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The Potential for CO_2 Geosequestration in Kenya: A Suitability Assessment of the Lamu Basin

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ABSTRACT

There is a consensus that current trends in climate change may be due to increasing concentrations of greenhouse gases (predominantly methane and carbon dioxide) from anthropogenic emissions. Among measures proposed for curbing this increase is Carbon Capture and Sequestration (CCS) in geological media. CCS incorporates three technologies comprising; (a) carbon capture, (b) compression and transportation, and (c) injection into geological media. This paper focuses on CO_2 injection into geological media and its applicability to the Lamu basin. Sedimentary basins, which host the geological formations suitable for subsurface CO_2 storage, are ideal to varied extents determined by such factors as their tectonic settings. A (coarse) basin scale suitability assessment of the Lamu basin was undertaken using the following parameters; size and depth, tectonic and structural settings, seismicity, geothermal-hydrodynamic regimes, basin maturity (based on hydrocarbon well density) and economic resources. The assessed attributes are used to constrain GIS data, delineating possible CCS trap areas with the production of a preliminary map of potential trap areas. Also, a suitability matrix table is generated in comparison with analogous basins such as the Alberta basin in Canada. Following this assessment, the Lamu basin can be considered geologically suitable for geosequestration given its stable tectonic settings, good depth and size. However, the western flanks of the basin and the coastal strip are unsuitable due to shallowness, population and protected zones respectively.

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1. Introduction

Carbon dioxide (CO_2) has been ranked as the leading causative greenhouse gas (GHG) for current trends in climate change. The increase in its atmospheric concentrations is mainly due to industrial processes utilising fossil fuels [1]. The net emissions for any nation have been shown to be linearly related to the Gross Domestic Product (GDP) growth, population increase, the carbon intensity of the energy system and the energy intensity of the economy [2, 3] (Eq. 1). According to [4–6], fossil fuels account for 85% of current world energy and despite being high carbon intensity sources, will remain as primary energy sources over the foreseeable future.

$$NetEmission = Population * \left(\frac{GDP}{Population}\right) * \left(\frac{Energy}{GDP}\right) * \left(\frac{Emissions}{Energy}\right) - S \qquad (1)$$

As a control mechanism, the United Nations Framework Convention on Climate Change (UNFCCC) has proposed ways for adapting to and mitigating CO_2 driven climate change [6, 7]. An example is Carbon Capture and Sequestration (CCS) in terrestrial media where the CO_2 is taken up by trees and agricultural practices that limit CO_2 release, accelerated oceanic uptake where CO_2 is injected into deep ocean waters, and injection into deep geological formations. Details on the capture and transportation components of CCS are given elsewhere, e.g. [8–11]. CO_2 geosequestration involves the injection of supercritical CO_2, captured at sizeable stationary point sources, into suitable formations such as depleting or depleted hydrocarbon fields, deep coal beds and deep saline aquifers [3, 12–15]. This technology allows deep cuts to be made in net CO_2 emissions. It also secures the continued use of fossil fuels while other long-term green energy options are sought since current alternative energy sources cannot entirely replace fossil fuels [4].

A large amount of literature has been generated on the rigorous criteria and approaches for evaluating geological formations for suitability concerning CCS [2, 3, 16–23]. These methodologies are designed to prove that a geological formation has sufficient storage capacity, physical traps and injectivity required to contain the injected gas for long periods [24]–[26]. According to the International Panel on Climate Change (IPCC) report on CCS [3] "…the geological setting must be characterized to determine if the overlying cap rock will provide an effective seal, if there is a sufficiently voluminous and permeable storage formation, and whether any abandoned or active wells may compromise the integrity of the seal." The capacity required is available in the form of pore spaces while barriers include structural and stratigraphic traps similar to those in hydrocarbon reservoirs. Long-term trapping takes the form of hydrodynamic, solution and mineral trapping. Current commercial CCS projects include the In-Salah project in Algeria, the Sleipner and Snohvit projects in Norway, the Weyburn-Midale project in Canada and several other projects in the USA [3, 23, 27, 28].

