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Portfolio analysis of carbon sequestration technologies and barriers to adoption: General methodology and application to geological storage

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Abstract

Effective targeting of funds and research efforts to reduce industrial CO_2 emissions can benefit from quantitative analysis methods that assess and compare a variety of carbon sequestration technologies. We develop a general methodology and quantitative scoring system, and then apply it to the specific CCS technology of Geosequestration. Our results indicate that the most critical barriers to widespread commercial adoption of Geosequestration are not technology- or capacity-related, but instead relate to issues of public acceptance and economics. Our analysis suggests that geosequestration has a medium to high probability of success as a commercial-scale CO_2 storage option.

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Keywords: Geosequestration; CCS Portfolio Analysis; Risk Assessment Methodology; Geological Storage; Carbon Sequestration

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1. Introduction

Global emissions of greenhouse gases (GHG) covered by the Kyoto Protocol have increased approximately 70% from 1970–2004, and by 24% from 1990–2004. Carbon dioxide (CO_2) is the largest contributor to this increase, having grown by about 80% [1]. In order to limit temperature increases from pre-industrial levels to 2 degrees Celsius, several global climate models suggest that atmospheric concentrations of GHG must be stabilised at 450ppm of CO_2 equivalent by 2050 [2]. In 2004, Pacala and Socolow [3] published their Stabilisation Triangle Model (Figure 1), outlining in a schematic manner a

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set of suggested measures to restrict the atmospheric CO_2 concentration to 500+/-50 ppm (less than twice the pre-industrial concentration of 280 ppm). The difference between a business-as-usual scenario and a constant 2004 base level is reflected by the Stabilisation triangle. The triangle is subdivided into seven wedges, each representing a current technology with a reduction potential of 1 Gigatons of carbon per year (GtC/a) by 2054 (Figure 1).

According to the IEA 2008 report [4], carbon capture and storage (CCS) may be capable of accounting for about 20% of the recommended $C0_2$ emissions reduction by 2054. The CCS option covers a diverse range of technologies. For example, ocean fertilization technologies aim to spur the growth of plankton by the addition of nutrients and increase the dead biomass and naturally sequestered CO_2 at the ocean floor. Biofuel production aims to provide a near-carbon neutral energy source by using biomass as the basis for fuel generation instead of hydrocarbons. The conversion of any bio-material into charcoal creates a material with very high carbon content which can be used as a fuel, for soil enrichment, or as a space efficient long term storage solution. However, one of the most promising technologies in the CCS category is Geosequestration.

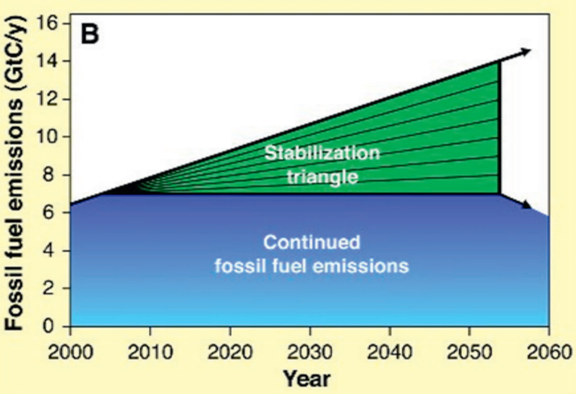


Figure 1. Stabilisation Wedge Model
(Image source: Pacala and Socolow, 2004 [3]).

Geosequestration involves the capture of CO_2 at industrial emission source points (e.g. coal-fired power generation, steel, chemical, fertilizer, cement, mineral, or LNG plants), and transport of the captured CO_2 via pipeline or alternative method to suitable sites for underground injection and long-term geological storage. Suitable storage sites are typically geological formations deeper than 1 km where a combination of porous reservoir rock (e.g., sandstone) and non-permeable cap-rock (e.g., shale) form a reservoir-seal pair. The most favorable storage formations are depleted oil and gas fields, saline aquifers or unmineable coal seams deep in the subsurface. The CO_2 in liquid supercritical phase is injected deep into the rock and sequestered by a variety of trapping mechanisms over time (e.g., structural and stratigraphic traps, capillary pressure / residual saturation, solubility and mineralization). Figure 2 shows a schematic of the Geosequestration process [5].

