitigating climate change, national policies, prospects, challenges, and pathways for developing a BECCS market in Africa. It discusses the technical, economic, and policy dimensions of BECCS, identifies the key biomass resources available in Africa, and explores strategies for overcoming barriers to implementation. The review concludes with recommendations for fostering a sustainable BECCS market in Africa that aligns with the continent's development goals and bioenergy policy.

Categories: Bioprocess Engineering, Biotechnology and Engineering, Environmental and Sustainable Engineering
Keywords: carbon market, negative emissions, climate change, bioenergy policy, beccs, biomass

Introduction And Background

In the last decades, climate change has become a huge challenge to the international community. With the Montreal Protocol in 1987, the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, the Kyoto Protocol in 1997, and the Paris Agreement in 2015 [1-3], climate change has been of interest for urgent action to keep at a safe level of the pre-industrial era. Today, the world is facing the existential challenge of global warming with significant implications for our environment and economies [4]. The urgent need to adapt and mitigate climate change has led to increased interest in negative emission technologies (NETs) [5]. The IPCC has highlighted the need for technologies that can remove CO_2 from the atmosphere to meet the targets of the Paris Agreement [4]. Bioenergy with Carbon Capture and Sequestrations (BECCS) is one such technology that offers the dual benefit of providing renewable energy while removing carbon dioxide (CO_2) from the atmosphere [6]. Climate change poses a significant threat to our planet and humans, and there is an increasing focus on technologies that not only reduce greenhouse gas emissions but also remove CO_2 from the atmosphere [7]. According to the International Energy Agency (IEA), BECCS is one such technology that has the potential to contribute to global carbon reduction targets while also providing renewable energy [8]. However, the deployment and development of BECCS in Africa face unique challenges and opportunities that require careful consideration [9]. It requires a supportive policy and regulatory framework that encourages investment, community engagement, innovation, and sustainable practices [10]. This includes the establishment of clear guidelines for land use, carbon pricing, and environmental protection. Governments and regional organizations must also work to harmonize policies across borders to facilitate cross-border cooperation in BECCS projects [11,12].

BECCS involves the production of bioenergy from biomass and the subsequent capture and storage of the CO_2 generated during the conversion process [13]. This combination of bioenergy production and carbon capture can result in NETs, as the CO_2 absorbed by plants during their growth is removed from the atmosphere and sequestered underground or in geological formations [14,15]. While BECCS shows promise in reducing atmospheric CO_2 concentrations, challenges remain, including concerns about food security, land and water use, and large-scale implementation feasibility [16]. Economic modeling suggests that BECCS could contribute substantially and sustainably to energy supply and emissions reduction in the second half of the 21st century, given appropriate carbon pricing policies [17]. However, uncertainties persist regarding biomass availability, carbon capture technology improvements, CO_2 storage costs, and social acceptance [18], especially in Africa. To realize BECCS's potential in Africa, further research, development, and strong policy support are needed to address these challenges and ensure its effectiveness in meeting climate goals [16], as well as financing.

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Africa is endowed with significant bioenergy resources, including vast arable land, diverse ecosystems, and a wide range of biomass feedstocks such as agricultural residues, forest resources, and energy crops like *Prosopis africana* [19,20]. The continent's tropical climate and agricultural potential make it an ideal region for bioenergy production [21]. However, the development of these resources for BECCS requires careful consideration of food security, land use, and ecological skilled workforce in many African countries, presenting a challenge that must be addressed through capacity building and technology transfer.

The economic viability of BECCS in Africa is influenced by several factors, including the cost of biomass feedstocks, the capital and operational costs of BECCS facilities, and the market value of carbon credits [22,23]. While the high upfront costs of BECCS may be a barrier, opportunities exist for leveraging international climate finance, carbon markets, and public-private partnerships to support the development of a BECCS market in Africa [6].

Additionally, the integration of BECCS with existing industries, such as agriculture, forestry, steel, cement, paper, ethanol, and chemicals, could provide economic co-benefits [24]. Bioethanol production facilities and pulp and paper mills show potential for capturing CO_2 due to high concentrations and excess heat [25,26]. BECCS pilot and demonstration projects are under development in power stations and waste-to-energy facilities [27]. Transportation and storage infrastructure for captured CO_2 will likely be shared among carbon capture, utilization, and sequestration systems. The implementation of BECCS in Africa must have social and environmental concerns at the center, including the land tenure system, community engagement, and the preservation of biodiversity [28]. It is essential to ensure that BECCS projects do not exacerbate existing inequalities or negatively impact local communities. Moreover, the environmental impacts of large-scale biomass production, such as deforestation and water use, must be carefully managed to ensure sustainability [29].

This review aims to synthesize the prospects for establishing a BECCS market in Africa, a continent with vast biomass resources and significant potential for renewable energy development. It will evaluate its potential to mitigate climate change and identify strategies to overcome challenges, fostering sustainable development and carbon sequestration.

Review

Methodology

The resources utilized in this review include studies, reviews, and other written materials/articles that have already been published in recognized journals and have authoritatively described historical and present developments in the bioenergy status across African nations, and the world at large, particularly in the last decade. A comprehensive review of these papers revealed a lack of precise information on the relationship between historical, current, and future successes and possibilities for bioenergy technology in Africa. This prompted the careful selection and collection of crucial material demonstrating the amount of acceptance of these technologies in Africa and their potential, as well as the projection of a solid environmental-friendly bio-economic future for the continent, resulting in this review.

Theoretical and conceptual framework

Overview of BECCS Technology

BECCS combines the production of energy from biomass with the capture and permanent storage of the CO_2 generated during energy production [30]. Biomass, which absorbs CO_2 during growth, is converted into energy through processes such as combustion or gasification [31]. The CO_2 released is then captured and stored in geological formations, effectively removing CO_2 from the atmosphere [32,33]. Globally, BECCS has been implemented in a few pilot projects and large-scale facilities, primarily in North America and Europe. The global deployment of BECCS remains limited due to high costs, technological challenges, and policy uncertainties [24]. However, it is increasingly recognized as a vital component of climate mitigation strategies. Figure *1* shows the carbon cycle, highlighting the role of biomass in capturing CO_2 from the atmosphere. It compares different carbon management strategies, including BECCS, Sustainable biomass conversion (BC), carbon capture and storage (CCS), and traditional fossil fuel combustion. BECCS is presented as a potential net-negative emissions technology, while fossil fuels contribute to net-positive emissions.

