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To develop a geology-driven screening and ranking methodology for prioritizing global prospect areas suitable for combined co_2 sequestration and geothermal energy production

By

Uwaoma, Blessing Ugoeze[1], Onyekuru Samuel Okechukwu[2], Enyioko Nzenwa Dan[3], Nwadike Cynthia B.N[4] and Michael Simeon Chisom[5]

[1]Department of Civil Engineering, Abia state Polytechnic, Aba, Nigeria
[2-4]Department of Geology, Federal University of Technology, Owerri, Nigeria
[5]Department of Mechanical Engineering, Abia state Polytechnic, Aba, Nigeria.

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Abstract

This study develops a geology-driven screening and ranking methodology for prioritizing global prospect areas suitable for combined carbon dioxide (CO_2) sequestration and geothermal energy production. Geological CO_2 storage is widely recognized as an essential climate mitigation technology, while geothermal energy represents a reliable, low-carbon, and dispatchable energy source. Increasing interest in integrated subsurface utilization has highlighted the potential to use injected CO_2 not only as a stored greenhouse gas but also as a working fluid for geothermal heat extraction. However, geological conditions that ensure long-term CO_2 containment and those that enable viable geothermal energy production do not always coincide, creating a critical need for systematic, integrated site-selection methodologies.

To address this challenge, a tiered, geology-first screening framework is developed that treats storage security as a non-negotiable constraint and geothermal potential as a graded attribute. The methodology integrates geological containment and trapping theory, geothermal reservoir and sustainability theory, coupled subsurface utilization concepts, and multi-criteria decision analysis (MCDA). Prospect areas are evaluated using four interacting domains: CO_2 storage suitability, geothermal energy potential, risk and monitoring feasibility, and enabling factors. Fatal-flaw screening is applied to eliminate geologically unsuitable settings, followed by basin-scale and prospect-scale evaluation using standardized scoring and normalization procedures. Weighted aggregation within an MCDA framework produces composite suitability indices and ranked prospect lists. Uncertainty and sensitivity analyses are incorporated to test ranking robustness and identify data gaps.

The methodology generates basin-scale suitability classifications, prospect-level rankings, domain-specific score profiles, and shortlists of robust candidates for detailed appraisal. The framework is transferable across geological settings and supports transparent, reproducible, and defensible decision-making. By providing a unified geological basis for identifying prospects capable of delivering both long-term CO_2 storage and geothermal energy production, this study contributes a practical tool for advancing integrated subsurface energy and storage systems in support of global decarbonization.

Keywords: *CO_2 sequestration; geothermal energy; integrated subsurface systems; screening and ranking methodology; geology-driven framework; MCDA; site prioritization.*

1.0 INTRODUCTION

The accelerating pace of global climate change and its associated environmental, economic, and societal consequences has intensified the global search for mitigation strategies capable of achieving substantial reductions in anthropogenic greenhouse gas emissions. Carbon dioxide (CO_2) remains the dominant greenhouse gas driving global warming due to its high emission volume, long atmospheric lifetime, and strong radiative forcing effect (IPCC, 2022).

*Corresponding Author: Uwaoma, Blessing Ugoeze

Major anthropogenic sources of CO_2 include fossil-fuel combustion for electricity generation, transportation, cement and steel manufacturing, and petrochemical industries (Bui et al., 2018). Although renewable energy technologies such as solar and wind have expanded rapidly, global energy demand continues to rise, and fossil fuels still constitute a large proportion of the world's energy mix (IEA, 2023). Consequently, achieving deep decarbonization while sustaining energy security presents a profound scientific and technological challenge.

Carbon capture and storage (CCS), and more broadly carbon capture, utilization, and storage (CCUS), has emerged as a critical mitigation option for reducing emissions from large stationary sources. CCS involves capturing CO_2 at the point of generation, compressing and transporting it, and injecting it into suitable geological formations for long-term isolation from the atmosphere (Bui et al., 2018). The Intergovernmental Panel on Climate Change identifies CCS as an essential component of many mitigation pathways compatible with limiting global temperature rise to below 2°C and pursuing 1.5°C targets (IPCC, 2022). Large-scale deployment of CCS has been demonstrated in several countries, confirming the technical feasibility of injecting and storing CO_2 in deep saline aquifers and depleted oil and gas reservoirs under appropriate conditions (IEAGHG, 2017).

At the same time, the global energy transition requires reliable, low-carbon, and dispatchable energy sources to complement intermittent renewables. Geothermal energy provides a continuous supply of electricity and direct-use heat with low life-cycle emissions and minimal surface footprint (Randolph & Saar, 2011). Traditionally, geothermal development has focused on volcanic and tectonically active regions where high temperatures occur at shallow depths. However, recent advances in drilling technology, subsurface imaging, and reservoir characterization have expanded geothermal exploration into sedimentary basins and mature petroleum provinces (Randolph & Saar, 2013).

An important conceptual advancement in subsurface energy systems is the recognition that geological formations suitable for CO_2 storage may also possess characteristics favorable for geothermal energy extraction. This realization has led to the development of the CO_2-Plume Geothermal (CPG) concept, in which injected CO_2 acts both as a stored greenhouse gas and as a working fluid for heat extraction (Gupta, 2016). Compared with water, CO_2 has lower viscosity and higher mobility under reservoir conditions, which can enhance circulation and potentially improve heat recovery efficiency (Randolph & Saar, 2011).

The integration of CO_2 sequestration and geothermal energy production offers multiple advantages. Geothermal co-production can offset some operational costs of CCS, thereby improving overall project economics (Gupta, 2016). In addition, combined systems maximize the societal value of subsurface pore space by delivering both climate mitigation and clean energy (Randolph & Saar, 2013). Nevertheless, not all geological settings that are suitable for CO_2 storage are capable of supporting geothermal production, and not all geothermal reservoirs provide adequate containment for long-term CO_2 sequestration. Storage-favorable geology does not automatically imply geothermal viability, and vice versa.

Therefore, the fundamental scientific challenge is to identify where the geological requirements for secure CO_2 storage and viable geothermal energy production overlap. Existing screening frameworks generally address CCS and geothermal systems independently (NETL, 2017; ISO, 2017). There is presently a lack of globally applicable methodologies that integrate both objectives within a single geology-driven screening and ranking framework.

This study addresses this gap by developing a geology-driven screening and ranking methodology for prioritizing global prospect areas suitable for combined CO_2 sequestration and geothermal energy production. The methodology adopts a tiered approach, beginning with basin-scale screening, progressing through prospect-scale evaluation, and culminating in multi-criteria decision analysis (MCDA) ranking supported by uncertainty and sensitivity analysis (Malczewski, 2006). By grounding the framework in geological principles and internationally recognized best practices, the study aims to provide a transparent and transferable basis for global prospect prioritization.

Geological storage of CO_2 has been investigated extensively over the past three decades as a means of achieving long-term isolation of anthropogenic CO_2 from the atmosphere. Global assessments indicate that deep saline aquifers alone possess storage capacities of several thousand gigatonnes, which is sufficient to accommodate a large fraction of projected future emissions (OECD/IEA, 2022). Depleted oil and gas reservoirs represent additional attractive storage targets because they have demonstrated hydrocarbon containment over geological timescales and are commonly supported by extensive subsurface datasets (IEAGHG, 2017).

The suitability of a geological formation for CO_2 storage is controlled by several key factors, including reservoir porosity and permeability, net thickness, lateral continuity, depth, pressure-temperature conditions, seal lithology and integrity, and structural configuration (Ringrose, 2020). After injection, CO_2 is retained by a combination of trapping mechanisms, including structural trapping, residual (capillary) trapping, solubility trapping, and mineral trapping. Among these, capillary trapping plays a particularly important role in immobilizing CO_2 shortly after injection ceases, thereby enhancing storage security (Krevor et al., 2015).

International standards and best-practice documents have been developed to guide site screening, selection, and operation of CO_2 storage projects. ISO 27914:2017 outlines requirements and recommendations for geological storage aimed at ensuring long-term containment and risk minimization (ISO, 2017). Similarly, the NETL best-practice manual provides a structured workflow for progressing from regional screening to site selection and characterization (NETL, 2017).

*Corresponding Author: Uwaoma, Blessing Ugoeze

In parallel, geothermal energy research has evolved from a focus on volcanic systems to include sedimentary basin geothermal resources. Basin geothermal systems are typically characterized by moderate geothermal gradients but large areal extent, making them suitable for direct-use heat and, in some cases, electricity generation. The viability of geothermal development depends primarily on temperature at depth, reservoir transmissivity, and thermal sustainability (Randolph & Saar, 2013). Basin thermal state studies, such as those conducted in the Niger Delta, demonstrate that geothermal gradients vary significantly due to burial history, sedimentation rate, and fluid flow (Akpabio et al., 2011).