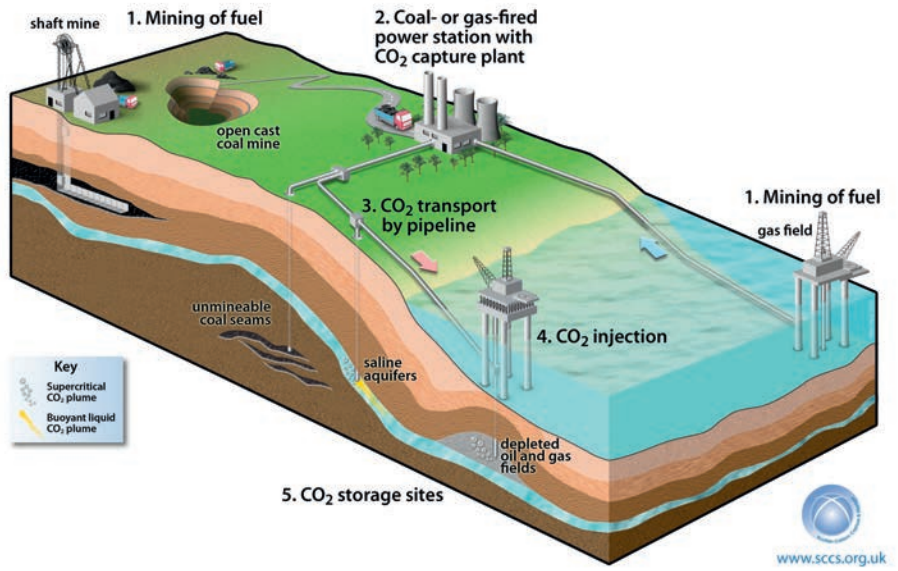


Figure 2.

Schematic Diagram of the Geosequestration Process

(Image source: Scottish Centre for Carbon Storage, 2011 [5])

There are currently only a few commercial-scale Geosequestration projects active around the world. Sleipner, a gas field in the North Sea, was the first commercial CO_2 storage project. Since 1996, 16Mtpa CO_2 has been injected at a rate of 1Mtpa, at about 1,000m below sea level into the Utsira Formation, a saline sandstone formation [6]. The Weyburn project (Saskatchewan, Canada), operational since 2000, utilises CO_2 piped from a coal gasification plant in North Dakota for enhanced oil recovery, injecting 1Mtpa CO_2 into the Weyburn and Midale carbonate reservoir oil fields [7]. Since 2004, 1.2Mtpa CO_2 from gas processing has been injected 1800m into the Krechba Formation, a depleted oil reservoir at the In Salah CCS Project in Algeria [6]. The Cranfield Project in Mississippi, USA, began in 2008 as a pilot test project and is now injecting 1.5Mtpa CO_2 at commercial scale from the Jackson Dome natural source into the Tuscaloosa Formation, a sandstone deep saline aquifer [14]. At the Snøhvit project in the Barents Sea, 0.7 Mtpa CO_2 from LNG processing has been injected 2,600m into saline Tubasan sandstone formation reservoirs since the field became operational in 2008 [6]. Projects which will soon be operational include the Decatur Project in Illinois (USA), which plans to inject 1Mtpa CO2 from ethanol processing into the Mount Simon Sandstone Formation (saline sink), as well as the Gorgon Project and the South West Hub Project, both located in Western Australia. At Gorgon, 3-4 Mtpa from LNG and gas processing will be injected 2,200m below Barrow Island into the Dupuy Formation, a turbidite sandstone reservoir, from 2014 onwards, making this the largest Geosequestration project worldwide [8]. The South West Hub Project is projected to inject between 3-7 Mtpa of CO_2 from various industrial sources into the Lesueur Formation, an onshore sandstone deep saline aquifer [9]. An overview of the location of active and proposed projects is given in Figure 3 [10].

Figure 3. Overview on active and proposed Geosequestration projects (Image source: CO2CRC, 2012 [10])

A wide range of numerous small CCS pilot and demonstration projects of < 100 ktpa have been implemented globally over the past 10+ years [11][12][13]. These include the Otway Project in Victoria (Australia) where a total of 70kt CO_2 has been injected at a depth of 2000m into the Waarre-C Formation, a sandstone depleted gas reservoir [11]. In Germany, Ketzin became a major European CO_2 storage test site in 2008, injecting 60kt CO_2 at about 650m depth into a shallow saline formation [12]. Since 2010, the TOTAL Lacq Project has injected 75kt of CO_2 from oxyfuel combustion 4,500m into an onshore depleted natural gas field [13]. A key objective of these many test projects is to perform research experiments and develop the necessary expertise for commercial upscaling.