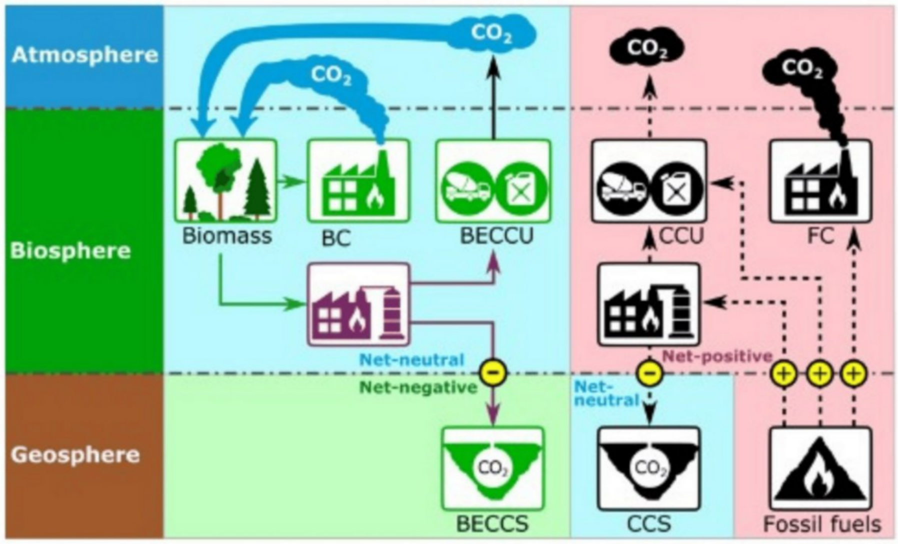

FIGURE 1: Comparison of the different carbon management strategies

Ref: [34]; BC, biomass conversion; CCS, carbon capture and storage; BECCU, Bioenergy with Carbon Capture and Utilization; FC, Fossil Conversion; CCU, Carbon Capture and Utilization; BECCS, Bioenergy with Carbon Capture and Sequestrations

BECCS combines biomass utilization for energy production with carbon capture and storage, potentially reducing atmospheric CO_2 concentrations below current levels [15]. In Figure *2*, the BECCS process begins with the cultivation of energy crops and the utilization of biomass residues, which are characterized by high biomass yield and extensive availability. CO_2 is captured during the combustion, fermentation, aerobic digestion, and gasification processes within the biomass-based energy production facility. The captured CO_2 is then compressed for efficient transport. Compressed CO_2 is transported to the storage site, where it is injected into suitable geological formations, such as saline aquifers, and depleted oil and gas fields, for long-term storage. The biomass-based energy production facility generates a range of energy products, including biohydrogen, biomethane, synthetic biofuels, and electricity. The process also results in non-energy byproducts, which are not explicitly detailed in the image. These byproducts could potentially have value or require further treatment. Heat is generated as a byproduct of the biomass conversion processes and can be utilized for various purposes, such as electricity generation or industrial applications.

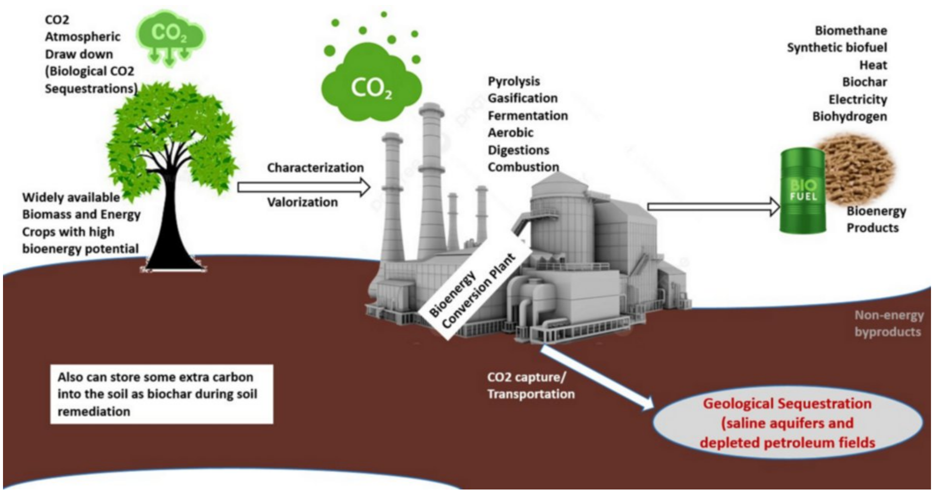

FIGURE 2: Bioenergy with carbon capture, utilization, and sequestrations

Role of BECCS in Mitigating Climate Change

BECCS is often considered a complementary technology to other climate change mitigation strategies [22]. It can be integrated into low-carbon energy systems to enhance their overall performance. For example, combining BECCS with renewable energy sources like wind and solar can create a more resilient and sustainable energy mix [35]. It is essential to note that BECCS should not be seen as a silver bullet for climate change. A comprehensive approach that includes reducing emissions from other sectors, improving energy efficiency, and promoting renewable energy is necessary to achieve climate goals [36]. Unlike other carbon reduction technologies that aim to reduce CO_2 emissions, BECCS goes a step further by actively removing CO_2 from the atmosphere. This makes it a crucial tool in achieving net-zero emissions and limiting global warming to 1.5°C, as outlined in the Paris Agreement. Several studies have highlighted the potential of BECCS to contribute significantly to negative emissions. For instance, a study published in Nature Climate Change estimated that BECCS could remove up to 10 billion tons of CO_2 per year by 2050, which is equivalent to roughly 10% of global emissions [37]. One of the primary concerns is the sustainability of biomass production. Ensuring that biomass is produced sustainably without competing with food production or causing deforestation is crucial. Additionally, the energy intensity of the carbon capture and storage process can reduce the overall efficiency of BECCS.

As a promising negative emission technology for mitigating climate change, further studies suggest BECCS could potentially sequester 2.5 $GtCO_2$ annually over 30 years or 40 $GtCO_2$ annually over 80 years [37]. While BECCS plays a crucial role in many climate mitigation scenarios, its implementation faces challenges including large land requirements and socioeconomic barriers [38]. Some research indicates that limiting radiative forcing to 2.6 Wm^{-2} by 2100 may be achievable without BECCS, though its inclusion could reduce mitigation costs [39]. However, delayed action by major regions could make it impossible to meet this target. Despite uncertainties in crop yields and soil quality over time, BECCS offers a biophysically viable route for significant emissions sequestration throughout the century, with earlier implementation providing greater benefits for meeting end-of-century climate targets [40].

BECCS and Sustainable Development

BECCS offers the potential to contribute significantly to sustainable development by aligning with multiple Sustainable Development Goals (SDGs) (Table *1*) and delivering co-benefits for energy security, rural development, and economic growth.

United Nation’s SDGs	BECCS Contributions
SDG7: Affordable and Clean Energy	By producing renewable energy from biomass and capturing CO_2 emissions, BECCS can help to ensure access to affordable, reliable, sustainable, and modern energy for all.
SDG11: Sustainable Cities and Communities	BECCS can contribute to reducing greenhouse gas emissions and improving air quality in urban areas by providing a clean energy source.
SDG13: Climate Action	BECCS has the potential to play a crucial role in mitigating climate change by removing CO_2 from the atmosphere.
SDG15: Life on Land	While the sustainability of biomass feedstock production is crucial, BECCS can contribute to sustainable land management practices by promoting the use of agricultural residues and dedicated energy crops.

TABLE 1: BECCS contributions to United Nation’s SDGs

BECCS, Bioenergy with Carbon Capture and Sequestrations; SDG, Sustainable Development Goal

By diversifying the energy mix and reducing reliance on fossil fuels, BECCS can enhance energy security. Additionally, biomass-based energy generation can provide local energy sources, reducing dependence on imported fuels. The development of biomass energy projects can create job opportunities in rural areas, contributing to rural development. Moreover, the cultivation of energy crops can provide additional income sources for farmers and support rural livelihoods. The deployment of BECCS technology can stimulate economic growth through investments in research and development, infrastructure, and the creation of new industries. The production and export of biofuels can also generate significant revenue for countries.

Biomass resources in Africa

Africa is the world's greatest user of traditional biomass energy (firewood, charcoal, and agricultural leftovers). Two-thirds of African countries rely on biomass for more than half of their ultimate energy usage. One-third is anticipated to rely on the resource for more than 80%, and a few countries for more than 90%. Biomass contributes to up to two-thirds of total final energy consumption in the sub-Saharan area. According to the African Energy Commission (AFREC) Energy Statistics Database, the continent utilized 269 million tonnes (MT) of oil equivalent (Mtoe) of biomass and 295 Mtoe of conventional energy in 2019. The Sub-Saharan area accounts for 91.38% of total African consumption, with North Africa accounting for 0.22% and South Africa accounting for 8.4% [41].