There are plans to improve Kenya's installed power capacity in line with Kenya's flagship projects collectively called Vision 2030 [29]. Within the energy docket, there are plans to establish coal and natural gas-powered power plants, for example, the 960 Mw coal power plant in Kitui by 2017 (to be scaled up to 4500 Mw) by 2030 [30]. This installation will increase Kenya's net CO_2 emissions from fossil fuel use.

2. Overview of Kenya’s Sedimentary Basins

Kenya has four major sedimentary basins comprising: The Tertiary rift basins along the N-S trending Kenya rift; the Lamu basin which extends into the Indian Ocean passive margin; Anza basin which trends NW-SE within the Anza rift from Garissa to join the Melut-Muglad basins of South Sudan; and the Mandera basin which trends N-S along the Karroo rift (Fig. 1). The sedimentary basins are characteristic of failed continental rift systems with fault-bounded crustal depressions and intrabasinal faults. Most of the sedimentary basins are half graben and full graben systems with fault controlled basin infill. Detailed geological and geophysical reviews are given elsewhere, e.g., [31]–[36].

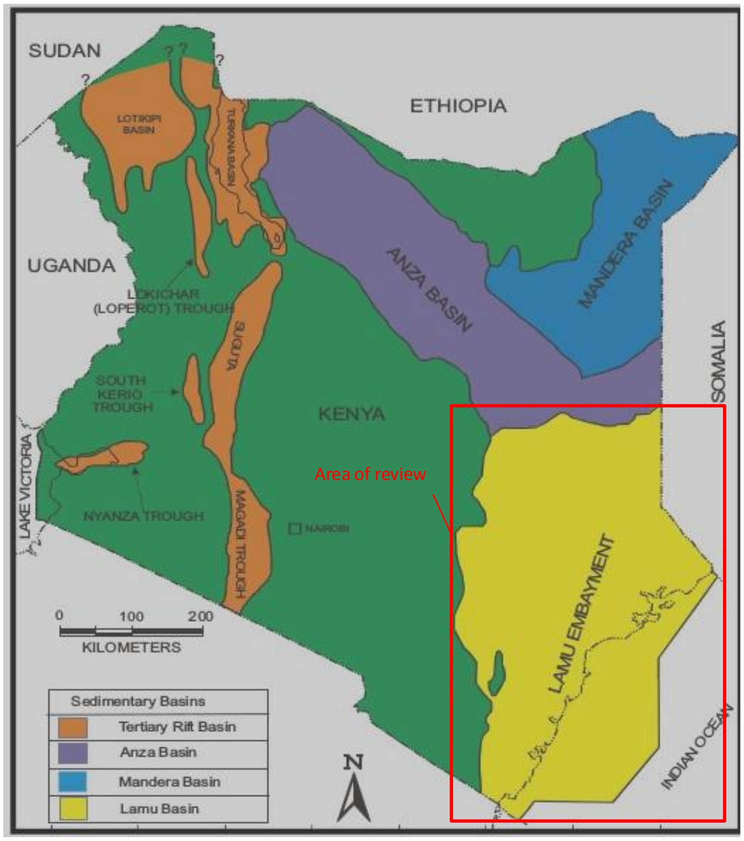

Figure 1: Simplified map of Kenya's sedimentary basins. The red box highlights the current area of investigation. *Source Nyaberi and Rop (2014).*

3. Methodology

The data presented herein were synthesized from literature covering CO_2 geosequestration, current energy developments in Kenya, environmental policies both global and local, and hydrocarbon exploration in Kenya with emphasis on the Lamu basin. The model of evaluation is a GIS-based coarse (basin-scale) suitability assessment as used in, e.g. [2, 12] and other CCS best practice manuals, e.g. [15, 19, 37, 38] using eleven-point criteria. The geological parameters used to assess the suitability of the Lamu basin comprised of the following: basin size and depth, tectonic and structural attributes, seismicity, geothermal and hydrodynamic regimes, basin maturity, and natural resources. Social and economic factors were considered for further constraining of the CCS trap areas on the land surface are population, accessibility, CO_2 point sources and public acceptance. The process chart below [Fig. 2] summarises the flow of analyses undertaken.