The conceptual integration of CCS and geothermal energy arose from recognition that many deep sedimentary formations targeted for CO_2 storage also exhibit elevated temperatures. Randolph and Saar (2011) demonstrated that CO_2 could function effectively as a geothermal working fluid in permeable formations, enabling heat extraction even in regions lacking conventional hydrothermal systems. Gupta (2016) further described the CPG concept as a new pathway for combined geothermal energy production and geologic storage.

Despite these advances, practical implementation of combined CO_2–geothermal systems remain limited. One major limitation is the absence of systematic tools for identifying and ranking suitable geological settings at regional to global scales. Existing CCS screening frameworks prioritize containment and capacity, whereas geothermal assessments focus on temperature and transmissivity. Few methodologies explicitly evaluate compatibility between these two sets of requirements.

Risk considerations further complicate combined system deployment. CO_2 storage projects must demonstrate low leakage risk, minimal impact on groundwater, and acceptable induced seismicity risk (Zoback & Gorelick, 2012). Geothermal operations introduce additional risks related to scaling, corrosion, and reservoir cooling. In combined systems, these risks interact and must be assessed together rather than independently.

Accordingly, there is a strong scientific and practical motivation to develop a unified, geology-driven screening and ranking framework that integrates CO_2 storage criteria, geothermal energy criteria, and risk considerations while accounting for data uncertainty. Such a framework would enable governments, industry, and researchers to focus detailed appraisal efforts on the most promising prospect areas, thereby accelerating deployment and reducing project failure rates.

1.2 PROBLEM STATEMENT

Despite significant advances in carbon capture and storage (CCS) technologies and increasing global recognition of geothermal energy as a reliable low-carbon resource, the practical integration of these two subsurface utilization pathways remains limited and poorly systematized. Current global deployment of CCS is far below the scale required to meet climate mitigation targets, largely due to high costs, long project development timelines, regulatory complexity, and public acceptance challenges (Bui et al., 2018; IPCC, 2022). Similarly, although geothermal energy is technically mature in certain high-enthalpy regions, its expansion into sedimentary basins and non-volcanic settings has progressed more slowly than anticipated, despite large theoretical resource potential (Randolph & Saar, 2013).

A central challenge is that existing site selection and screening methodologies treat CCS and geothermal systems largely as independent technologies. CCS screening frameworks prioritize geological containment, storage capacity, injectivity, and pressure management (NETL, 2017; ISO, 2017), whereas geothermal assessment methodologies focus primarily on temperature at depth, geothermal gradient, and reservoir transmissivity (Randolph & Saar, 2011). As a result, there is no widely accepted methodology that systematically evaluates whether a geological formation can simultaneously satisfy the requirements for safe long-term CO_2 storage and viable geothermal energy production.

This separation in assessment approaches has several consequences. First, formations that may be highly attractive for geothermal energy may be prematurely dismissed for CCS due to perceived containment risks, while formations ideal for storage may never be evaluated for geothermal potential. Second, opportunities for value co-production, where geothermal energy offsets part of CCS operational costs, are frequently overlooked. Third, limited resources for detailed site appraisal may be expended on prospects that ultimately prove incompatible with combined utilization, thereby increasing project failure rates and development costs.

Another critical problem is the strong spatial variability of geological conditions across and within sedimentary basins. Reservoir quality, seal integrity, fault architecture, thermal regime, and stress state can vary significantly over short distances (Ringrose, 2020). Consequently, qualitative or generalized assessments at basin scale are insufficient for identifying specific prospect areas suitable for combined applications. A structured, prospect-scale screening and ranking methodology that is anchored in geology is therefore required.

Data availability and quality present additional challenges. In many regions, subsurface datasets are sparse, inconsistent, or of variable reliability, particularly outside mature petroleum provinces. Without a framework that explicitly incorporates data-quality classification and uncertainty, screening results may convey a false sense of precision and lead to misguided decision-making (Malczewski, 2006). Therefore, an effective methodology must not only rank prospects but also communicate confidence levels and identify critical data gaps.

Risk considerations further compound the problem. CO_2 injection alters subsurface pressure conditions and can, under certain circumstances, induce seismicity or reactivate faults (Zoback & Gorelick, 2012). Geothermal circulation can similarly influence reservoir pressure and temperature fields. In combined systems, these effects interact, making it

*Corresponding Author: Uwaoma, Blessing Ugoeze

essential to evaluate geomechanical stability, fault transmissivity, and pressure management in an integrated manner. Existing frameworks do not adequately address these coupled risks.

In summary, there is presently no globally applicable, geology-driven, and risk-aware screening and ranking methodology that integrates CO_2 storage suitability, geothermal energy potential, and uncertainty into a unified decision-support framework. This methodological gap limits the ability of policymakers, industry, and researchers to efficiently identify and prioritize prospect areas for combined CO_2 sequestration and geothermal energy production. Addressing this gap forms the central problem that this research seeks to solve.

1.3. SIGNIFICANCE AND JUSTIFICATION OF STUDY

The significance of this study arises from its direct response to two of the most pressing global challenges of the twenty-first century: climate change mitigation and sustainable energy supply. Anthropogenic CO_2 emissions continue to increase globally, and current mitigation efforts remain insufficient to meet internationally agreed climate targets (IPCC, 2022). Carbon capture and storage (CCS) has been identified as an indispensable component of deep decarbonization pathways, particularly for industrial sectors where emissions are difficult to eliminate through electrification or fuel switching (Bui et al., 2018). However, the large-scale deployment of CCS is constrained by high costs, long development timelines, and uncertainties associated with site selection and long-term performance. By proposing a methodology that explicitly integrates geothermal energy production with CO_2 sequestration, this study addresses a critical barrier to CCS deployment: project economics.

Geothermal co-production offers the potential to generate electricity or useful heat from the same subsurface system used for CO_2 storage. This additional energy output can offset operational costs associated with injection, monitoring, and maintenance, thereby improving the financial viability of CCS projects (Gupta, 2016; Randolph & Saar, 2013). The significance of this study therefore lies in its potential to support economically sustainable CCS deployment by transforming storage sites into dual-purpose assets that provide both climate mitigation and energy supply.

From a scientific perspective, this research contributes to the emerging field of integrated subsurface energy systems. Most existing studies evaluate CCS and geothermal resources independently, using different conceptual frameworks and assessment criteria (NETL, 2017; ISO, 2017). By developing a unified, geology-driven screening and ranking methodology, this study advances scientific understanding of how geological parameters simultaneously control storage security and geothermal productivity. The framework formalizes compatibility relationships between reservoir properties, seal integrity, thermal regime, and geomechanical conditions, thereby providing a more holistic interpretation of subsurface system behavior.

The study is also significant in terms of methodological innovation. The integration of geological screening with multi-criteria decision analysis (MCDA) introduces a transparent and reproducible approach to prospect prioritization (Malczewski, 2006). By incorporating uncertainty and sensitivity analysis, the methodology moves beyond deterministic ranking toward probabilistic and robustness-based decision support. This is particularly important for global-scale assessments, where data quality and coverage vary widely. The resulting framework enables decision-makers to distinguish between genuinely high-potential prospects and those that merely appear attractive due to data gaps or optimistic assumptions.

From a technological standpoint, the study supports the development of novel geothermal concepts such as the CO_2-Plume Geothermal (CPG) system. Although CPG has been demonstrated conceptually and through numerical modeling (Randolph & Saar, 2011; Gupta, 2016), its practical deployment requires systematic identification of suitable geological settings. This research provides the foundational screening tool necessary to move CPG from conceptual studies toward pilot-scale and commercial applications.

The justification for this study is further strengthened by its relevance to policy and strategic planning. National governments and international organizations are increasingly developing CCS roadmaps and geothermal development strategies (IEA, 2023; OECD/IEA, 2022). However, these strategies often lack integrated guidance on where combined projects should be prioritized. A geology-driven global screening methodology offers policymakers an objective basis for allocating funding, selecting demonstration sites, and designing incentive structures that encourage integrated subsurface utilization.

In addition, the study has important environmental and societal significance. Secure geological storage of CO_2 reduces atmospheric emissions and mitigates climate change, while geothermal energy provides clean, reliable power with minimal land-use footprint. Combined systems therefore contribute to environmental protection, energy security, and sustainable development. By reducing reliance on fossil-fuel-based power generation, such systems also have the potential to improve air quality and public health outcomes.

Finally, this research is justified by the need to maximize the value of existing subsurface data and infrastructure, particularly in mature petroleum basins. Many regions possess extensive well, seismic, and production datasets that can be repurposed for combined CO_2–geothermal assessments. A systematic screening and ranking framework enables efficient utilization of these data, reducing duplication of effort and accelerating project development.