Africa's diverse ecosystems provide an abundance of biomass resources, including agricultural residues, forestry waste, and dedicated energy crops. This section details biomass resource availability, distribution, and sustainability across different African regions. Africa produces substantial agricultural residues from crops such as maize, *Prosopis africana*, millets, yam, sugarcane, rice, and others [19]. These residues, often underutilized, represent a significant potential feedstock for BECCS. The continent's forestry sector generates considerable waste, including sawdust and wood chips, which can be harnessed for bioenergy production. The cultivation of dedicated energy crops like *Prosopis africana*, switch grass, and Miscanthus can provide a steady and sustainable supply of biomass for BECCS [20,42].

Biomass is a renewable energy source derived from plants and animals, primarily organic material (Table *2*). It can be burned directly or converted into liquid biofuels or biogas. Plants and algae are primary producers of biomass, which converts CO_2 and water into primary and secondary metabolites through photosynthesis. These metabolites are valuable bio-chemicals used in various industries. Primary metabolites are lignocellulose biomass, which mainly includes carbohydrates like cellulose, hemicelluloses, starch, and lignin. Carbohydrates can be transformed into biofuels like bio-gasoline, bioethanol, and bio-butanol through biochemical, thermochemical, and catalytic processes. Lignin is typically used for producing heat and electricity through combustion. A wide range of alteration technologies have been developed to effectively utilize each biomass fraction. Biomass can be derived from various sources for energy production [43]. The growing population demands sustainable agriculture, necessitating the development of bio-refineries using plant, animal, and human biomass. These bio-refineries aim to produce energy, food, and chemicals, collaborating with private and public organizations to create a sustainable ecosystem by efficiently utilizing chemical biomass energy [20].

Biomass initiatives often demand significant financial investment, with their success heavily dependent on factors such as feedstock cost structures, inherent quality, and procurement logistics [44,45]. The design of efficient supply chains not only influences cost but also affects the integrity of the feedstock, which must meet predefined criteria tailored to the intended final products [46,47]. Market preferences are gradually shifting, with increasing demand for advanced solid biofuels that meet higher performance and environmental standards [48]. Technology deployment varies widely, ranging from low-cost, traditional combustion systems to high-end, low-emission power plants, each affected by local regulations and cost structures. For example, Germany enforces stringent emissions standards, leading to the development of advanced but costly biomass systems [49]. In contrast, regions with relaxed regulatory environments may adopt lower-cost technologies, albeit with potential trade-offs such as higher emissions and reduced operational efficiency [50]. Combustion performance is often hindered by the presence of non-combustible materials, which can cause technical issues such as slagging and fouling. Moreover, proper handling of particulate emissions and residual waste is essential. Therefore, any proposed technology must be compatible with target applications like pyrolysis and gasification, ensuring reliability and compliance with environmental and operational benchmarks [51].

Biomass Source	Subcategories	Examples
Dedicated Energy Crops	a. Conventional Annual Crops	Oil crops: palm, canola, sunflower, etc.
		Sugar and starch crops: sugar cane, sugar beet, corn, cereals, etc.
	b. Perennial Crops and Energy Grasses	Miscanthus, reed canary grass, switchgrass, etc.
Forestry and Forestry Residues	a. Short Rotation Forestry (SRF)	Alder, ash, Southern Beech, birch, eucalyptus, paper mulberry, Australian Blackwood, sycamore, etc.
	b. Short Rotation Coppice (SRC)	Willow, Salix viminalis, poplar, etc.
	c. Forestry Residues	Wood chips from branches/tips/poor-quality stemwood, etc.
		Sawmill by-products: chips, sawdust, bark, etc.
		Material from municipal tree management, waste wood, etc.
Other Residues and Wastes	a. Agricultural Crop Residues	Straw from cereals/oilseeds, bagasse, etc.
	b. Municipal Organic Waste	Paper/cardboard, food, garden, textiles, etc.
	c. Sewage Sludge	
	d. Animal Manure	
	e. Landfill Gas	
Marine Biomass		Cyanobacteria, microalgae/phytoplankton, macroalgae/seaweed

TABLE 2: Energy derived biomass sources

In Figure *3* [52], the overall trend of electricity capacity from biogas, solid biofuels, and renewable municipal waste in Africa shows a consistent increase from 2012 to 2023. This suggests a growing adoption and utilization of these renewable energy sources for electricity generation. While the overall trend is upward, the growth rates for each biofuel type vary. Some years exhibit more significant increases compared to others. This variability might be attributed to factors such as policy changes, technological advancements, economic conditions, and resource availability [53].

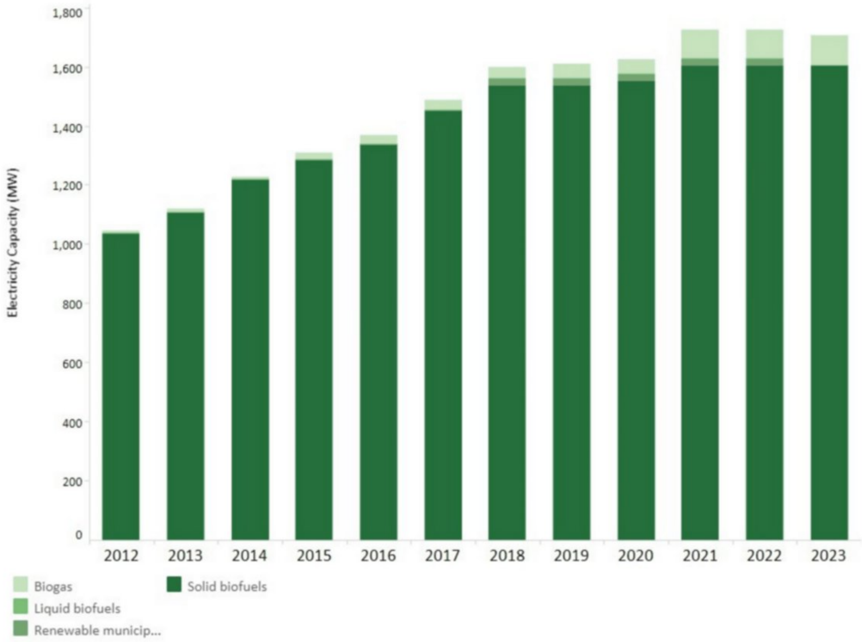

FIGURE 3: Potential electricity capacity of bioenergy in Africa (generated from IRENA database)

Technical feasibility of BECCS in Africa

The implementation of BECCS in Africa requires a thorough understanding of the current state of relevant technologies. The advancements in bioenergy production, carbon capture technologies, and storage capabilities.

Bioenergy Production Technologies

A recent investigation into 25 potential energy crops demonstrated that agricultural residues alone could play a huge role in fulfilling Africa's renewable energy (RE) needs, with estimated outputs of 62.62 Mtoe of bioethanol, 83.05 Mtoe of biomethane, and 139.79 Mtoe of solid biofuel per year [16,19]. Biofuels, particularly those derived from biomass, are recognized for their carbon neutrality and have been instrumental in improving air quality in countries like China through the reduction of pollutants such as sulfur dioxide and nitrogen oxides [54]. Scaling up biofuel usage demands innovation in fuel processing and performance enhancement. Densification techniques, used to manufacture fuel briquettes, are especially promising, offering improved energy density and ease of transport [55]. Optimization of particle size plays a critical role in enhancing combustion properties [56-58]. Before densification, feedstocks must undergo several preparatory steps including pretreatment, drying, and pulverization, all of which contribute to better fuel characteristics and reduced handling costs [59]. While densification can be performed using various methods, applying high pressure, sometimes with binding agents, has proven most effective for producing briquettes with optimal performance and durability [60].