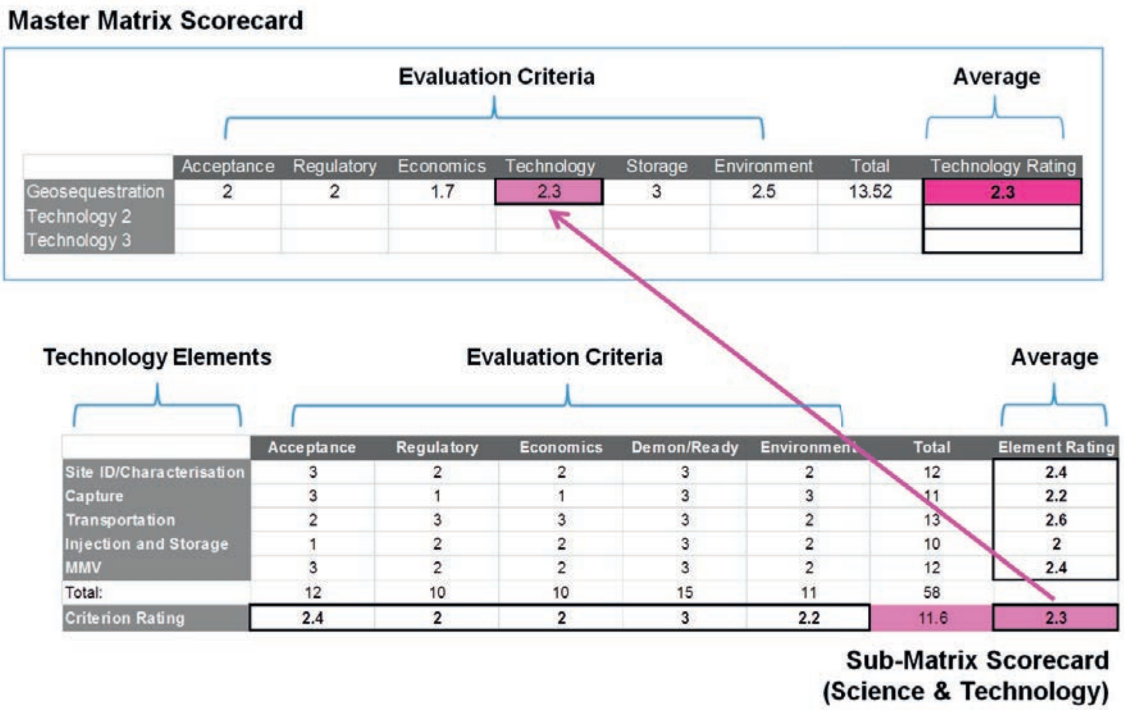
Fossil fuels are predicted to remain a major and necessary part of the global energy supply for the next 50+ years. Since CCS accounts for ~20% of the overall mitigation potential and is one of the most effective methods to deal with industrially produced CO_2, it will likely be a key component of any comprehensive carbon mitigation strategy. All of the currently proposed CCS technologies face challenges and barriers to wide scale commercial adoption. Industry and government may need to manage their risk exposure by utilising a portfolio of CO_2 sequestration technologies rather than relying on a single method. A case in point is the Snøhvit Project, where Statoil initially encountered lower permeability and CO_2 injectivity than predicted, resulting in low injection rates [15]. This impacted the project on both technical and economic levels as the operator did not have an alternate storage option ready to rely upon. To enable governments and industry to effectively target investment funds and research efforts, as well as manage their risk exposure across a variety of projects, a quantitative methodology to rank projects and CCS technologies is desirable.

In the following sections, we will first present our semi-quantitative methodology for the ranking of different CCS technologies. We will then define the evaluation criteria and sub-criteria scoring system, giving examples for high and low scores to demonstrate how this method can be used to assess a variety of CCS technologies. The methodology will then be applied specifically to Geosequestration to evaluate its current status and capability as part of a carbon mitigation strategy, and to highlight its positives and negatives to full-scale commercial adoption. Case studies and examples will be provided to support the assessed scores. We conclude the paper with a discussion of the applicability of our methodology to CCS technologies in general and the outcome of its application to Geosequestration.

Methodology

2.1 Framework Components

We have developed a semi-quantitative methodology to assess various diverse CCS technologies using multiple evaluation criteria. The methodology provides a systematic framework and combines both quantitative and qualitative measures into numerical scores to facilitate comparison. The Master Matrix shows the six general evaluation criteria against which any CCS technology can be assessed: 1. Public Acceptance, 2. Regulatory Framework, 3. Economics, 4. Science and Technology, 5. Storage Quality and 6. Environmental Impact (Figure 4). The technology elements specific to Geosequestration and analysed in the Sub-Matrix are: Site ID/Characterisation, Capture, Transportation, Injection and Storage, and Measurement, Monitoring and Verification (MMV). These are analysed across the evaluation criteria, and the resulting Science and Technology score is transferred to the Master Matrix. The matrix scorecards provide a quick overview for an investment portfolio risk analysis to identify technologies for investment (lowest risk) and candidates for improvement (with high risk or high uncertainty).



	Acceptance	Regulatory	Economics	Technology	Storage	Environment	Total	Technology Rating
Geosequestration	2	2	1.7	2.3	3	2.5	13.52	2.3
Technology 2								
Technology 3								

	Acceptance	Regulatory	Economics	Demon/Ready	Environment	Total	Element Rating
Site ID/Characterisation	3	2	2	3	2	12	2.4
Capture	3	1	1	3	3	11	2.2
Transportation	2	3	3	3	2	13	2.6
Injection and Storage	1	2	2	3	2	10	2
MMV	3	2	2	3	2	12	2.4
Total:	12	10	10	15	11	58	
Criterion Rating	2.4	2	2	3	2.2	11.6	2.3

Figure 4. Master Matrix and Science and Technology Sub-Matrix Scorecards: Results of Application of Methodology to Geosequestration.