In summary, this study is significant because it provides a scientifically rigorous, economically relevant, and policy-relevant framework for identifying geological settings where combined CO_2 sequestration and geothermal energy production are most plausible. It is justified by the urgent need to scale up CCS, expand geothermal energy deployment,

*Corresponding Author: Uwaoma, Blessing Ugoeze

and develop integrated subsurface solutions that support a sustainable low-carbon future.

1.4 SCOPE OF THE STUDY

This study focuses on the development of a geology-driven screening and ranking methodology for prioritizing global prospect areas suitable for combined CO_2 sequestration and geothermal energy production. The scope is primarily methodological and conceptual, rather than site-specific implementation. The research is concerned with establishing a transferable framework that can be applied across different geological settings worldwide, rather than performing detailed feasibility studies for individual sites.

Spatially, the study operates at multiple scales. At the broadest level, global sedimentary basins constitute the primary domain of investigation, because they host the majority of potential CO_2 storage capacity and are increasingly recognized as viable targets for basin-centered geothermal development (OECD/IEA, 2022; Randolph & Saar, 2013). Within these basins, the methodology is designed to progressively narrow down from basin-scale screening to prospect-scale evaluation of specific reservoir–seal pairs. The framework is therefore applicable to a wide range of geological contexts, including passive margin basins, intracratonic basins, rift basins, foreland basins, and mature petroleum provinces.

Thematically, the study encompasses three main domains: (i) geological controls on CO_2 storage suitability, (ii) geological and thermal controls on geothermal energy production, and (iii) risk and monitoring considerations relevant to combined operations. Storage-related aspects include reservoir quality, depth, pressure–temperature conditions, seal integrity, structural configuration, trapping mechanisms, and geomechanical stability (Ringrose, 2020; ISO, 2017). Geothermal-related aspects include temperature at depth, geothermal gradient or heat-flow proxies, reservoir transmissivity, and thermal sustainability (Randolph & Saar, 2011; Randolph & Saar, 2013). Risk-related aspects include fault transmissivity, legacy well density and integrity, induced seismicity susceptibility, and monitoring feasibility (Gilliland et al., 2013; Zoback & Gorelick, 2012).

Methodologically, the study is restricted to screening- and ranking-level analysis. It does not attempt to perform detailed reservoir simulation, coupled thermo-hydro-mechanical-chemical (THMC) modeling, or full techno-economic optimization for specific sites. Instead, it establishes a tiered workflow that identifies which prospect areas warrant such detailed studies. The ranking is based on multi-criteria decision analysis (MCDA), incorporating normalized scores, weighting scenarios, and uncertainty treatment (Malczewski, 2006).

The scope of this study also includes the identification of minimum datasets required at each screening tier and the classification of data quality. However, the acquisition of new field data, such as drilling new wells, conducting seismic surveys, or performing injection tests, is outside the scope of this work. The methodology assumes that users will rely on existing geological, geophysical, and well datasets, supplemented where necessary by targeted data acquisition in later project phases.

In terms of application, the study is not limited to a specific country or basin. While examples and conceptual discussions may draw from sedimentary basin analogs worldwide, the framework is intended to be globally applicable. The study also does not prescribe specific regulatory regimes or economic incentive structures, recognizing that these vary significantly between jurisdictions. Instead, regulatory readiness and enabling factors are treated as contextual inputs within the broader screening framework.

Finally, the study does not aim to design surface geothermal power plants, CO_2 capture facilities, or transport networks. These engineering and infrastructure components are recognized as critical for project success but are considered downstream of geological suitability. The present research therefore, confines itself to subsurface geological feasibility and early-stage prospect prioritization.

In summary, the scope of this study is limited to the development of a transferable, geology-driven screening and ranking methodology for combined CO_2 sequestration and geothermal energy production at global to prospect scale. Detailed site characterization, numerical simulation, and economic design are intentionally beyond the scope and are envisioned as follow-on activities for high-ranked prospects identified using the proposed framework.

2.0 LITERATURE REVIEW

The literature relevant to this study spans several interrelated domains, including carbon capture and geological sequestration, geothermal energy systems in sedimentary basins, integrated CO_2–geothermal concepts, geological screening and site selection methodologies, and decision-support frameworks for subsurface resource prioritization. This section critically reviews these bodies of work with emphasis on identifying key findings, methodological approaches, and gaps that justify the development of a geology-driven screening and ranking framework for combined CO_2 sequestration and geothermal energy production.

2.1 THEMATIC REVIEW OF CO_2 SEQUESTRATION STUDIES

Research on carbon capture and geological sequestration (CCS) has evolved from early conceptual feasibility studies to advanced investigations of storage security, monitoring strategies, and long-term system behavior. This body of literature establishes the scientific and technical foundation upon which combined CO_2 sequestration and geothermal energy production concepts are built.

Early assessments of CCS emphasized the enormous theoretical storage capacity available in deep geological formations. Global-scale evaluations indicated that deep saline aquifers, depleted oil and gas reservoirs, and certain coal seams possess sufficient pore volume to store hundreds to thousands of gigatonnes of CO_2, exceeding projected cumulative emissions over the coming century (IEA, 2023; OECD/IEA, 2022). These findings positioned geological storage as the only mitigation option capable of delivering emission reductions at the scale required for climate stabilization.

Subsequent studies shifted attention from capacity alone to the conditions required for safe and effective storage. Bui et al. (2018) synthesized advances in capture technologies, transport infrastructure, and storage engineering, highlighting that storage site performance is primarily controlled by geological characteristics rather than surface facilities. They emphasized that reservoir porosity and permeability, seal integrity, depth, and pressure-temperature conditions are the most critical parameters governing storage feasibility.

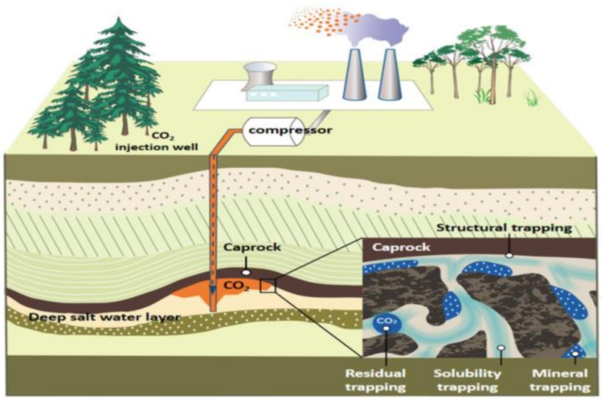

Fig.2.1 trapping mechanisms hierarchy

The development of international standards and best-practice guidelines reflects maturation of the field. ISO 27914:2017 establishes requirements and recommendations for geological storage, including site selection, characterization, risk assessment, monitoring, and closure, with a strong emphasis on long-term containment (ISO, 2017). Similarly, the NETL best-practice manual provides a staged workflow for site screening, site selection, and site characterization, emphasizing early identification of fatal flaws that could compromise storage integrity (NETL, 2017).

A major theme in CCS research concerns trapping mechanisms and their role in long-term security. Structural and stratigraphic trapping initially confine injected CO_2 beneath impermeable seals, while residual (capillary) trapping immobilizes CO_2 as disconnected ganglia within pore spaces. Krevor et al. (2015) demonstrated that capillary trapping occurs rapidly following injection and can significantly reduce plume mobility, thereby enhancing containment. Over longer timescales, dissolution of CO_2 into formation brines and mineral trapping further stabilize stored CO_2.

Another important theme is pressure management. Injection of large volumes of CO_2 inevitably increases pore pressure, which can reduce effective stress and potentially reactivate pre-existing faults. Zoback and Gorelick (2012) argued that induced seismicity represents one of the most significant risks associated with large-scale CO_2 storage, particularly in tectonically stressed regions. Their work emphasizes the need for conservative pressure limits, careful fault characterization, and geomechanical screening during site selection.

Monitoring, reporting, and verification (MRV) has also received extensive attention. Gilliland et al. (2013) reviewed monitoring techniques for carbon storage projects and concluded that monitoring strategies must be tailored to site-specific risk pathways. Commonly applied techniques include pressure and temperature monitoring, well integrity testing, time-lapse seismic imaging, and geochemical sampling. Effective MRV is essential for demonstrating storage security to regulators and the public.

Depleted oil and gas reservoirs have been widely studied as storage targets due to their proven trapping behavior and extensive datasets. Case studies compiled by IEAGHG (2017) demonstrate successful injection and containment in such reservoirs, but also highlight challenges related to legacy wells and complex infrastructure. Saline aquifers, in contrast, often have fewer penetrations and potentially larger capacity but greater uncertainty due to limited characterization (Ringrose, 2020).

Collectively, the CO_2 sequestration literature establishes a clear set of geological criteria for storage suitability: adequate depth for dense-phase CO_2, sufficient reservoir pore volume and injectivity, competent and continuous seals, manageable pressure conditions, and low-risk fault and well configurations. However, these studies generally evaluate storage suitability in isolation and do not consider the potential for co-production of geothermal energy.