Bioenergy production technologies have advanced significantly in recent years, offering potential solutions to energy challenges and climate change mitigation [61]. Various conversion methods (Table *3*), including thermochemical and biochemical processes, are used to transform biomass into biofuels and bioenergy [62]. Thermochemical technologies, such as combustion, gasification, and pyrolysis, can efficiently convert diverse biomass feedstocks into solid, liquid, and gaseous biofuels [63]. However, these processes face challenges like low energy efficiency and high costs. Innovative approaches, such as microwave pyrolysis and the use of catalysts, are being explored to enhance conversion efficiency and product quality [64]. Integration of different technologies, like combining torrefaction or hydrothermal carbonization with combustion or gasification, may optimize biomass energy use efficiency and minimize harmful byproducts [63]. Nevertheless, the development of biofuels has been a major focus of bioenergy research, with significant advancements in recent years.

Conversion Methods	Various Technologies	Ref.
Thermochemical Conversion	Combustion - The direct burning of biomass to produce heat and electricity. While simple and widely used, combustion has limitations related to efficiency and emissions, particularly particulate matter and greenhouse gases.	[65], [66]
	Gasification - Biomass is converted into a combustible gas mixture (syngas) through partial oxidation at high temperatures. Gasification is more efficient than direct combustion and produces cleaner energy, with the potential for combined heat and power (CHP) applications.	[67], [68]
	Pyrolysis - In this process, biomass is decomposed in the absence of oxygen to produce bio-oil, syngas, and biochar. Pyrolysis is particularly notable for its flexibility, as the resulting bio-oil can be refined into various fuels and chemicals.	[69], [70], [71], [72]
Biochemical Conversion	Anaerobic Digestion - Organic material is broken down by bacteria in the absence of oxygen, producing biogas (a mixture of methane and carbon dioxide) and digestate, a nutrient-rich byproduct. Anaerobic digestion is widely used for waste treatment and energy production, particularly in rural and agricultural settings	[73], [74], [75]
	Fermentation - Sugars in biomass are converted into ethanol or other alcohols by microorganisms. This process is central to the production of bioethanol, a key biofuel for transportation. Advances in fermentation technologies, such as the development of cellulosic ethanol, have improved the efficiency and sustainability of bioethanol production.	[76], [77], [78]
Physico-Chemical Conversion	Trans-esterification - This process is used to produce biodiesel from vegetable oils or animal fats by reacting them with alcohol in the presence of a catalyst. Biodiesel is a cleaner-burning alternative to petroleum diesel and can be used in existing diesel engines with minimal modifications (Meher et al., 2006).	[79], [80]

TABLE 3: Bioenergy production technologies

Carbon Capture Technologies

Carbon capture technologies are crucial for mitigating greenhouse gas emissions and combating global warming. Various methods have been developed, including pre-combustion, post-combustion, and oxy-fuel combustion systems. However, these technologies can reduce CO_2 emissions by over 85% [81,82]. Recent advancements include the use of ionic liquids, membranes, and hybrid systems, which offer less energy-intensive alternatives to traditional solvents [83]. Emerging technologies such as nano-fluids, phenoxide salt, and micro-encapsulation show promise for future CO_2 capture [83]. The energy sector, particularly thermoelectric and bioenergy plants, is a key focus for carbon capture implementation [84]. Novel methods like chemical looping combustion are being compared to traditional capture techniques [85]. Despite progress, challenges remain in technological maturity, economic viability, and combustion system knowledge, necessitating further research and development.

Carbon Sequestration Potential in Africa

Africa holds significant potential for carbon storage through various ecosystems and land management practices. Agroforestry systems in sub-Saharan Africa could sequester between 8 and 54 Billion Tonnes (BT) of carbon, offsetting African emissions for 20 to 125 years [86]. Central African ecosystems, containing 10% of the world's tropical moist forests, could sequester 18.32 BT through improved forest management and an additional 10 BT through reforestation of formerly forested land by 2050 [87]. Carbon sequestration projects in Africa offer multiple benefits, including poverty alleviation, biodiversity conservation, and ecological restoration [88]. However, these projects currently constitute less than 3% of international carbon offset trade. To maximize carbon storage potential and co-benefits, spatial optimization across tropical Africa can identify top-ranked sites that balance carbon-stocking capacity with ecosystem and social benefits [89]. Forests, particularly tropical rainforests, are among the most effective natural carbon sinks. Africa's vast forests, such as the Congo Basin (Figure *4*) and Amazon basin, store immense amounts of carbon [90]. The basin cuts across six countries; the Democratic Republic of the Congo (DRC), Republic of the Congo, Central African Republic (CAR), Cameroon, Equatorial Guinea, and Gabon, with the DRC containing 61% of the basin. However, deforestation and degradation pose significant threats to these valuable ecosystems. As the second-largest tropical rainforest globally, the Congo Basin plays a vital role in global climate regulation. Protecting and restoring its forests is essential for maintaining its carbon sequestration capacity [91]. Although a significant portion lies outside Africa, the Amazon Basin's interconnectedness with the continent's ecosystems, particularly through atmospheric circulation patterns, makes it relevant to Africa's carbon sequestration efforts [92]. Also, the Savannas and Grasslands cover a substantial portion of Africa. While often overlooked, grasslands can be effective carbon sinks, especially when managed sustainably. Practices such as rotational grazing, controlled burns, and conservation tillage can enhance carbon sequestration in grasslands [93].