2.2 *Evaluation Criteria*

The Portfolio Analysis Taxonomy (Figure 5) illustrates the six evaluation criteria which affect the wide-spread commercial adoption of all CCS technologies; these are: 1) public acceptance, 2) regulatory framework, 3) economics, 4) science and technology, 5) storage quality, and 6) environmental impact. The evaluation criteria are defined in Table 1. The sub-criteria are used to define quantitative scores on a scale from 1 to 3 (1ow to high). The sub-criteria provide the specific questions or issues which are assessed under each evaluation to generate the numerical scores (Table 2). They represent the characteristics used to weight or establish the quantitative scale values under each criterion and generate numerical scores. Quantitative measures, case studies, reports and other data are used to guide ranking and calibrate scores. The ratings of each sub-criterion are summed and averaged to obtain the evaluation criteria score. The evaluation criteria scores are then compiled and averaged to obtain an overall score for a specific CO_2 sequestration technology. The technical readiness of the given technology is analysed in a separate sub-matrix to take into account the technology elements specific to each CCS technology.

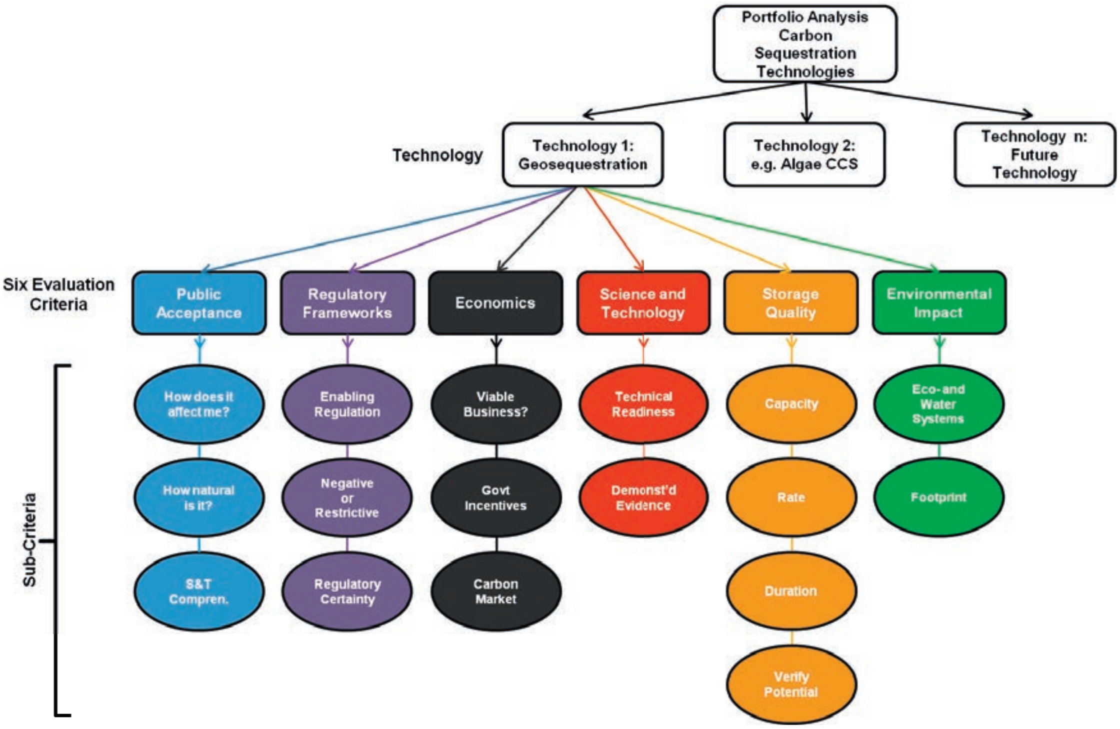


Figure 5. Portfolio Analysis Taxonomy showing elements (evaluation criteria and sub-criteria) assessed in our Methodology for each carbon sequestration technology in order to perform a portfolio evaluation

Table 1.

Evaluation Criteria Scorecard illustrating the condition which characterises the standard of judgment under each criterion, as well as the low, medium and high cut-off scores for each. This Scorecard works together with the Rating System Sub-criteria Scorecard to provide a semi-quantitative analysis for each CCS technology.

Evaluation Criteria	Low (1)	Medium (2)	High (3)
Public Acceptance	Public negative	Public neutral	Public positive
Regulatory Frameworks	Unsupportive	Neutral	Supportive
Economics	Unprofitable	Affordable	Profitable
Science and Technology	Long term (10+ years) Blue Sky (concept)	Mid-long term (5-10 years)	Ready/ Short term (1-5 years)
Storage Quality	Low	Medium	High
Environmental Impact	High	Medium	Low

Table 2. Rating System Sub-Criteria Scorecard with measures to establish ratings.

Evaluation Criteria	Sub-Criteria
Public Acceptance	1. How does it affect me? 2. How natural is it? 3. Science and technology comprehension (level of awareness and accurate understanding)
Regulatory Frameworks	1. Existence of or substantial progress made towards enabling/conducive international, national, state body of conducive laws/regulations to govern a particular aspect of the carbon sequestration option 2. Existence of restrictive/negative regulation 3. Regulatory certainty, e.g. requirements for industry compliance
Economics	1. Viable business case? Stand-alone or with supplementary associated income, e.g. enhanced hydrocarbon recovery 2. Government funding/incentives – level of dependency or reliance upon 3. Carbon market – level of sensitivity, e.g. to low activity and carbon trading price
Science and Technology	1. Level of technical readiness of application? Does it need research, design and development, or is it ready for demonstration and commercial level of use? 2. Demonstrated evidence – laboratory experiments, field trials, large scale demonstrations, operational or commercial projects
Storage Quality	1. Capacity, i.e. storage volume 2. Rate (volume per unit time), e.g. Geosequestration - injectivity) 3. Duration – sequestration time, related to containment and leakage 4. Verification (monitoring potential), tools, legal and physical accessibility for safety, risk and uncertainty management plan for contingency and remediation
Environmental Impact	1. Potential impact on ecosystem and/or water systems, e.g. plant, marine, animal, food sources, human life, etc. Could be beneficial. 2. Environmental footprint, e.g. pipelines, induced seismicity, infrastructure