This thematic review demonstrates that while the geological basis for secure CO_2 storage is well established, existing frameworks do not assess whether storage-suitable formations also possess the thermal and hydraulic characteristics required for geothermal energy extraction. This limitation provides a direct justification for integrating CCS screening criteria with geothermal evaluation within a unified geology-driven framework.

2.2 THEMATIC REVIEW OF GEOTHERMAL ENERGY STUDIES

Geothermal energy has long been recognized as a reliable and low-carbon energy resource capable of providing continuous electricity generation and direct-use heat. Early geothermal research and development focused predominantly on high-enthalpy hydrothermal systems associated with volcanic arcs, rift zones, and tectonically active regions where high temperatures occur at shallow depths. In such settings, naturally occurring permeability and circulating fluids enable economic exploitation with relatively shallow drilling. However, these classical geothermal provinces represent only a small fraction of global geological environments, motivating increased interest in geothermal potential within sedimentary basins and other non-volcanic settings.

*Corresponding Author: Uwaoma, Blessing Ugoeze

A central theme in geothermal research is the control of temperature at depth. Temperature is governed by geothermal gradient, regional heat flow, thermal conductivity of rocks, and advective heat transport by fluids. Studies demonstrate that sedimentary basins commonly exhibit moderate geothermal gradients, but large sediment thickness and widespread lateral continuity can result in substantial heat-in-place resources (Akpabio et al., 2011). Basin thermal regime is strongly influenced by burial history, sedimentation rate, radiogenic heat production, and fluid flow pathways, leading to significant spatial variability even within the same basin.

Another dominant theme is the importance of reservoir transmissivity. Commercial geothermal systems require sufficient permeability and thickness to allow sustainable fluid circulation at economic flow rates. In sedimentary basins, permeability is primarily controlled by depositional facies, diagenetic processes such as cementation and dissolution, and structural features including faults and fractures. Randolph and Saar (2013) emphasized that geothermal viability in sedimentary basins depends not only on temperature but also on the ability to circulate fluids without excessive pressure drawdown or thermal breakthrough.

Thermal sustainability represents an additional critical theme. Sustainable geothermal development requires that heat extraction rates be balanced by conductive and advective heat replenishment from surrounding rocks. Early-stage geothermal assessments often rely on volumetric heat-in-place calculations and temperature-depth relationships, while advanced studies employ coupled fluid-flow and heat-transport modeling to evaluate long-term performance (Randolph & Saar, 2013). These studies highlight that high initial temperatures alone do not guarantee sustainable energy production.

Geochemical and petrological processes form another important research theme. Geothermal fluids interact with reservoir rocks, leading to mineral dissolution and precipitation that can alter porosity and permeability over time. Reyes (2015) reviewed mineral alteration patterns in geothermal systems and demonstrated that such processes can significantly influence reservoir performance, scaling, and corrosion. Although geochemical effects are often considered during later stages of geothermal project development, their implications reinforce the importance of understanding reservoir lithology and diagenetic history during early screening.

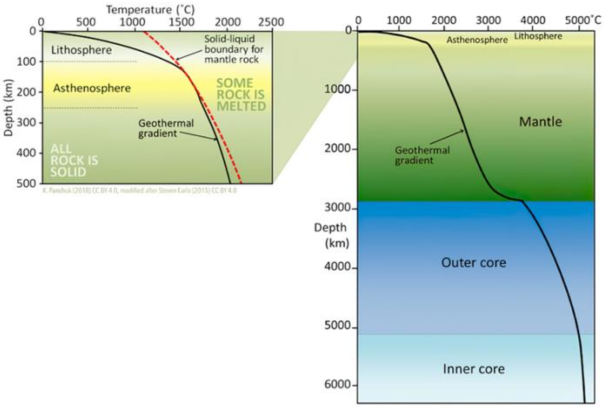

Fig.2.2 Reinforces geothermal theory & basin variability

In recent years, attention has expanded toward unconventional geothermal concepts, including enhanced geothermal systems (EGS) and basin-centered geothermal systems. These approaches aim to exploit heat in regions lacking natural hydrothermal circulation by creating or enhancing permeability through stimulation or by leveraging existing sedimentary basin permeability. While EGS research has demonstrated technical feasibility, induced seismicity and high stimulation costs remain major concerns. Basin-centered geothermal systems, in contrast, emphasize utilization of naturally permeable formations, aligning more closely with geological settings targeted for CO_2 storage.

A particularly important advancement in geothermal research is the proposal to use CO_2 as an alternative working fluid. Randolph and Saar (2011) demonstrated that CO_2 possesses thermophysical properties—such as lower viscosity and higher expansivity than water under reservoir conditions—that may improve circulation efficiency and heat extraction. This work laid the foundation for the CO_2-Plume Geothermal (CPG) concept, which directly links geothermal energy production with geological CO_2 storage.

Despite substantial progress, the geothermal literature reveals several limitations. Most geothermal assessments focus on thermal and hydraulic properties without explicitly considering long-term containment of injected fluids, which is central to CCS. Moreover, geothermal screening methodologies are rarely integrated with storage-oriented site selection frameworks. As a result, there is limited guidance on identifying geological settings where geothermal productivity and storage security coexist.

In summary, geothermal research has established clear geological controls on temperature, transmissivity, sustainability, and geochemical behavior. However, these studies generally evaluate geothermal potential in isolation. The absence of integrated screening approaches that consider both geothermal and CO_2 storage requirements highlights a critical gap that this research seeks to address.

*Corresponding Author: Uwaoma, Blessing Ugoeze

2.3 THEMATIC REVIEW OF INTEGRATED CO_2–GEOTHERMAL STUDIES

Integrated CO_2–geothermal studies represent an emerging research domain that bridges two historically separate subsurface technologies: geological CO_2 sequestration for climate mitigation and geothermal energy extraction for low-carbon power/heat supply. The central premise of this literature is that deep geological formations can be managed as multi-purpose subsurface assets, where injected CO_2 is not only stored but can also serve as a heat-transport medium capable of delivering useful thermal energy to the surface. This theme has gained traction because it offers a pathway to improve CCS economics, accelerate deployment through co-benefits, and expand geothermal utilization beyond traditional volcanic provinces (Randolph & Saar, 2011; Gupta, 2016).

A foundational contribution in this field is the introduction of the CO_2-Plume Geothermal (CPG) concept. Randolph and Saar (2011) provided early quantitative demonstration that CO_2 can function effectively as a geothermal working fluid in deep permeable formations. Their work emphasized key thermophysical advantages of CO_2 relative to water under reservoir conditions, including lower viscosity (supporting mobility), favorable density–temperature relationships (supporting buoyancy-driven circulation), and potential improvements in heat extraction efficiency in appropriately configured reservoir–well systems (Randolph & Saar, 2011). This early work was important because it reframed CO_2 storage formations—previously treated mainly as "sinks"—into dual-function reservoirs with potential economic value. Randolph and Saar (2013) further extended the concept by evaluating geothermal energy production at geologic CO_2 sequestration sites, reinforcing the idea that co-production can be designed in a way that remains compatible with long-term storage objectives.

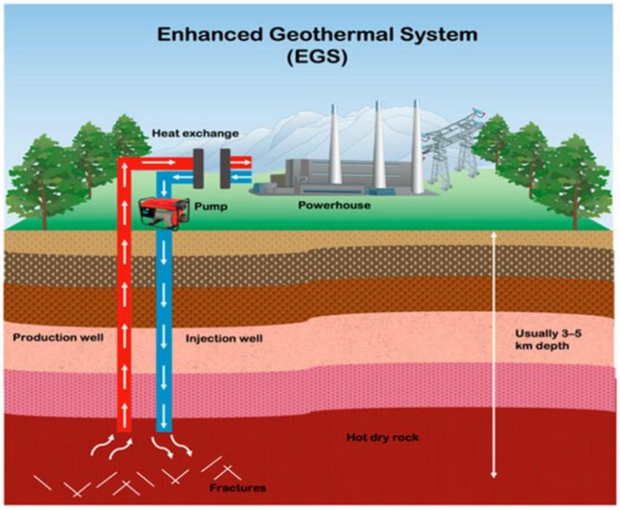

Fig. 2.3 Enhanced Geothermal System

Gupta (2016) advanced this theme by articulating CPG as a "new perspective" that links geothermal production directly to geologic storage projects, particularly in sedimentary basins with moderate geothermal gradients. Gupta's framing is significant because it emphasizes the systems-level value proposition: even if geothermal output is modest relative to conventional high-enthalpy geothermal fields, it can still meaningfully offset CCS operational costs, contribute to local energy supply, or provide direct-use heat for industrial applications (Gupta, 2016). This economic argument aligns with broader CCS literature that identifies cost as a key barrier to scale-up and emphasizes the need for complementary value streams (Bui et al., 2018; IPCC, 2022).