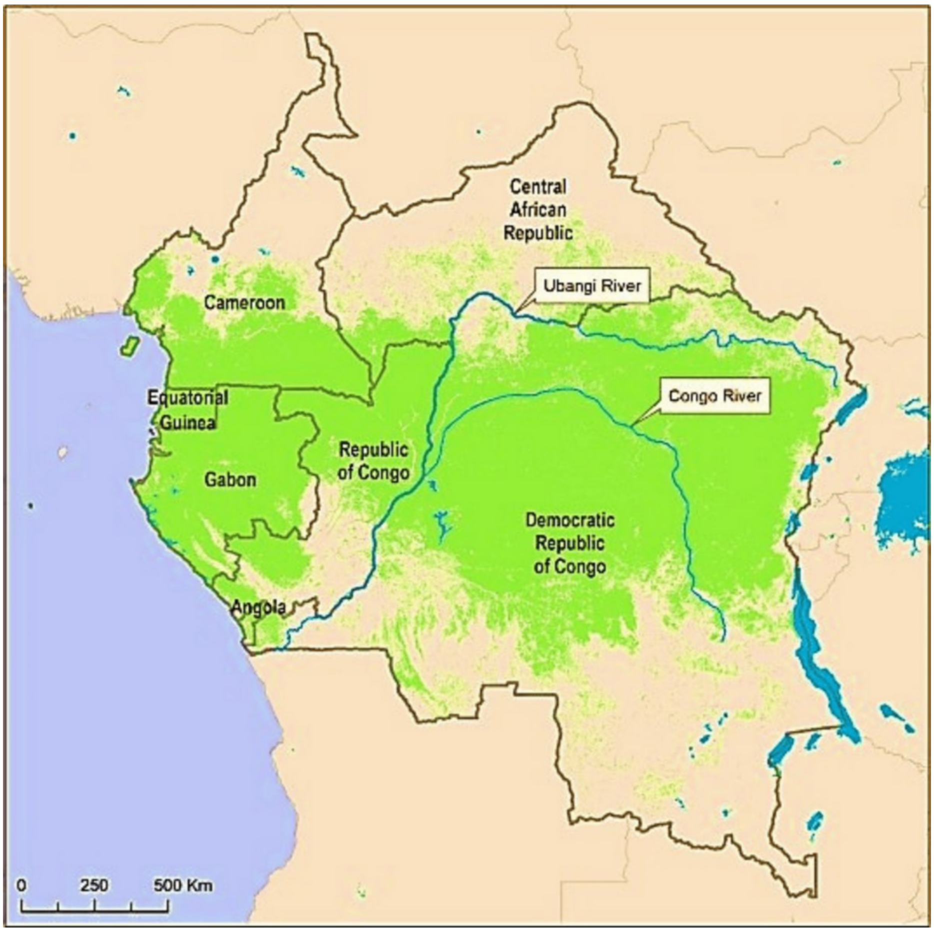

FIGURE 4: Congo rainforest and basin as a potential biological carbon sink

As global efforts intensify to mitigate climate change, CCS has emerged as a crucial strategy for reducing CO_2 emissions. CCS involves capturing CO_2 emissions from industrial processes and storing them in geological formations underground, preventing them from entering the atmosphere. Africa, with its diverse geological landscape, holds significant potential for CO_2 storage, particularly in deep saline aquifers, depleted oil and gas fields, and unmineable coal seams. In Africa, several sedimentary basins are identified as potential candidates for CO_2 storage in deep saline aquifers. The North African basins, such as the Ghadames and Illizi basins in Libya and Algeria, offer substantial storage potential [94]. These basins have extensive sedimentary formations with thick, porous layers that can accommodate large volumes of CO_2. Additionally, the tectonically stable nature of these basins minimizes the risk of leakage. The Ghadames Basin alone could potentially store up to 6.2 gigatons of CO_2, making it one of the most promising sites in Africa [95]. In Sub-Saharan Africa, the potential for CO_2 storage in deep saline aquifers is also significant [96]. The Congo Basin, which spans several Central African countries, has been identified as a promising region for engineered CO_2 storage. The basin's thick sedimentary layers and widespread distribution offer substantial storage capacity [97]. However, the lack of detailed geological data and infrastructure in this region poses significant challenges to the development of CCS projects [98].

Depleted oil and gas fields are another attractive option for CO_2 storage (Figure *5*), particularly in regions with a history of hydrocarbon production. These fields have proven structural traps and sealing mechanisms that have contained hydrocarbons for millions of years, making them ideal candidates for CO_2 storage. Moreover, the existing infrastructure associated with these fields, such as wells and pipelines, can be repurposed for CO_2 injection and monitoring, reducing the overall cost of CCS projects [99]. North Africa, particularly Algeria, Egypt, and Libya, has several depleted oil and gas fields that are suitable for CO_2 storage [100]. The In Salah project in Algeria is a notable example [101], where CO_2 captured from natural gas processing has been successfully injected into a depleted gas field since 2004 [102]. The project has demonstrated the technical feasibility of CO_2 storage in depleted fields and has provided valuable insights into the monitoring and verification of stored CO_2. In West Africa, the Niger Delta Basin offers potential for CO_2 storage in depleted oil fields. The basin's extensive history of oil production has resulted in numerous depleted fields that could be repurposed for CO_2 storage. However, the region's complex geology, characterized by faults and fractures, presents challenges for ensuring long-term CO_2 containment [103].

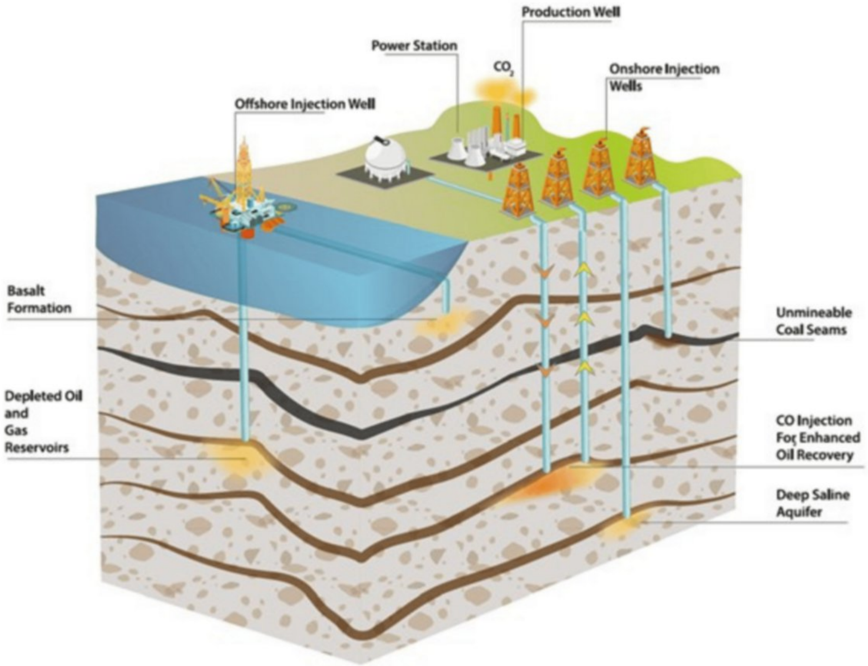

FIGURE 5: Various carbon sinks for sequestrations

Ref: [104]

The unmineable coal seams also represent another option for CO_2 storage as shown in Figure *5*, particularly through a process known as CO_2-enhanced coalbed methane (CO_2-ECBM) recovery [104]. In this process, CO_2 is injected into coal seams, where it adsorbs onto the coal surface, displacing methane and enhancing gas production. This not only stores CO_2 but also produces additional methane, which can be used as an energy source. South Africa, with its extensive coal reserves, particularly in the Karoo Basin, has significant potential for CO_2 storage in unmineable coal seams. The Karoo Basin contains large volumes of deep, unmineable coal seams that could be used for CO_2-ECBM projects [105]. The potential CO_2 storage capacity in South Africa's coal seams could be as high as 1.5 gigatons. However, the complex geological characteristics of the Karoo Basin, including its faulted and fractured nature, present challenges for ensuring the long-term stability of stored CO_2 [106]. In contrast, the coal basins in Mozambique and Botswana, such as the Moatize and Mmamabula basins, also offer the potential for CO_2 storage in unmineable coal seams. These basins have significant coal reserves and could play a role in regional CCS strategies. However, the development of such projects is contingent on further geological assessments and the establishment of supporting infrastructure [107].

Despite all these huge potentials for carbon sinks with different options, there is still no operational CCS and BECCS in Africa, as seen in the latest global CCS report (Figure *6*). This could be as a result of the lack of detailed geological assessments, limited infrastructure, and the need for more robust regulatory frameworks to support the development and deployment of CCS and BECCS technologies.

FIGURE 6: Global carbon capture and sequestration facilities at various developmental stages

Ref: [95]

Policy and regulatory landscape

The development of a BECCS market requires supportive policies and regulatory frameworks. This section explores the current policy landscape in Africa, highlighting key policies, incentives, and regulations that can drive BECCS adoption.