2.2.1 Public Acceptance

The definition of "Public Acceptance" refers to public, political and other stakeholder acceptance, and is often referred to as "social licence to operate."

2.2.1.1 How does it affect me?

This question refers to the impact on the individual, and entails how much the project is likely to cause a "not in my backyard" (NIMBY) reaction related to concerns about property devaluation, or health, safety and environmental risks. A high scoring example may be a project in a remote offshore location with no direct impact on individuals, such as the ongoing Sleipner project in the North Sea [16]. A low scoring example may be an onshore storage site in a densely populated area with significant concerns from the public, such as the Barendrecht project that was cancelled in the Netherlands [17][18].

2.2.1.2 How natural is it?

The more natural, or less deviated from the natural carbon cycle, a CCS technology is perceived to be, the higher the level of public acceptance and adoption is likely to be by the local community and environmental groups. A high scoring carbon mitigation option may be one that enhances the natural carbon cycle, for example like reforestation projects [19][20]. A low scoring option may be one which interferes with the carbon cycle on a global scale, like Ocean Fertilisation [21].

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2.2.1.3 *Science and technology comprehension*

An educated public with a solid comprehension of the scientific and engineering concepts underpinning a CCS technology is likely to be less influenced by misinformation and special interest groups. A high score may be given to a project where the public is actively updated, informed and involved, such as at the Otway Project [22]. A low scoring example may be a case in which insufficient communication or education with the local community results in unjustified fears, perhaps as may have caused the cancellation of the Barendrecht project [17][18].

2.2.2 Regulatory Frameworks

"Regulatory Frameworks" refers to a system of rules, regulations and legislation, and the means to enforce them. These rules are established by state and federal governments as well as international bodies and range from comprehensive frameworks to rules for very specific activities.

2.2.2.1 Enabling regulation

The existence of enabling legislation or flexibility in the adaptation of existing rules to new requirements, will favour the uptake of CCS technologies. A high score is given to a flexible regulator like the amendment of existing pipeline legislation to allow for CO_2 transportation by the State Government of Western Australia [23]. Regulatory requirements which encourage industry compliance can positively affect adoption of a CCS technology as they create a base need for research and development as well as deployment of a technology. A high scoring example would be the required retrofitting of CCS equipment to coal-fired power plants, as in the United Kingdom [24]. A low scoring example would be the retraction of planned legislation, or the passing of politically controversial regulations which are dependent on single party support.

2.2.2.2 Restrictive or negative regulation

The existence of restrictive or negative legislation, or a comprehensive but negative regulatory framework, can negatively impact the adoption of certain technical aspects of CCS technologies. A high scoring example may be a country with no negative or restrictive regulation. A low scoring scenario may be a government banning access to a significant portion of technically and economically suitable storage sites, as in the Netherlands [25].

2.2.2.3 Regulatory certainty

Regulatory certainty refers to the presence or absence of a comprehensive regulatory framework. A high score is given for the existence of either positive or negative legislation, because this provides the ability to conduct economic analysis and planning with a significant degree of certainty. A low score is assigned where the absence of a regulatory framework yields high risk for a project since there is no regulation and it is difficult to plan in the face of regulatory uncertainty. For example, the delay in enactment of proposed CCS legislation by the German government, apparently led Swedish power utility Vattenfall to recently cancel the Jänschwalde project in Brandenburg [26].

2.2.3 Economics

"Economics" refers to the economic and financial aspects affecting CCS technologies, projects and investment.

2.2.3.1 Viable business case

Significant funds are required to invest in CCS technologies (capital expenditure (CAPEX), operating expenditure (OPEX), monitoring, regulatory compliance and carbon accounting) and operators need these to be offset by consistent revenue streams and sustainable business models. A high scoring example may be the presence of sufficient carbon tax savings through the use of CCS technology as is the case at Sleipner [27]. A low scoring example would a project which is dependent on a highly uncertain revenue stream, especially to cover OPEX. Dependence on direct government funding of OPEX, or dependency on floating CO_2 surcharges to electricity prices would be additional examples.

2.2.3.2 Government Funding/Incentives

This sub-criterion refers to the level of dependence upon government funding or other incentives. A high scoring example would be a project that is not reliant upon such subsidies to encourage the adoption of the technology. Enhanced Oil Recovery (EOR) projects with sufficient increased oil production are currently one of the few high-scoring profitable examples which can achieve such a high score [28]. A high reliance on subsidies or incentives would score a low rating, for example a project which cannot proceed without significant government financial intervention, e.g., Longannet [29][30][31].