A major thematic emphasis across integrated CO_2–geothermal studies is the requirement for compatibility between storage security and geothermal productivity. Storage security requires reliable containment (seal integrity, fault behavior, well integrity) and conservative pressure management, while geothermal productivity often requires high transmissivity and sustained circulation. Integrated studies therefore commonly focus on identifying the "overlap zone" where both sets of requirements can be met. This overlap is not automatic; it depends strongly on reservoir architecture, heterogeneity, compartmentalization, structural style, and the regional stress regime. The emphasis on compatibility links directly to best-practice storage guidance, which treats containment and risk control as non-negotiable constraints in site screening and selection (NETL, 2017; ISO, 2017).

Another recurrent theme is the role of trapping mechanisms and plume evolution in shaping geothermal feasibility. CO_2 storage research shows that plume migration and immobilization evolve over time through structural trapping, residual trapping, dissolution, and long-term mineralization (Krevor et al., 2015; Ringrose, 2020). Integrated studies build on this by recognizing that geothermal co-production may interact with plume behavior: production wells can influence pressure gradients, modify plume migration directions, and potentially enhance dissolution trapping through increased contact between CO_2 and brine. However, these potential benefits are conditional and must be weighed against risks such as creating preferential migration paths, increasing pressure transients, or complicating monitoring interpretation. Thus, integrated studies often stress that co-production strategies should be designed to support, not compromise, long-term containment (Randolph & Saar, 2013; ISO, 2017).
Monitoring and verification is another key theme. Conventional CO_2 storage projects require robust MRV to demonstrate containment performance and to satisfy regulatory and public assurance needs. Integrated operations introduce additional dynamic signals (production flow rates, temperature trends, pressure changes) that can improve reservoir understanding but also complicate interpretation of plume movement. Literature on monitoring technique selection emphasizes that monitoring must be risk-driven and phase-specific, suggesting that combined projects should adopt MRV designs that explicitly anticipate operational complexity and evolving risk pathways (Gilliland et al., 2013). At the same time, the presence of geothermal production data streams can strengthen the evidence base for reservoir behavior if properly integrated into monitoring plans.

*Corresponding Author: Uwaoma, Blessing Ugoeze

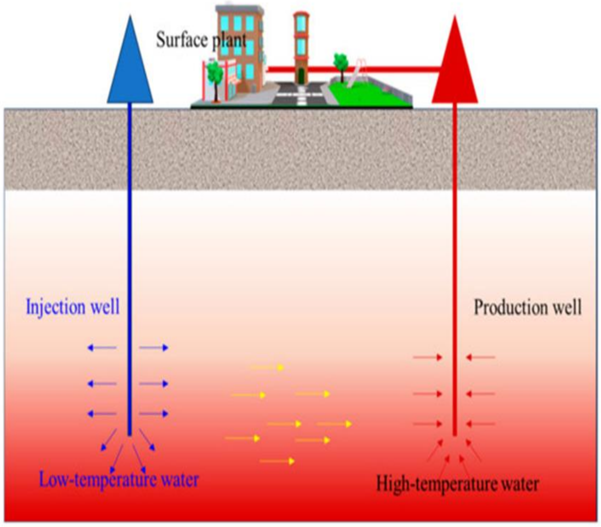

Fig. 2.4 Integrated CO_2–Geothermal

Induced seismicity and geomechanical integrity are strongly emphasized in integrated studies, largely because both CO_2 injection and geothermal circulation alter subsurface pressures. Zoback and Gorelick (2012) caution that large-scale CO_2 injection can trigger seismic events if pressure increases approach critical conditions on faults. Integrated systems—especially those involving both injection and production—may offer opportunities to manage net pressure, but they also require careful geomechanical screening and operational constraints to avoid fault reactivation. This theme supports the need to treat stress regime, fault orientation, fracture pressure, and pressure management as central criteria within any integrated screening methodology (Zoback & Gorelick, 2012; NETL, 2017).

A final theme is the need for standardized, scalable screening and ranking tools. While integrated studies have demonstrated conceptual feasibility, much of the literature remains focused on modeling experiments, conceptual scenarios, or limited case-style evaluations. There is still limited consensus on how to compare prospects globally or how to select candidate basins and reservoir–seal pairs systematically under variable data conditions. CCS best-practice manuals and ISO standards provide structured workflows for storage projects, but they do not explicitly provide integrated geothermal ranking logic; geothermal assessments similarly rarely include containment-centric screening constraints. This creates a methodological gap that justifies the present study's goal of developing a geology-driven, globally transferable screening and ranking framework, supported by transparent MCDA logic and uncertainty treatment (Malczewski, 2006; NETL, 2017; ISO, 2017).

In summary, integrated CO_2–geothermal literature establishes strong conceptual justification for combined subsurface utilization and demonstrates that CO_2 can function as an effective geothermal working fluid in suitable settings (Randolph & Saar, 2011; Randolph & Saar, 2013; Gupta, 2016). It also highlights that success is highly site-dependent and constrained by geology, especially reservoir transmissivity, thermal regime, seal integrity, fault behavior, and pressure limits (Ringrose, 2020; Zoback & Gorelick, 2012). However, the literature also shows that integrated project selection lacks a unified, globally applicable screening and ranking methodology that merges storage security, geothermal productivity, MRV feasibility, and uncertainty in a transparent decision-support framework. Addressing this gap is the direct motivation for the geology-driven global screening and ranking methodology proposed in this research.

3.0 THEORETICAL AND CONCEPTUAL FRAMEWORK

The theoretical and conceptual framework of this study integrates principles from subsurface geology, reservoir engineering, geothermal science, geomechanics, geochemistry, and multi-criteria decision analysis (MCDA) to establish a coherent basis for developing a geology-driven screening and ranking methodology for combined CO_2 sequestration and geothermal energy production. The framework explains how fundamental geological processes control storage security and geothermal productivity, how these controls interact within a coupled subsurface system, and how they are operationalized into a structured decision-support methodology.

The framework is underpinned by four complementary theoretical pillars:

i. Geological containment and trapping theory for CO_2 sequestration
ii. Geothermal heat extraction and reservoir sustainability theory
iii. Coupled subsurface utilization theory for integrated CO_2–geothermal systems
iv. Decision theory implemented through multi-criteria decision analysis (MCDA)

These pillars are synthesized into a conceptual model that treats the subsurface as a multi-functional geological system capable of simultaneously storing CO_2 and producing geothermal energy under strict containment and risk constraints.

3.1 Geological Containment and Trapping Theory for CO_2 Sequestration

Geological CO_2 sequestration is founded on the principle that deep subsurface formations can provide long-term isolation of injected CO_2 from the atmosphere when appropriate geological conditions exist. The theoretical foundation is rooted in subsurface fluid dynamics, multiphase flow behavior, capillary sealing, reservoir geomechanics, and long-term geochemical stabilization. Geological storage is typically implemented through injection into deep saline aquifers, depleted oil and gas reservoirs, or other porous and permeable formations overlain by competent sealing units (ISO, 2017).

A fundamental requirement for effective storage is sufficient depth to ensure CO_2 exists in a dense or supercritical phase. Dense-phase CO_2 possesses higher density and lower specific volume, which improves storage efficiency, enhances plume controllability, and reduces buoyancy-driven migration

*Corresponding Author: Uwaoma, Blessing Ugoeze

(IEAGHG, 2022). At the reservoir scale, injected CO_2 behaves as a buoyant non-aqueous phase fluid relative to formation brine and migrates through porous media under the combined influence of buoyancy forces, pressure gradients, and reservoir heterogeneity.

Multiphase flow theory describes CO_2 plume movement as a function of relative permeability, capillary pressure, viscosity contrast between CO_2 and brine, and anisotropy of the pore system. Injection creates localized pressure buildup around the wellbore that dissipates outward depending on reservoir transmissivity and boundary conditions. This theoretical behavior forms the basis for injectivity assessment and dynamic storage capacity estimation.

Beyond physical flow processes, long-term storage security relies on multiple trapping mechanisms that progressively immobilize CO_2. Structural and stratigraphic trapping provide early-stage containment beneath impermeable caprocks. Residual (capillary) trapping immobilizes CO_2 as disconnected ganglia within pore spaces following brine imbibition (Krevor et al., 2015). Solubility trapping occurs as CO_2 dissolves into formation brines, forming denser CO_2-charged fluids that tend to sink. Mineral trapping involves geochemical reactions between dissolved CO_2 and reservoir minerals, leading to precipitation of carbonate phases and permanent fixation of carbon.