National Policies

Africa's approach to bioenergy development is generally more advanced than its policies on CCS and BECCS. Countries like South Africa, Nigeria, and Kenya have more established policies toward bioenergy, while CCS and BECCS are still in their nascent stages. Although BECCS is not yet widely recognized as a standalone policy focus, the combination of bioenergy development and emerging CCS strategies across the continent suggests that BECCS could play a significant role in Africa's future climate change mitigation efforts (Table *4*). National and local governments must take the lead in developing laws and regulations, as well as promoting bioenergy production, investment, and trade. The Government's role is to create a sustainable bioenergy policy as part of the national development strategy, including suitable legal measures for bioenergy production, distribution, consumption, and trade. They also should establish environmental standards, and strategically select the best feedstock and technology options, and reach economically, socially, and environmentally acceptable agreements. As Governments are the enablers, the private sector is ultimately the driver of bioenergy development. Civil society organizations (CSOs) function as watchdogs for government and commercial policies, advocating for bioenergy on a national and community scale. Africa Bioenergy Policy Framework and Guidelines has been designed toward harmonizing sustainable bioenergy development in Africa. The main objectives of this framework and guidelines are to build a consensus on a shared framework that inspires and provides guidance to individual countries in developing policies and regulations, as well as enhance awareness among African leaders and the civil society about the need for environmentally friendly and socially responsible bioenergy development policies [53].

Country	Bioenergy Development Policies	CCS Policies	BECCS Policies
South Africa	Integrated Resource Plan (IRP) 2019: Aims to diversify energy sources, including bioenergy [108].	South African Carbon Capture and Storage Atlas: Identifies potential geological storage sites for CCS [109].	National Climate Change Response White Paper: Recognizes BECCS as a potential technology but no specific policy has been implemented [110].
	Renewable Energy Independent Power Producer Procurement Programme (REIPPPP): Promotes investment in bioenergy projects [111].	South African CCS Roadmap: Outlines plans for CCS development [112].	
Nigeria	National Renewable Energy and Energy Efficiency Policy (NREEEP) 2015: Promotes bioenergy as part of the renewable energy mix [113].	No specific national CCS policy, but potential for development given Nigeria’s oil and gas infrastructure [114].	No specific BECCS policy, but bioenergy and CCS are recognized in national energy and climate strategies [115].
Kenya	National Energy Policy 2018: Supports bioenergy development, particularly in the	No dedicated CCS policy, but CCS is recognized as part of Kenya’s climate change mitigation strategies in the National Climate	BECCS is not explicitly mentioned in national policies, but bioenergy and CCS are

	form of biogas and biomass [116,117].	Change Action Plan (NCCAP) 2018-2022 [118].	acknowledged separately [119].
Egypt	Integrated Sustainable Energy Strategy (ISES) 2035: Promotes renewable energy including bioenergy [120,121].	Egypt's National Strategy for Climate Change 2050: CCS is included as part of broader climate change mitigation efforts [122].	BECCS is not explicitly mentioned in current national policies, but bioenergy and CCS are recognized independently as part of the energy and climate change strategies [123].
Morocco	Moroccan Energy Strategy 2020: Focuses on renewable energy, including bioenergy from agricultural and forestry residues [124,125].	No specific national CCS policy, but potential for CCS development recognized as part of the Moroccan Climate Change Policy [126].	BECCS is not explicitly mentioned, but the combination of bioenergy and CCS is recognized as a potential strategy for emissions reduction [127].
Ethiopia	Climate Resilient Green Economy (CRGE) Strategy 2011: Emphasizes bioenergy development to reduce deforestation and promote sustainable energy [128].	CCS is recognized as a potential technology in Ethiopia's CRGE, but no specific policy has been implemented [128].	BECCS is not explicitly mentioned, but bioenergy is a key component of Ethiopia's low-carbon development strategy [129].
Ghana	Renewable Energy Master Plan 2019: Promotes bioenergy development, particularly in rural areas for energy access [130,131].	No specific CCS policy, but Ghana is exploring CCS as part of its commitments under the Paris Agreement [132,133].	BECCS is not specifically mentioned, but bioenergy and CCS are considered in broader discussions of climate change mitigation and renewable energy development [132,133].
Angola	National Energy Security Strategy and Policy (NESSP) 2025: Bioenergy is included as a key component for rural electrification and sustainable energy [134].	No specific CCS policy, but Angola's oil and gas sector could support future CCS initiatives [134].	BECCS is not explicitly mentioned, but there is potential for integration given the country's focus on bioenergy and emerging interest in CCS technologies [134].
Tunisia	Tunisia Solar Plan 2030: Includes bioenergy as part of the renewable energy mix, focusing on agricultural waste and biomass [135].	No specific CCS policy, but Tunisia is exploring CCS potential as part of its national climate change strategy [135].	BECCS is not explicitly mentioned, but bioenergy and CCS are recognized in Tunisia's national energy and climate strategies [135].
Mozambique	Renewable Energy Feed-In Tariff (REFIT) Policy: Encourages the development of bioenergy projects, particularly from biomass and agricultural residues [136,137].	No dedicated CCS policy, but CCS is being considered in the context of Mozambique's large gas reserves and LNG projects [138].	BECCS is not specifically mentioned, but bioenergy is promoted, and there is potential for integrating CCS into future climate and energy strategies [139].
Botswana	Botswana Energy Master Plan 2004-2024: Promotes the use of bioenergy, particularly in rural areas, focusing on biomass and biogas [140].	No specific CCS policy, but Botswana has significant coal resources, making it a potential candidate for future CCS development [141,142].	BECCS is not explicitly included in national policy, but the focus on bioenergy and the emerging interest in CCS present opportunities for BECCS in the future [141].
Uganda	Renewable Energy Policy for Uganda 2007: Focuses on expanding bioenergy, particularly biomass and biogas, to improve energy access and reduce deforestation [143].	No specific CCS policy, but Uganda's climate action plans recognize CCS as a potential technology for reducing emissions [144].	BECCS is not specifically mentioned, but Uganda's focus on bioenergy and interest in CCS suggests potential for future BECCS development [144].
Tanzania	Tanzania Energy Access and Development Programme (EADP) 2013: Promotes the use of bioenergy, particularly in rural areas, focusing on biomass and biogas [145].	No specific CCS policy, but Tanzania's natural gas sector presents opportunities for future CCS deployment [146].	BECCS is not explicitly included in national policy, but the emphasis on bioenergy and emerging discussions on CCS offer potential for future BECCS strategies [146].
Namibia	Namibia Renewable Energy Policy 2017: Promotes bioenergy development, focusing on biomass from invasive species and agricultural residues [147].	No dedicated CCS policy, but Namibia's focus on renewable energy and climate change mitigation includes consideration of CCS as a future option [148,149].	BECCS is not specifically mentioned, but the focus on bioenergy and interest in CCS indicate potential for future BECCS initiatives in the national climate strategy [148,149].

TABLE 4: National bioenergy policies in Africa–bioenergy development, CCS and BECCS policies

BECCS, Bioenergy with Carbon Capture and Sequestrations; CCS, carbon capture and storage

International Agreements

Africa's commitments under international agreements like the Paris Agreement (PA), Nationally

Determined Contributions (NDCs), Adaptation Strategies, and the United Nation's SDGs provide a very strong foundation for the development of BECCS initiatives across the continent [150]. Many African countries have highlighted bioenergy and CCS in their climate and energy strategies, suggesting a growing recognition of the potential for BECCS [146]. Table *5* shows these commitments for selected 15 countries, and their potential to support BECCS initiatives. These are voluntary commitments-NDCs by countries to reduce their greenhouse gas emissions and adapt to the impacts of climate change [2]. Many African countries have included bioenergy and related technologies in their NDCs as seen in Table *5*. The African states are prioritizing adaptation measures to cope with the adverse effects of climate change, such as droughts, floods, and sea-level rise [151]. BECCS can play a role in both mitigation and adaptation by providing renewable energy and enhancing ecosystem resilience [152]. Even though the continent is the lowest emitter of carbon, it feels the brunt of the consequences of climate change and therefore must strategize to adapt [153].