2.2.3.3 Carbon Market

This sub-criterion is defined by the level of sensitivity to the carbon market. A high score would be given to a business model which does not rely upon trade or sale of carbon credits. A high sensitivity to trade volumes and carbon price is a disadvantage and would thus merit a low score as the market may be artificial and dependent on political will and cooperation.

2.2.4 Science and Technology

"Science and Technology" is defined as the capability and efficacy of a CCS technology in mitigating atmospheric CO_2 with a basis in sound scientific concepts and engineering solutions.

2.2.4.1 Technical readiness

Technical readiness refers to the status of a CCS application, that is, whether it needs more research and development, or is ready for demonstration, or is already available at commercial scale. A high scoring example may be CO_2 capture technologies used by the O&G industry for gas processing since they are currently available and in use, and may be possibly adapted for use by other industries, such as coal-fired power generators. A low scoring example may be Algae CCS which needs significant R&D efforts to discover the most suitable microalgae strains for high volume production of biofuel, energy and biomass [32].

2.2.4.2 Demonstrated Evidence

Demonstrated evidence refers to the established nature of scientific concepts, engineering solutions, benefits and safety for each technical element specific to a given CCS option both in the lab and field. A high scoring example would be Geosequestration, which has been safely demonstrated for over forty years of EOR for CCS purposes via numerous large-scale demonstration projects. A low scoring example would be an immature or unproven scientific concept or technical solution, such as the deposition of CO_2 in solid phase on the deep ocean floor.

2.2.5 Storage Quality

"Storage Quality" is defined as the capacity and the quality of the space available for long-term secure storage of CO_2. This sub-criteria reflect the standards proposed by international agencies for the qualification of storage sites by considering capacity, injectivity, containment, and monitoring potential [33][34].

2.2.5.1 Capacity

Capacity refers to the total volume of CO_2 which can be stored. A high score example would be given to a massive deep saline formation with an assessed storage volume capable of supporting a number of major commercial CCS projects, for example 10+ GtC, such as the Mount Simon Sandstone [35]. A low scoring example would be a very localised storage site, such as a small depleted hydrocarbon reservoir, or an unreasonably large dependency on areal space requirements such as that required for algae ponds [32].

2.2.5.2 Rate

Rate is the volume of CO_2 that can be stored per unit time, or the speed at which CO_2 can be sequestered. A high scoring example would be the ability to store CO_2 at the same rate as which the CO_2 is captured or produced, such as Geosequestration is capable of doing, for example at the Sleipner Project [6]. A low scoring example may be Reforestation since the rate of CO_2 storage is constrained by the relatively slow growth of trees.

2.2.5.3 Duration

Duration refers to the length of secure CO_2 storage time, and is therefore related to containment and leakage issues. A high scoring example may be Geosequestration since it has four separate trapping mechanisms which increase in security over time. A low scoring example may be Algae CCS, since the CO_2 is only stored temporarily until the algae is harvested and converted into biofuel or biomass.

2.2.5.4 Verification

Verification is the ability to monitor the sequestered CO_2 for storage behaviour, environmental interactions, containment, leakage and economic auditing. A high scoring example would be the commercial availability of geophysical methods and equipment used by the energy industry for 40+ years in CO_2–injection enhanced oil recovery. A low scoring example may be Afforestation because it is difficult to access and monitor large tracts of land to check if the planted trees are still standing, and to accurately account for the carbon they are sequestering.

2.2.6 Environmental Impact

The "Environmental Impact" criterion relates to the possible positive or negative environmental impacts that a CCS technology or project may have locally, regionally or globally. Other issues related to this criterion are health and safety, as well as food sources and security.

2.2.6.1 Potential impact on ecosystems and water systems

Impacts include any potential side-effects or changes experienced in eco- and water systems and may even occur thousands of kilometres away from the project site. A high scoring example may be Geosequestration, where any CO_2 leakage is likely to be small and constrained to the immediate site vicinity. A low scoring example may be Ocean Fertilisation, since the effects of micronutrients at commercial scales with the addition of tidal effects are unknown, and could impact coastal areas and food sources tens of thousands of kilometres from the site of fertilisation.

2.2.6.2 Environmental footprint

Environmental footprint refers to the physical effects a CCS technology has on the ground. A high scoring example may be Ocean Fertilisation since little, if any, physical infrastructure is needed. A low scoring example may be Algae CCS since it requires large ponds next to emissions sources and significant infrastructure for overnight storage of the CO_2 [32].

3. Application to Geosequestration

In this section, we apply the general concepts of our methodology as described in detail above, to a quantitative assessment of the specific CCS technology of Geosequestration in its current state of development.