The theoretical significance of this trapping hierarchy is that storage security increases with time, provided early-stage containment is maintained. Consequently, screening methodologies prioritize parameters that control early containment, including seal integrity, fault transmissivity, pressure margin, and well integrity.

Pressure management theory further emphasizes that injection-induced pressure increases must remain below fracture pressure and below thresholds capable of reactivating critically stressed faults (NETL, 2017). Zoback and Gorelick (2012) demonstrate that induced seismicity represents a key risk when pressure perturbations approach fault failure conditions. Therefore, geological containment theory establishes storage security as a hard constraint within this study. Any prospect that fails to satisfy minimum containment requirements is excluded from further consideration, regardless of its geothermal attractiveness.

3.2 Geothermal Heat Extraction and Reservoir Sustainability Theory

Geothermal energy extraction is based on the availability of accessible subsurface heat and the capacity to transfer that heat to the surface through circulating fluids. The theoretical framework is grounded in conductive heat transfer through rock matrices and convective heat transport via fluids. In sedimentary basins, geothermal prospects exist where sufficient temperature is attained at manageable depths and where formation permeability allows sustainable circulation (Randolph & Saar, 2013).

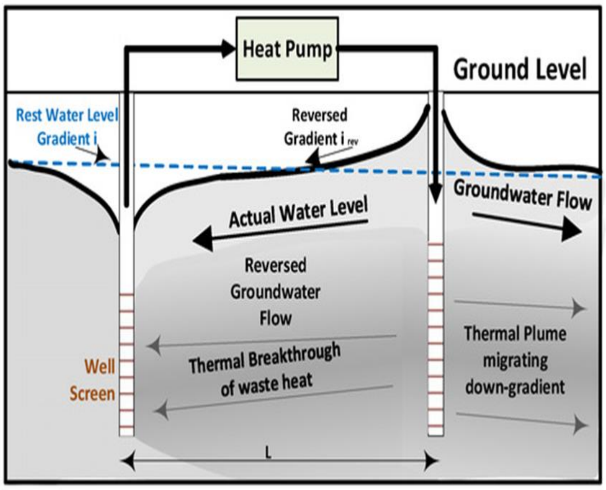

Fig. 3.2 Heat Extraction

The geothermal resource base is controlled primarily by geothermal gradient, heat flow, reservoir depth, rock thermal conductivity, and reservoir thickness. Temperature generally increases with depth, but spatial variability arises due to basin evolution, sediment thickness, radiogenic heat production, structural architecture, and fluid flow pathways. Consequently, geothermal screening typically begins with assessment of geothermal gradient distribution and predicted temperature at target reservoir depths.

Sustainable geothermal production requires that heat extraction rates be balanced by heat replenishment through conduction and advective inflow from surrounding rocks. High initial temperature alone does not guarantee long-term productivity. Reservoir thickness, lateral continuity, pore volume, and transmissivity strongly influence the sustainability of production. Excessive production rates may lead to premature thermal breakthrough and declining output.

The thermophysical properties of the working fluid also play a critical role. CO_2 exhibits lower viscosity and favorable density–temperature relationships compared with water under typical reservoir conditions, enabling enhanced mobility and buoyancy-driven circulation (Randolph & Saar, 2011). These properties provide the theoretical basis for using CO_2 as an alternative geothermal working fluid.

Within this study, geothermal theory defines geothermal viability as a graded attribute. Prospects may exhibit low, moderate, or high geothermal potential; however, only those that simultaneously satisfy storage security constraints are advanced.

3.3 Coupled Subsurface Utilization Theory

Coupled subsurface utilization theory recognizes that injection and production operations modify pressure, temperature, stress, and fluid composition simultaneously within the same geological system. Therefore, CO_2 storage and geothermal operations cannot be evaluated independently.

- Three major coupling processes are emphasized:
- Pressure coupling between injection and production wells

*Corresponding Author: Uwaoma, Blessing Ugoeze

- Thermal–hydraulic coupling between circulating fluids and host rocks
- Geomechanical coupling between pore pressure and in-situ stress

Integrated CO_2–geothermal studies demonstrate that balanced injection–production schemes may help manage net pressure while enabling heat extraction, but poorly designed operations can increase leakage or seismic risk (Randolph & Saar, 2013; Zoback & Gorelick, 2012).

This theory supports the need for integrated screening in which containment performance is evaluated simultaneously with geothermal productivity rather than in parallel disciplinary silos.

3.4 Conceptual Basis of Integrated CO_2 Storage and Geothermal Energy Production

Integrated CO_2 sequestration and geothermal energy production is conceptualized through the CO_2-Plume Geothermal (CPG) concept, where injected CO_2 functions both as a stored greenhouse gas and as a working fluid for heat extraction (Randolph & Saar, 2011).
In this conceptual model, CO_2 is injected into a deep permeable reservoir through an injection well, migrates through reservoir pathways, absorbs heat from surrounding rock, and is produced through a production well. The produced CO_2 transfers heat through surface heat exchangers before being reinjected. Simultaneously, a portion of the injected CO_2 remains permanently trapped within the formation through residual, solubility, and structural trapping.

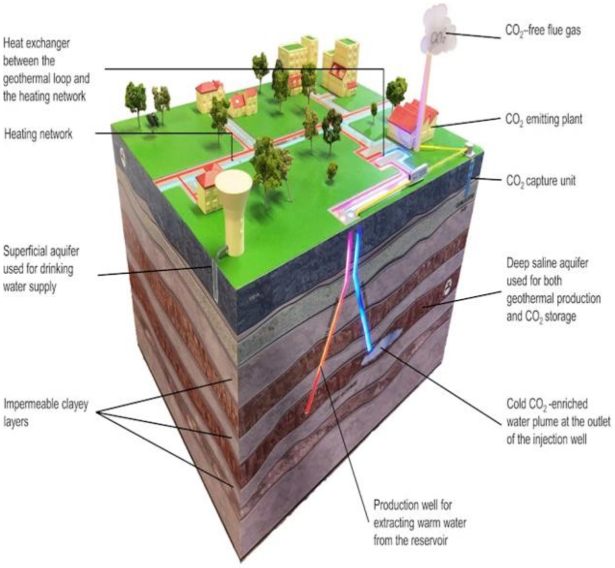

Fig. 3.4 CPG Conceptual Basis

This configuration creates a dual-value system: climate mitigation through storage and energy generation through geothermal heat recovery. The conceptual significance is that geothermal revenue can offset CCS operational costs, improving project economics and encouraging wider deployment.

However, integrated systems demand a careful balance. High permeability that benefits circulation may also enhance leakage risk if associated with transmissive faults or compromised seals. Consequently, international standards emphasize that geothermal utilization must not compromise containment objectives or violate pressure safety constraints (ISO, 2017; IEAGHG, 2022).

3.5 Decision Theory and Multi-Criteria Decision Analysis (MCDA)

Prospect selection for integrated CO_2–geothermal systems constitute a complex multi-variable decision problem involving geological, thermal, risk, and operational factors. MCDA provides a formal theoretical basis for structuring such problems, assigning weights, normalizing scores, and generating transparent rankings (Malczewski, 2006).

Within MCDA:

- Criteria are defined
- Suitability is scored
- Scores are normalized
- Weights are assigned
- Weighted aggregation produces a suitability index

This logic transforms heterogeneous datasets into comparable metrics and reduces ad hoc decision-making.

3.6 Conceptual Framework of the Study

Each prospect area is conceptualized as a system composed of four interacting domains:

CO_2 Storage Domain
Reservoir depth, porosity, permeability, thickness, seal integrity, trapping mechanisms, pressure margin

Geothermal Domain
Temperature at depth, geothermal gradient, transmissivity, thermal sustainability

Risk and MRV Domain
Fault behavior, legacy wells, induced seismicity susceptibility, monitoring feasibility

Enabling Domain
Data availability, proximity to CO_2 sources, infrastructure, regulatory context

These domains are evaluated through a tiered screening sequence:

Tier 1 – Fatal-flaw screening
Tier 2 – Basin-scale screening
Tier 3 – Prospect-scale scoring
Tier 4 – MCDA ranking
Tier 5 – Uncertainty and sensitivity testing

Only prospects that pass Tier 1 proceed.

3.7 Conceptual Cause–Effect Model

Basin Evolution → Stratigraphy & Structure → Reservoir–Seal Architecture →
Porosity & Permeability → Storage Capacity & Injectivity →
Thermal Regime → Geothermal Potential →
Pressure & Stress Conditions → Risk Level →
Integrated Suitability Ranking

This chain links geological history to present-day combined system performance.