The PA aligns with the United Nation's SDGs, particularly those related to clean energy, poverty reduction, and sustainable land use (Table *5*). BECCS can contribute to achieving these goals by providing energy access, creating jobs, and promoting sustainable agricultural practices [154].

Countries	PA Commitments	NDCs	SDGs	Potential to Support BECCS Initiatives	[Ref]
South Africa	Ratified in 2016.	Emphasizes renewable energy (RE), with CCS as a potential technology for the coal sector.	SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action).	Strong potential for BECCS, with bioenergy and CCS recognized. Integration into climate policy is feasible.	[155], [156], [155]
Nigeria	Ratified in 2017.	Focuses on reducing flare gas and fugitive emissions, while expanding RE.	SDG 7, SDG 13, SDG 8 (Decent Work and Economic Growth).	High potential with significant bioenergy resources; infrastructure for CCS is emerging.	[114], [156], [157]
Kenya	Ratified in 2016.	Targets RE expansion mentions CCS technology needs.	SDG 7, SDG 13, SDG 2 (Zero Hunger).	BECCS could be integrated with existing bioenergy and climate strategies, especially in the agriculture and energy sectors.	[158], [156], [159], [160]
Ethiopia	Ratified in 2017.	Emphasizes climate-resilient green economy with a focus on bioenergy.	SDG 7, SDG 13, SDG 1 (No Poverty).	Significant potential for BECCS due to focus on bioenergy and climate resilience. CRGE provides a framework for BECCS integration.	[129], [156]
Ghana	Ratified in 2016.	Focuses on RE, including bioenergy for rural development.	SDG 7, SDG 13, SDG 6 (Clean Water and Sanitation).	Potential for BECCS through bioenergy in rural areas; CCS infrastructure development needed.	[131], [156], [161]
Morocco	Ratified in 2016.	Promotes bioenergy from agricultural waste, as well as recognizing CCS as a potential strategy.	SDG 7, SDG 13, SDG 12 (Responsible Consumption and Production).	Potential for BECCS exists with a strong focus on bioenergy and emerging interest in CCS.	[125], [156], [162]
Egypt	Ratified in 2017.	Includes RE targets, as well as CCS as part of long-term climate strategy.	SDG 7, SDG 13, SDG 6, SDG 11 (Sustainable Cities and Communities).	The potential for BECCS is strong, especially with the existing focus on CCS and RE development.	[122], [156], [163], [164]
Algeria	Ratified in 2016.	Prioritizes CCS, and also considers bioenergy in RE strategies.	SDG 7, SDG 13, SDG 8, SDG 9 (Industry, Innovation, and Infrastructure).	High potential for BECCS due to established CCS projects (e.g., In Salah) and bioenergy initiatives.	[101], [156], [165]
Senegal	Ratified in 2016.	Highlights bioenergy, with CCS as a mitigation option.	SDG 7, SDG 13, SDG 14 (Life Below Water).	Potential for BECCS exists, especially in coastal bioenergy projects, but infrastructure for CCS needs development.	[156], [166], [167]
Uganda	Ratified in 2016.	Emphasizes bioenergy for rural energy access; CCS recognized as a potential.	SDG 7, SDG 13, SDG 2, SDG 15 (Life on Land).	Potential for BECCS in rural bioenergy projects; CCS technology and infrastructure still in early stages.	[156], [168], [169]
Botswana	Ratified in 2016.	Promotes bioenergy in the energy mix; CCS is mentioned for the coal sector.	SDG 7, SDG 13, SDG 12.	Potential for BECCS in the coal sector with bioenergy integration, though CCS infrastructure is limited.	[156], [170], [171]
Mozambique	Ratified in 2018.	Bioenergy is promoted in rural areas; CCS is considered for LNG projects.	SDG 7, SDG 13, SDG 15.	Potential for BECCS in agriculture and LNG projects, but requires significant investment in CCS infrastructure.	[137], [156], [172]

Namibia	Ratified in 2016.	Supports bioenergy from invasive species, with CCS considered in climate strategy.	SDG 7, SDG 13, SDG 15.	Potential for BECCS in the bioenergy sector, particularly with biomass from invasive species; CCS infrastructure development needed.	[147]–[149], [156]
Tanzania	Ratified in 2018.	Bioenergy is emphasized for rural energy access, while CCS is considered in the natural gas sector.	SDG 7, SDG 13, SDG 2, SDG 6.	Potential for BECCS in rural bioenergy and natural gas sector; CCS technology still in nascent stages.	[156], [146], [173]
Tunisia	Ratified in 2017.	Bioenergy is included in the RE strategy; CCS is being explored.	SDG 7, SDG 13, SDG 12.	Potential for BECCS with a focus on bioenergy from agriculture and emerging CCS strategies, especially in water-scarce regions.	[156], [135], [174]

TABLE 5: International agreements and commitments of selected African nations

PA, Paris Agreement; NDC, Nationally Determined Contribution; SDG, Sustainable Development Goal; BECCS, Bioenergy with Carbon Capture and Storage; CCS, carbon capture and storage

Financial Incentives (FIs)

Combining financial mechanisms, including carbon pricing, subsidies, and international funding opportunities, can incentivize BECCS projects (Figure 7) and accelerate the transition to a low-carbon economy [175]. However, it is essential to tailor these mechanisms to individual countries and projects' specific needs and circumstances. BECCS, as a complex and capital-intensive technology, requires significant financial support to be deployed at scale [176]. A variety of financial mechanisms can be employed to incentivize BECCS projects (Figure 7).

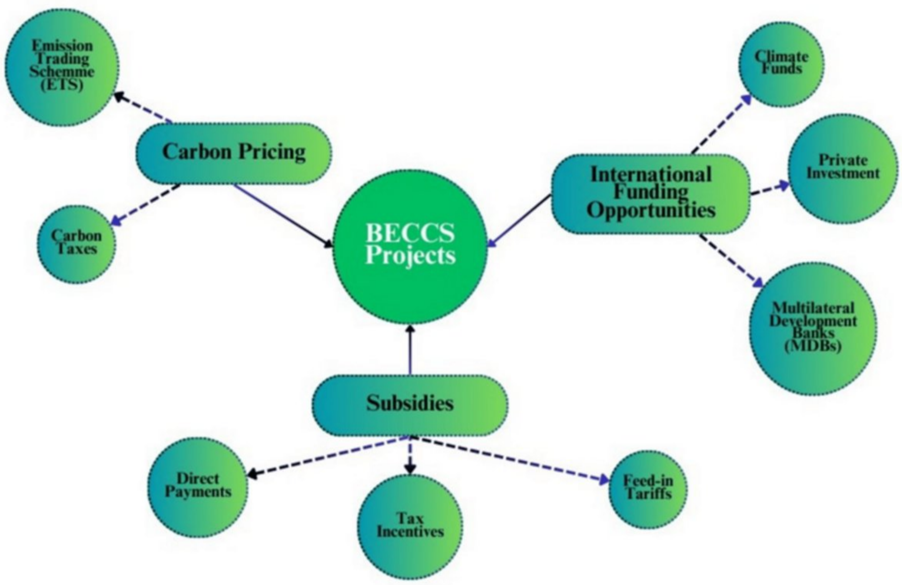

FIGURE 7: Spider diagram of the financial mechanisms toward BECCS deployment in Africa

BECCS, Bioenergy with Carbon Capture and Storage

Carbon Pricing: The emission trading schemes (ETS) create a market for carbon emissions, allowing companies to buy and sell permits to emit. BECCS projects can generate carbon credits by capturing and storing CO_2, which can be sold in the ETS market, providing a revenue stream. Carbon taxes impose a direct cost on carbon emissions, incentivizing companies to adopt technologies like BECCS that reduce their carbon footprint [177,178].