3.1 Public Acceptance

The CCS benefits of Geosequestration are generally accepted by the wider public [36][37], and storage in remote and offshore locations is generally deemed to be publically acceptable, as for example at Sleipner [16]. Concerns about onshore storage due to feared loss in property values, and health and safety issues, often result in a not in my backyard (NIMBY) response that can lead to cancellation of projects such as Barendrecht [17] and the Midwest Regional Carbon Sequestration Project [39]. The balancing of these two competing factors leads to an overall score of 2 for the *how does it affect me* sub-criterion. Geosequestration is viewed as an acceleration of a natural process in the carbon cycle for geological sites to sequester CO_2 for tens of thousands to millions of years [18] and thus the *how natural is it* sub-criterion scores a 3. The public generally has a limited knowledge about the scientific concepts underlying Geosequestration and this can negatively impact the level of acceptance [39][40]. Unreasonable fears of asphyxiation due to pressure build up and sudden CO_2 release are partly responsible for the cancellation of projects such as Barendrecht [17], therefore *science and technology comprehension* scores a 1. The balancing of these various factors thus results in an overall "public neutral" (2) rating.

3.2 Regulatory Frameworks

Much progress has been made in establishing regulatory frameworks for the implementation of Geosequestration with the UK, EU, Alberta (Canada), State Government of Western Australia, and the Commonwealth of Australia leading. Examples include the amendment of existing legislation to allow for CO_2 storage and transportation in Western Australia [23] and Australia's Clean Energy Legislative Package [41]. Inconsistencies in legislation exist internationally and on national levels, for example in the USA and Australia [42]. The amendment of the London Convention and Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter in 2006 allows for sequestration of CO_2 but does not allow for trans-border transportation [42]. Thus the *enabling regulation* sub-criterion scores a 2 rating. *Negative legislation* in the form of restricted access to onshore storage sites, as in the Netherlands [25], or CO_2 transport infrastructure, as in the UK [43] limits the uptake of Geosequestration, therefore this scores a 1. Regulatory compliance is country-specific and can significantly speed up the adoption process by making it a cost of doing business; for example the mandated retrofitting of coal-fired power plants with CCS equipment by 2025 in the UK [42] or the EU's Large Combustion Plant Directive [44]. *Regulatory certainty* scores a 2 and thus brings the overall Regulatory Frameworks scores to a "neutral" (2) rating.

3.3 Economics

Oil and gas (O&G) operators use CCS to generate supplementary income from EOR which is not readily available to other industrial CO_2 emitters. In the presence of CO_2 emissions penalties, the CAPEX and OPEX costs can be offset through financial savings in penalty rates [27]. The cost of CO_2 avoided is lower for coal-fired CCS power plants than for some alternatives [45]. The *viable business case* sub-criterion scores a 2 rating. There is currently a high level of dependency on government financial incentives, for example. Longannet [29][30][31] and the South West Hub Project [9], therefore government *funding/incentives* dependency earns a rating of 1. CCS was only recently included in the Kyoto Protocol's Clean Development Mechanism and is not sensitive to a weak carbon price and immature market at this time. Cap and trade systems are still under development and cannot be relied upon for long-term reliable revenue streams [46] therefore the *carbon market* sub-criterion earns a neutral (2) rating. The sub-criteria average out to a score of 1.7 which may represent an "affordable" economic assessment.

3.4 Storage Quality

Global estimates of storage sites available for Geosquestration range from 1,700 – 11,000 Gt CO_2 [47]. Worldwide research efforts are underway to assess storage capacity in suitable geological formations [35][48]. Economic and social constraints result in a differentiation of technical and economic storage capacity because of land and resource competition and the matching of emissions sources to logistically suitable and publically acceptable sinks; however the large volumes of technical capacity around the world justify a *volume* rating of 3. While the rate of injection is related to the number of injection wells [49], the injectivity rate is site specific and largely dependent on the permeability of the reservoir rock, thickness of the formation and the pressure gradient. From a comparative perspective, the rate of Geosequestration compares more favourably to other CCS technologies such as reforestation or Algae which depend on photosynthesis and individual growth rates, therefore *rate* earns a 3. Sequestration of CO_2 in geological formations is considered long-term and secure with duration and storage integrity increasing over time, and dependent on the four CO_2 trapping mechanisms (structural and stratigraphic, residual saturation or capillary, solubility, and mineralisation) [47]; therefore *duration* earns a 3. Current commercially available MMV technologies are capable of monitoring the CO_2 plume migration, identifying the presence of CO_2 leakage, and provide input to static and dynamic reservoir models in offshore and onshore environments. *Verification* also merits a 3 rating. Storage quality scores a "high" (3) rating and is a major advantage of Geosequestration as a carbon mitigation option.

3.5 Environmental Impact

Globally, CCS prevents the discharge of GHG and contributes to the mitigation of climate change, thereby positively impacting the environment [47]. Injection occurs at depths where the CO_2 is unlikely to interfere with surface resources, unlike other CCS technologies such as Ocean Fertilisation. There are no recorded incidents of sudden CO_2 emissions from sedimentary basins, and although slow natural seepage has been detected along faults or from boreholes, very few examples of localised environmental damage have been linked to this phenomena [18][50]. Hazardous CO_2 release requires the build up of trapped CO_2 in gas phase [50], which can be identified through ongoing MMV activities. The concern that the injection of large volumes of CO_2 in areas close to faults can result in sufficient pressure build-up to trigger earthquakes (induced seismicity) and may lead to the fracturing of the reservoir seals and release of the stored CO_2 [51] seems highly improbable, and in any event such risks can be minimised by active monitoring and engineering mitigation solutions [52]. *Potential impact on ecosystems and water systems* scores a 3. There is some environmental footprint from characterisation, infrastructure, transportation (pipelines) and MMV activities. The footprint is not larger than for conventional O&G activities, which is commonly considered tolerable if not in highly environmentally sensitive areas; therefore *environmental footprint* earns a 2 rating. Environmental Impact thus has an overall "high" (2.5) score.