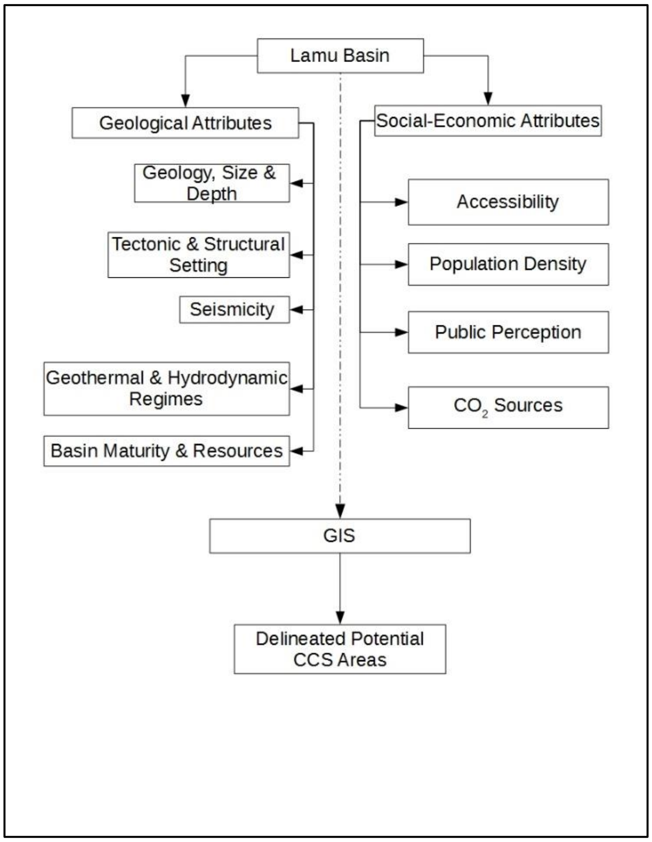

Figure 2: A flowchart for the assessment of the Lamu basin for CCS suitability.

4. Suitability Assessment of the Lamu Basin

The assessments provided in the sections below lead to the suitability scores indicated in Table 1.

Geology, Size and Depth

The Lamu basin covers a total area of 261, 000 Km^2 from Garissa north to the Indian Ocean (Fig. 1). The depth of the basin increases seaward (eastwards), from 3 Km on its western flanks to about 13 km in the marine area [39]. This areal extent and depth are conducive for CCS as it surpasses the lower depth threshold (approximated at 700m) where injected CO_2 will attain a supercritical phase to optimise storage [2]. The sediment infill ranges from Karroo which overlies the Neoproterozoic to Upper Neogene constituting the four regionally extensive Megasequences described in [39] (Fig. 3).

Potential sequences for storage of CO_2 with the requisite porosity and permeability include the Mariakani and Mazeras Sandstones, Ewaso-Kofia Sands, and Freretown, Kambe and Mtomkuu Carbonates [39–42]. The upper successions from Jurassic to Neogene are the most suitable for CO_2 injection having been described to contain good reservoir-seal paring and are within drillable depths of current technology (Fig. 3A) [40, 42]. The saline formation within the Pliocene Merti beds and the offshore Jurassic salt formation also form potential CCS trap areas [43, 44].