*Corresponding Author: Uwaoma, Blessing Ugoeze

3.8 Justification of the Framework

This framework is justified because it:

- Is grounded in established CCS theory
- Incorporates geothermal reservoir science
- Reflects coupled system behavior
- Uses recognized MCDA decision logic
- Treats storage security as non-negotiable
- Enables transparent and reproducible ranking

4.0 METHODOLOGY

This chapter presents the methodology adopted for developing a geology-driven screening and ranking framework for prioritizing global prospect areas suitable for combined CO_2 sequestration and geothermal energy production. The methodology is designed as a tiered, progressive, and data-driven workflow that integrates geological, thermal, risk, and decision-analysis components into a unified system. It emphasizes early elimination of unsuitable settings, objective comparison of viable prospects, and transparent handling of uncertainty.

The methodological structure is informed by best-practice CCS site screening workflows (NETL, 2017; ISO, 2017), geothermal resource assessment principles (Randolph & Saar, 2013), and spatial multi-criteria decision analysis (Malczewski, 2006). The overall approach combines qualitative geological reasoning with quantitative scoring and ranking techniques.

4.1 Research Design

The study adopts a **conceptual–analytical research design**. It does not rely on new field data acquisition, but instead synthesizes existing theories, datasets, standards, and case studies to construct a transferable screening and ranking framework. The research proceeds through the following stages:

1. Identification of key geological and thermal criteria controlling combined CO_2 storage and geothermal feasibility.
2. Development of fatal-flaw (go/no-go) screening rules.
3. Definition of scoring and normalization schemes.
4. Construction of a multi-criteria decision analysis (MCDA) ranking model.
5. Incorporation of uncertainty and sensitivity analysis.

This design ensures that the methodology is both scientifically grounded and practically applicable.

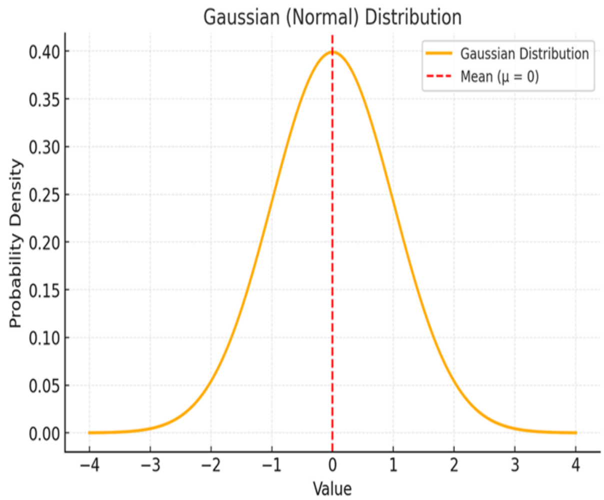

Fig. 4.1 MCDA Model Explanation

4.2 Definition of Decision Unit

The fundamental unit of analysis in this study is the **prospect area**, defined as a discrete subsurface volume characterized by a specific reservoir–seal pair within a sedimentary basin. A prospect area may correspond to:

- A depleted oil or gas field
- A structural closure in a saline aquifer
- A stratigraphic trap or reservoir fairway

Each prospect area is evaluated independently, allowing spatial variability within a basin to be captured.

4.3 Data Sources and Input Parameters

The methodology is designed to utilize commonly available subsurface datasets, including:

- Geological maps and basin atlases
- Seismic interpretation products
- Well logs and core data
- Bottom-hole temperature measurements
- Pressure test data
- Structural and fault maps
- Heat-flow and geothermal gradient maps

Where direct measurements are unavailable, analog-based estimates and regional averages are permitted, but such inputs are assigned lower data-quality classes.

4.4 Tiered Screening Framework

The screening framework consists of five progressive tiers:

Tier 0 – Problem Definition and Use-Case Specification

At this stage, the intended geothermal application is defined:

- Direct-use heat
- Electricity generation
- Combined heat and power

Minimum temperature thresholds are established based on use-case.

*Corresponding Author: Uwaoma, Blessing Ugoeze

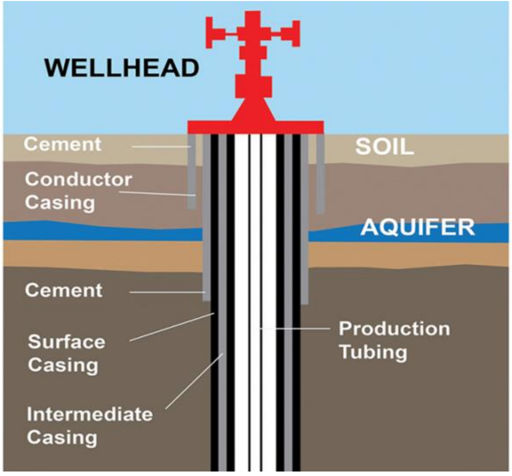

Fig.4.2 MRV Criteria

Tier 1 – Fatal-Flaw Screening (Go/No-Go)

Tier 1 eliminates prospect areas that fail to meet minimum geological requirements for safe storage or basic geothermal plausibility.

Typical fatal-flaw criteria include:

- Reservoir depth insufficient for dense-phase CO_2
- Absence of competent regional seal
- Extremely low reservoir permeability
- Unacceptable fault transmissivity risk
- Temperature below minimum use-case threshold

Prospects failing any fatal-flaw criterion are removed from further analysis.

This approach is consistent with NETL (2017) and ISO (2017) guidance.

Tier 2 – Basin-Scale Geological Screening

Prospects passing Tier 1 are evaluated at the basin scale using qualitative and semi-quantitative descriptors:

- Basin type and tectonic setting
- Stratigraphic architecture
- Structural style
- Regional thermal regime

This stage identifies basins with generally favorable geological frameworks.

Tier 3 – Prospect-Scale Quantitative Evaluation

At this tier, numerical or ranked estimates are generated for key parameters, including:

- Storage capacity
- Injectivity potential
- Seal quality
- Reservoir temperature
- Reservoir transmissivity
- Fault and well risk

These parameters form the basis for scoring.

Tier 4 – Integrated MCDA Ranking

All prospect-scale scores are integrated using MCDA to produce composite suitability indices.

Tier 5 – Uncertainty and Sensitivity Testing

Ranking stability is tested under alternative weights and parameter ranges.

4.5 Development of Evaluation Criteria

Criteria are grouped into four domains:

A. CO_2 Storage Suitability Criteria

- Reservoir depth
- Porosity and permeability
- Net thickness
- Storage capacity
- Seal lithology and thickness
- Trapping mechanisms
- Pressure margin

B. Geothermal Suitability Criteria

- Temperature at depth
- Geothermal gradient
- Reservoir transmissivity
- Thermal sustainability

C. Risk and MRV Criteria

- Fault transmissivity
- Legacy well density
- Induced seismicity susceptibility
- Monitoring feasibility

D. Enabling Criteria

- Data availability
- Proximity to CO_2 sources
- Infrastructure access

4.6 Scoring System

Each criterion is assigned an ordinal score on a 1–5 scale:

1 = Very poor
2 = Poor
3 = Moderate
4 = Good
5 = Excellent

Scores are based on threshold ranges defined from the literature (Ringrose, 2020; Randolph & Saar, 2013).

4.7 Normalization of Scores

To allow aggregation, scores are normalized to a 0–1 scale:

$$S_{norm} = \frac{S_i - S_{min}}{S_{max} - S_{min}}$$

where:

S_i= raw score

$$S_{min} = 1, S_{max} = 5$$

4.8 Weight Assignment

Weights reflect the relative importance of criteria. Because containment is non-negotiable, storage and risk criteria are typically assigned higher weights than geothermal and enabling criteria.

*Corresponding Author: Uwaoma, Blessing Ugoeze

Example domain weights:

- Storage domain: 0.35
- Geothermal domain: 0.30
- Risk/MRV domain: 0.25
- Enabling domain: 0.10

Weights can be modified for scenario analysis.

4.9 MCDA Aggregation Model

Overall suitability index for prospect *i*:

$$R_i = \sum_{j=1}^{n} w_j \times S_{ij}$$

where:
w_j= weight of criterion *j*
S_{ij}= normalized score
Prospects are ranked in descending order of R_i.

4.10 Data-Quality Classification

Each parameter is assigned a data-quality class:

- Class A – Direct measurement
- Class B – Interpreted from logs/seismic
- Class C – Regional average
- Class D – Analog estimate

Lower-quality data attract uncertainty ranges.

4.11 Uncertainty Analysis

Uncertainty is addressed by:

- Assigning ranges to uncertain parameters
- Running multiple MCDA scenarios
- Comparing rank stability

Prospects that remain highly ranked across scenarios are considered robust.

4.12 Sensitivity Analysis

Sensitivity testing identifies which criteria most influence rankings by systematically varying individual weights and observing changes in R_i.

4.13 Output Generation

The methodology produces:

- Basin suitability maps
- Ranked prospect lists
- Domain-specific scores
- Data-gap registers
- Shortlists for detailed appraisal

4.14 Validation Strategy

Validation is achieved through:

- Comparison with known CCS and geothermal project locations
- Consistency checks with published case studies
- Expert judgement review

4.15 Ethical and Environmental Considerations

Only sites meeting high containment and low-risk standards are advanced. Environmental protection and groundwater safety are treated as primary constraints.