Subsidies: Governments can provide direct payments to BECCS projects to offset upfront costs and make them more economically viable. Also, tax breaks, exemptions, or credits can be offered to reduce the tax burden on BECCS projects. Feed-in tariffs guarantee a premium price for electricity generated from renewable sources like BECCS, making it more attractive for investors.

International Funding Opportunities: International climate funds, such as the Green Climate Fund (GCF) and the Adaptation Fund, provide financial resources to support climate mitigation and adaptation projects in developing countries, including BECCS. Multilateral Development Banks, like the World Bank and the African Development Bank, can offer loans, grants, and technical assistance to support BECCS projects. Furthermore, BECCS projects can attract private investment through various financial instruments, such as equity, debt, and public-private partnerships (PPPs).

Socio-economic considerations

BECCS implementation and deployment in Africa must consider socio-economic factors, such as job creation, social acceptance, and the impact on local communities. The adoption of bioenergy technologies presents both environmental and economic opportunities and challenges. On the environmental front, bioenergy can significantly reduce greenhouse gas emissions compared to fossil fuels, particularly when using waste materials or sustainably sourced biomass [146]. However, the environmental benefits depend on the feedstock, production process, and land-use changes associated with bioenergy production [179,180]. From an economic perspective, bioenergy offers potential benefits such as job creation, rural development, and energy security. However, the high costs of some bioenergy technologies, particularly second- and third-generation biofuels, remain a barrier to widespread adoption. Continued research and development, along with supportive policies and incentives, are essential to overcoming these challenges and realizing the full potential of bioenergy [181]

Challenges and opportunities

Table *6* summarizes the key challenges to BECCS deployment in Africa, including technical, financial, and infrastructural barriers. The table also highlights opportunities for overcoming these challenges and potential policy interventions. Policy interventions are essential for creating an enabling environment for BECCS deployment. These could include financial incentives, regulatory frameworks, public education campaigns, and sustainable land management policies. By addressing these challenges and leveraging opportunities, Africa can make significant strides in adopting BECCS technology to meet its climate goals and contribute to global carbon reduction efforts.

Category	Key Challenges	Opportunities for Overcoming Challenges	Possible Policy Interventions	[Ref]
Technical	Lack of skilled personnel and expertise in BECCS technology.	Investment in education and training programs focused on BECCS technology.	Government incentives for universities and technical institutions to offer BECCS-specific training and research.	[33]
	CCS is technologically demanding and requires specialized knowledge.	Partnerships with countries/organizations with advanced CCS expertise to transfer knowledge.	Bilateral agreements for technology transfer and training programs in BECCS technology.	[9], [12]
	Lack of accurate data on CO_2 storage sites and monitoring capabilities.	Conducting detailed surveys and developing databases of suitable CO_2 storage sites.	Establish national geological data centers to map and monitor potential CO_2 storage sites.	[9], [39]
Financial	BECCS projects have high upfront costs, including technology deployment and infrastructure development.	Access to global climate funds, such as the Green Climate Fund (GCF), to support BECCS projects.	Policy frameworks that facilitate access to international climate finance and private investments in BECCS.	[22]
	Insufficient government subsidies or incentives for BECCS deployment.	Encouraging investment through public-private partnerships (PPPs) in BECCS projects.	Implement tax incentives, subsidies, and grants for companies investing in BECCS technology.	[176]
	Many African countries have limited financial resources to allocate to BECCS deployment.	Leveraging international aid and development programs focused on climate change mitigation.	Develop national strategies for BECCS that align with international donors' priorities for climate action.	[22], [24]
Infrastructural	Lack of necessary infrastructure, such as pipelines for CO_2 transport and storage facilities.	Integrating BECCS infrastructure development with existing energy and industrial projects.	National infrastructure plans that include provisions for BECCS-related projects, such as CO_2 transport and storage.	[34], [182]
	Insufficient and unstable energy grids can affect the feasibility of bioenergy projects.	Investing in grid modernization and expanding renewable energy capacity to support bioenergy projects.	Policies encouraging grid enhancements and the integration of renewable energy sources.	[183], [184]
	Challenges in sourcing, transporting, and processing biomass feedstocks.	Developing localized biomass supply chains to reduce transportation costs and enhance efficiency.	Policies promoting the development of local bioenergy supply chains and infrastructure.	[185]
Regulatory	Absence of specific regulations or standards for BECCS technology and CO_2 storage. Politicizing decarbonization.	Establishing clear, comprehensive regulations for BECCS and CCS operations.	Enactment of legislation specifically targeting BECCS, including CO_2 storage regulations and safety standards.	[186]
	Inconsistent or unstable policies can deter investment in BECCS projects.	Establishing long-term, stable policies that encourage investment in BECCS technology.	Create long-term climate action plans with dedicated BECCS goals and stable policy support.	[10]
Social and Environmental	Limited public knowledge about BECCS and potential social resistance.	Raising awareness through education campaigns about the benefits of BECCS.	Government-led public engagement strategies to increase awareness and acceptance of BECCS projects.	-
	Competition between land for bioenergy crops and food production.	Prioritizing marginal lands for bioenergy crops to avoid conflicts with food production.	Land use policies that support sustainable bioenergy production without compromising food security.	[39], [187]
	Potential negative impacts on biodiversity and ecosystems from bioenergy production.	Implementing sustainable farming practices and environmental safeguards in BECCS projects.	Environmental regulations ensuring that BECCS projects comply with sustainability criteria and protect biodiversity.	[187]

TABLE 6: Key challenges, opportunities, and possible policy interventions

BECCS, Bioenergy with Carbon Capture and Storage; CCS, carbon capture and storage

Conclusions

Building a BECCS market in Africa presents a unique opportunity to contribute to global climate goals while supporting sustainable development on the continent. However, realizing this potential requires addressing the technical, economic, policy, and social challenges specific to Africa. By leveraging its bioenergy resources and fostering collaboration at all levels, Africa can play a critical role in advancing BECCS as a viable solution for climate change mitigation.

Africa's geological formations, including deep saline aquifers, depleted oil and gas fields, and unmineable coal seams, offer significant potential for CO_2 storage. While challenges exist, the opportunities for CCS in Africa are substantial, and with the right investment and policy support, the continent could play a crucial role in global climate change mitigation efforts. Further research and development are needed to fully assess the potential of these geological formations and to overcome the technical, regulatory, and infrastructural challenges associated with CO_2 storage in Africa. To build a successful BECCS market in Africa, there is a need to strengthen policy frameworks and enhance capacity building by investing in education, training, and research to develop the technical expertise required for BECCS, and foster PPP needs to be encouraged. Africa needs to support regional initiatives that support the development of BECCS infrastructure and markets.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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