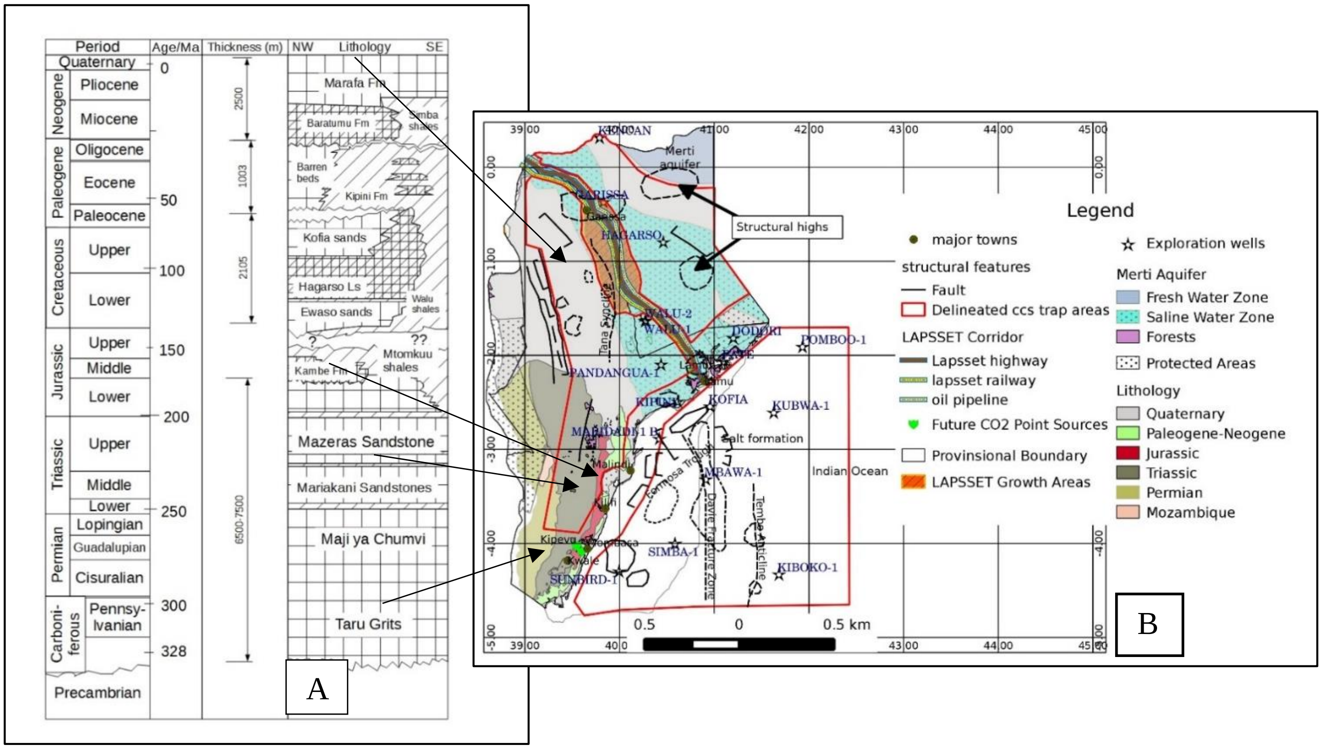

Figure 3(A) Simplified stratigraphic column of the Lamu basin from NW to SE. The representative successions are shown with unconformities separating the four megase*q*uences. Modified after [14] and [42]. Fig 3 (B) Delineated possible CCS trap areas outlined in red within the basin. The positioning of the suitable areas is relative to the constraints such as protected areas, population and development areas. The LAPSSET corridor has been digitized from maps available on the project's website. Structures and lithology have been adopted from the structural and geological map of Kenya and the GIS layers integrated using the open source Quantum GIS software.

Tectonic and Structural Setting

Sedimentary basins on stable continental crusts, on passive continental margins, and divergent margins are the most suitable for CO_2 geosequestration [2, 3, 12]. The Lamu basin occupies the passive continental margin of Kenya, and further onshore is underlain by Mozambiquan rocks [39, 41]. This setting is suitable for CO_2 storage as the created reservoirs are unlikely to be affected by events such as earthquakes common along convergent margins. The Lamu basin also has structures that are potential primary physical traps including the Walu-Kipini pinch out, roll-over faults and the inter-fingering of shales (Fig. 3). Most of the major structures have been mapped with regard to potential oil and gas reservoirs [40, 41, 43] but their consideration for CCS projects will require detailed characterisation to determine their *in situ* stress regime, failure models and ultimate reservoir performance as recommended in the best practice manuals [45–48].

Seismicity

Seismic studies in Kenya have shown that seismic events are spatially constrained within the Kenya Rift with major earthquakes (M>6) recorded in the Turkana and Subukia regions [49].

Minimal seismicity has been recorded in Lamu basin, with magnitudes ranging between I-VI on the modified Mercalli scale [50]. This low seismicity favours the basin for suitability consideration for CCS projects given that basins with high background seismicity have the risk of breach of the seal and subsequent leakages [12, 20]. However, a constraint is that the seismic network in Kenya doesn't cover well the area of review and the area needs to be connected to the Kenyan seismic network for better characterisation.