5.0 RESULTS AND EXPECTED OUTPUTS

This chapter presents the nature and form of results expected from applying the proposed geology-driven screening and ranking methodology for prioritizing global prospect areas suitable for combined CO_2 sequestration and geothermal energy production. As the present research is methodological, emphasis is placed on the structure, organization, and interpretation of outputs rather than site-specific numerical results. The expected outputs demonstrate how heterogeneous geological, thermal, and risk-related information are transformed into structured decision-support products.

5.1 Basin-Scale Suitability Classification

The first level of results is the classification of sedimentary basins into broad suitability categories based on Tier 1 and Tier 2 screening.

Table 5.1: Basin-Scale Suitability Classification Scheme

Suitability Class	General Description	Typical Geological Characteristics
Highly Suitable	Strong candidate for combined CO_2–geothermal systems	Thick sedimentary succession, laterally continuous reservoirs, competent regional seals, moderate–high geothermal gradient, stable tectonic setting
Moderately Suitable	Suitable with some limitations	Adequate reservoir–seal pairs, moderate temperature, localized structural complexity
Conditionally Suitable	Requires additional data	Sparse temperature data, uncertain seal continuity, limited well control
Unsuitable	Fails fatal-flaw criteria	Shallow basin, absent seal, very low temperature, highly active tectonics

This classification enables rapid global visualization of regions where combined systems are geologically plausible.

5.2 Prospect-Scale Suitability Indices

For each prospect area that passes basin-scale screening, a composite suitability index (0–1) is calculated using MCDA.

*Corresponding Author: Uwaoma, Blessing Ugoeze

Table 5.2: Example Prospect-Level Suitability Output

Prospect ID	Basin Name	Storage Score	Geothermal Score	Risk/MRV Score	Enabling Score	Composite Index (R_i)	Rank
P-01	Basin A	0.85	0.72	0.80	0.60	0.77	1
P-02	Basin A	0.78	0.75	0.70	0.55	0.72	2
P-03	Basin B	0.90	0.50	0.82	0.58	0.71	3
P-04	Basin C	0.65	0.80	0.60	0.50	0.67	4

Such tables allow direct comparison between prospects and identify the most promising candidates.

5.3 Domain-Specific Score Profiles

Beyond composite indices, individual domain scores are reported.

Table 5.3: Domain Score Profile for a Representative Prospect

Domain	Key Indicators	Normalized Score
CO_2 Storage	Capacity, injectivity, seal, depth	0.85
Geothermal	Temperature, transmissivity, sustainability	0.72
Risk/MRV	Fault risk, well integrity, seismicity	0.80
Enabling	Data availability, infrastructure	0.60

This table explains why a prospect achieved a particular rank and highlights strengths and weaknesses.

5.4 Robustness and Ranking Stability

Uncertainty and scenario testing generate ranking stability metrics.

Table 5.4: Ranking Stability under Multiple Weight Scenarios

Prospect ID	Best Rank	Worst Rank	Mean Rank	Probability of Top-5 (%)
P-01	1	2	1.3	98
P-02	1	4	2.5	90
P-03	2	6	3.4	75
P-04	3	9	5.8	55

Prospects with narrow rank ranges and high top-tier probability are considered robust.

5.5 Data-Gap Register

For each basin and prospect, missing or uncertain data are documented.

Table 5.5: Example Data-Gap Register

Prospect ID	Parameter	Data Quality	Impact on Ranking	Recommended Action
P-02	Reservoir temperature	Low	High	Acquire temperature log
P-03	Permeability	Medium	Medium	Conduct well test
P-04	Fault transmissivity	Low	High	Structural interpretation

This table guides efficient future data acquisition.

5.6 Spatial Outputs

Spatial products derived from results include:

- Global basin suitability maps
- Basin-level prospect density maps
- Heat maps of composite index values
- Overlays of prospects and major CO_2 emission sources

These outputs support strategic visualization and planning.

5.7 Shortlist for Detailed Appraisal

High-ranked and robust prospects are grouped into a shortlist.

Table 5.6: Shortlisted High-Priority Prospects

Prospect ID	Basin	Composite Index	Priority Level
P-01	Basin A	0.77	Very High
P-02	Basin A	0.72	High
P-03	Basin B	0.71	High

5.8 Interpretation of Expected Geological Patterns

Application of the methodology is expected to show that:

- Thick sedimentary basins with moderate geothermal gradients dominate high-suitability classes.
- Structurally complex and tectonically active basins tend to rank lower.
- Mature petroleum basins frequently appear in higher ranks due to data richness and proven containment.

*Corresponding Author: Uwaoma, Blessing Ugoeze

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study set out to address a critical methodological gap in subsurface energy and storage research: the absence of a unified, geology-driven framework for systematically identifying and prioritizing geological settings that can simultaneously support long-term CO_2 sequestration and viable geothermal energy production. Based on a comprehensive review of the literature, integration of geological and geothermal theories, and development of a tiered screening and MCDA-based ranking workflow, several key conclusions are drawn.

First, geological conditions that ensure secure CO_2 storage and those that enable geothermal energy production are partially overlapping but not identical. Secure storage requires adequate reservoir depth, sufficient porosity and permeability, competent and continuous seals, and manageable pressure conditions, while geothermal production requires sufficiently high temperatures and transmissivity. The study demonstrates that treating these requirements independently risks overlooking opportunities for synergy or, conversely, advancing prospects that are incompatible with one of the two objectives.

Second, a geology-first, fatal-flaw-based screening approach is essential. By imposing minimum containment and temperature thresholds at the earliest stage, the methodology ensures that only prospects with fundamental geological plausibility are subjected to detailed ranking. This approach aligns with international best practices for CO_2 storage and reduces the likelihood of late-stage project failure.

Third, the integration of storage, geothermal, risk/MRV, and enabling criteria within an MCDA framework provides a transparent and reproducible basis for comparing diverse prospect areas. The use of normalized scores and explicit weighting allows stakeholders to explore alternative priority scenarios while maintaining methodological consistency.

Fourth, uncertainty and sensitivity analysis are indispensable components of prospect ranking. The study demonstrates that ranking stability is as important as absolute ranking position. Prospects that consistently rank highly across multiple scenarios are more defensible candidates for detailed appraisal and demonstration projects.

Fifth, the expected results indicate that thick sedimentary basins and mature petroleum provinces are likely to dominate high-suitability classes globally. These settings combine proven containment, large pore volumes, and extensive subsurface datasets with sufficient thermal resources for geothermal co-production.

Finally, the study confirms that combined CO_2 sequestration and geothermal energy production represents a credible pathway for improving CCS project economics and expanding geothermal utilization beyond traditional volcanic regions. However, successful implementation is inherently site-specific and must be grounded in rigorous geological evaluation.

6.2 Recommendations

Based on the findings and conclusions of this study, the following recommendations are made:

1. **Application to Global Databases** The methodology should be applied to existing global basin and storage atlases to generate preliminary global maps of combined CO_2–geothermal suitability.
2. **Integration with Numerical Modeling** High-ranked prospects identified by the framework should be subjected to coupled thermo-hydro-mechanical-chemical (THMC) reservoir simulation to evaluate dynamic performance under realistic injection–production scenarios.
3. **Data Quality Enhancement** Priority should be given to acquiring temperature logs, permeability measurements, and fault characterization data in basins identified as conditionally suitable.
4. **Pilot and Demonstration Projects** Governments and industry should consider establishing pilot-scale combined CO_2–geothermal projects in high-ranked basins to validate the methodology and refine operational strategies.
5. **Methodological Refinement** Future studies should explore alternative MCDA techniques, such as fuzzy logic or Bayesian decision models, to better handle uncertainty and qualitative judgments.
6. **Regulatory Framework Development** Regulators should consider developing guidelines specifically addressing integrated CO_2 storage and geothermal operations.
7. **Economic and Life-Cycle Assessment Integration** The screening framework should be expanded to include techno-economic and life-cycle environmental metrics.

6.3 Final Remarks

This research provides a foundational, geology-driven decision-support framework for prioritizing global prospect areas suitable for combined CO_2 sequestration and geothermal energy production. By integrating geological containment theory, geothermal reservoir science, and multi-criteria decision analysis within a tiered screening structure, the study advances both scientific understanding and practical capability in integrated subsurface resource utilization. The framework offers a pathway toward more efficient, economically viable, and environmentally responsible deployment of combined subsurface energy and storage systems in support of global decarbonization objectives.

*Corresponding Author: Uwaoma, Blessing Ugoeze

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*Corresponding Author: Uwaoma, Blessing Ugoeze