Geothermal Regime

The warm basin class of sedimentary basins [2], includes those with high surface temperatures and high geothermal gradients such as the Lamu basin. The basin has surface temperatures averaging 22-27^oC and geothermal gradients of 3^oC/100m [40]. This setting is disadvantageous as the critical temperature (T_c =31^oC) isotherm is reached at shallow depths where the CO_2 cannot attain the supercritical phase. The solution would be to inject the CO_2 to depths between 1000-1500m to optimise storage by maximising CO_2 volume stored per unit pore space. However, as has been documented elsewhere, e.g. [2], geothermal regimes are basin-specific and may vary within the same basin. To compute the basin-specific CO_2 phase-envelops, linear relation of pressure, density, and geothermal gradient has been proposed [Equation 2] [2];

$$P = \frac{\rho * g * Tb - Ts}{G} \tag{2}$$

Where P = reservoir pressure, ρ = density of water, Tb = bottom hole temperature, Ts = surface temperature and G = geothermal gradient.

Hydrodynamic Regime

The most suitable sedimentary basins for CCS are those with deep, long-range flow regimes with flow rates driven by topography. These are mainly intra-cratonic, foreland and continental basins that have undergone recent uplift and erosion [2, 12]. The flow regimes in the Lamu basin follow topography signified by, for example, the Merti aquifer which recharges in the high ground areas of Habaswein, Yamicha and Mt. Marsabit and drains into the Liboi area. A good hydrogeological analysis of northeastern Kenya is given elsewhere [44, 51]. The best injection sites for CO_2 would be areas to the northern segment of the basin near the recharge zones. This strategy will enhance the potential for hydrodynamic trapping due to increased residence time low flow rates of about 2-10 m/year [44, 52].

Basin Maturity

The maturity of a basin can be assessed by the amount of data gathered on its geology, reservoir formations and resources [12]. Exploration works in the Lamu basin are ongoing with an emphasis on hydrocarbon potential. The Lamu Basin is, however, under-explored with only 19 wells completed both onshore and offshore [30, 43]. The lack of closely-spaced calibration points is a limitation on the precise evaluation of the basin maturity.

Basin Resources

Implementation of CCS should be preceded by a thorough analysis of resident resources that may potentially be degraded by CO_2 injection or whose future extraction could lead to a breach of created reservoirs. The literature on hydrocarbon exploration in the Lamu basin indicates active petroleum play systems with gas shows and recent oil strikes warranting more research [34, 35, 39, 40, 42, 43]. There are no proven reserves for coal, but exploration has started.

Water resources include the Tiwi and Baricho aquifers and the extension of Merti aquifer. The aquifers along the coastal strip disqualify this area for consideration as CO_2 injection may enhance the saline water intrusion documented in the coastal area [53]. On the other hand, the saline water segment of the Merti aquifer has total dissolved solids (TDS) of more than 10,000 mg/l and CCS projects may not be restricted by potable water contamination issues as this water has no practical use [18, 44, 52].

Accessibility

The Lamu basin has infrastructure connecting the urban areas along the coastline while the interior areas remain underdeveloped. Apart from the physical access, insecurity challenges in the areas north on Lamu may hinder CCS projects. Kenya's Vision 2030 sub-project, the LAPSSET corridor [54], after completion will open up the Lamu basin interconnecting it with other parts in the regions through the proposed railway, road and pipeline network. This project will also connect areas with large CO_2 point sources to potential sink areas, for example, the Kitui coal plant and the proposed natural gas plant in the Anza area. Legal access to the target areas may be provided in line with legislation such as the Climate Change Bill and bodies like the Kenya Climate Change Working Group (KCCWG) [55, 56]. However, protected areas such as forests, resorts and parks along the coast will remain unavailable for CCS projects.

Public Acceptance

On the merits of the Climate Change Bill 2014 [56], the KCCWG, and other initiatives by the energy and environment ministries [30, 57, 58], public acceptance may not pose a barrier to the penetration of CCS projects. These initiatives are enhancing public participation in climate change matters, and the public perception of CCS may be positive.

Population Distribution

According to [59] population distribution in the coastal region is disproportionate with urban areas being highly populated (>250 persons/Km^2) while remote areas are lowly populated (<100 persons/Km^2). CCS projects are required to be carried out away from highly populated areas to ensure public safety should leakages occur [3]. As such, the coastal strip is unsuitable for CCS while the interior areas and the offshore present suitable exploratory CCS trap areas.

CO_2 Point Sources

The current major point sources within the Lamu basin include cement factories, oil refineries and steel plants, and all of these are located on the coastal strip. The proposed fossil fuel power plants are to be situated in the basin with three in Lamu and three in Mombasa [29, 30], again in the coastal strip which means that the issue of high population density may render them unsuitable unless deeply seated and well-confined traps can be located in these areas. In such cases, these point sources will facilitate source-sink matching, and their proximity to potential sinks would reduce transportation costs for CCS projects.

Table 1: Suitability assessment of the Lamu basin outlining desired characteristics against those of the Lamu basin and the relative score (1 -poor, 2 - average, 3 - good).

S/N	CRITERIA	CHARACTERISTICS FOR SUITABILITY	CHARACTERISTICS OF LAMU	SCORE FOR SUITABILITY
1.	Geology, Size and Depth	• Porous and permeable successions • Low permeability sealing units • Large basin • At least 700m	• Karroo to Quaternary sandstones and carbonates • 261000 Km^2 • 3-13Km of sediment infill	3
2.	Tectonic and Structural Setting	• Divergent basins • Extensive structural and stratigraphic traps	• Passive continental margin • Divergent rift basin	2
3.	Seismicity	• Low background seismicity	• Low background seismicity, magnitude <5	3
4.	Geothermal Regime	• Cold basins (low surface temperature and low geothermal gradient)	• Warm basin (high surface temperatures, 22-27 ^{0}C, thermal gradient = 30 ^{0}/Km)	1
5.	Hydrodynamic Regime	• Erosional rebound driven long-range flow systems • No cross-formational flow	• Regional flows from the Mt. Marsabit areas towards the Indian Ocean (topography driven)	2
6.	Basin Maturity	• Mature basin (fully explored) • Developed infrastructure	• Immature (underexplored, exploration in progress)	1
7.	Basin Resources	• Oil and gas, coals and salt beds	• Unproven resources • Good leads so far • Offshore salt beds	2
8.	Accessibility	• Physical and legal accessibility during the projects' lifetime	• There is an indication of future accessibility, both physical and legal • Restricted areas (e.g. parks, forests) along the coast • Insecure areas on the northern part and along the border with Somalia	1
9.	Public Acceptance	• Receptive society towards implementation of CCS projects	• There are efforts by stakeholders to increase public awareness and acceptance	1
10.	Population Distribution	• Low population density	• Disproportionate distribution of population • Urban areas and the coastal strip are highly populated	2
11.	CO_2 Point Sources	• Major CO_2 point sources	• Proposed fossil fuel power plants and petrochemical plants • Existing cement factory, steel plants and oil refinery	1

5. Conclusions

The Lamu basin has been shown to possess both intrinsic and extrinsic properties that qualify it as suitable for carbon capture and storage projects. The regionally extensive sedimentary sequences with depth imply large enough reservoirs that will sufficiently accommodate injected CO_2. The sequences have been characterized as having good porosities and reservoir-seal pairing. The western margin of the basin where the Karroo rocks terminate against the Mozambique Belt is shallow and highly faulted, thus unsuitable for CO_2 sequestration. As the depth increases seawards, more suitable areas are in the central basin and the offshore segment. The Lamu Basin also has a stable tectonic configuration which is ideal for long-term CO_2 storage where created reservoirs are not prone to tectonic disturbances which might breach the seals.

The geothermal gradient is high, but as indicated in earlier sections, there is a need to carry out accurate thermal mapping to derive the basin-specific CO_2-phase envelops. Further, detailed characterisation within the delineated areas is required to determine the stress regimes and magnitudes of background seismicity. As more data becomes available, simulations may be done regarding failure mechanisms and the fate of injected CO_2.

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