3.6 Science and Technology

The science and technology elements are CCS technology type specific. The elements specific to Geosequestration are identified and rated across the evaluation criteria. Storage is not assessed under this Sub-Matrix as it is not applicable to all the technology elements.

3.6.1 Geosequestration - Technology Element 1: Site Identification and Characterisation

Geosequestration site identification and characterisation determines the economic and technical feasibility of suitable geological storage locations that are not only capable of sequestering $CO_{2,}$ for secure, long term storage but at the volumes necessary to adequately offset anthropogenic greenhouse gas levels. Public acceptance scores a 3 because in general the wider public are not typically aware of the activities undertaken to gather this information. Regulatory frameworks scores a 2 because there is no consistent legislation regulating these activities, however, the DNV CCS certification framework released in 2012 provides the basis for an internationally recognised process based on industry best practice and compliance with regulations, international standards and directives [53][54]. Economics scores a 2 with site characterisation being the most time-consuming and costly part of the site selection process. Demonstrated technical readiness rates a 3 as the technology needed is often the same technology used by the energy and minerals industries. Environmental impact scores a 2 as there is some footprint from characterisation activities, particularly geophysical surveys. The average rating for the Site Identification and Characterisation technology element is very positive (2.4).

3.6.2 Geosequestration - Technology Element 2: Capture

Capture involves the separation and removal of CO_2 (through absorption, adsorption, desorption and membranes) for example from flue gas produced by the burning of fossil fuels at power plants prior to venting into the atmosphere. This element gets a 3 rating for public acceptance because there is no perceived risk, and it is seen to benefit the environment. Few countries have legislated industry compliance to utilise capture technologies, therefore regulatory frameworks earns a 1. Economics earns a 1, with capture representing the most costly part of CCS because flue gas contains low concentrations of CO_2, making separation a complicated and expensive process. Technology scores a 3, with post-combustion the most mature capture method, capturing ~90% of CO_2 from industrial operations, although a system-dependent energy penalty of 16% to 30% applies [28]. Environmental impact scores a 3; capture prevents CO_2 release, and current technologies and management practices can mitigate the impact of amine solvents on environment and health [55]. Capture scores a “medium” (2.2) rating.

3.6.3 Geosequestration - Technology Element 3: Transportation

The third technology element of Geosequestration is the safe and secure transportation of the CO_2 (typically as a liquid or gas) from emissions source points to injection sites. Public acceptance of transportation rates a 2 because of pipeline infrastructure and its environmental footprint especially in densely populated or environmentally sensitive areas. Regulatory Frameworks is rated a 3 as CO_2 transportation can be covered by existing pipeline legislation. Economics earns a 3 with pipelines the most effective and economic onshore solution but costs typically 40-70% more for offshore [28]. Technical readiness scores a 3 as the use of pipeline technology for the transportation of more volatile gases than CO_2 is already mature. Environmental impact is rated a 2 because of the environmental footprint from pipeline networks. The overall score for Transportation technology is “ready/short term” (2.6) which counts as a high rating.

3.6.4 Geosequestration - Technology Element 4: Injection and Storage

Injection and storage refers to the injection of supercritical CO_2 (greater than 31.1 C and 7.3MPa) into geological formations suitable for long-term storage and secure containment. Public acceptance scores a 1 because of frequent community concerns about economic impact, health, safety and environmental damage from CO_2 injection activities and potential leakage at onshore storage sites. Regulatory frameworks scores a 2, as nation-specific legislation both supports (Australia) [41] and restricts (Netherlands) [35] the ability for storage of CO_2 in geological formations. Economics rates a 2 with the costs for injection and storage infrastructure site-specific, but these can be approximated from the drilling of similar wells in the O&G industry. Technical readiness has been proven with 40+ years of EOR experience by the O&G industry and it therefore earns a score of 3. Environmental impact rates a 2 because of environmental footprint from injection and monitoring wells. The rating for injectivity and storage is “medium” (2).

3.6.5 Geosequestration - Technology Element 5: Measurement Monitoring and Verification (MMV)

Measurement, Monitoring and Verification (MMV) refers to the use of tools and tests to monitor CO_2 injected into geological formations by use of geophysical and geochemical data (seismic, gravity, EM, inSAR, fluid, mineralisation, air, soil, etc.) to build an accurate accounting of the stored volume and its security or retention capability, for safety and economic purposes [43][47]. Public acceptance of MMV is rated 3, as all stakeholders want assurance about the safe and secure containment of the CO_2. Regulatory frameworks is rated 2, as some exists, but there is no consistent global legislation for the handover of liability, legal and MMV obligations [42]. Economics rates a 2 because although the costs of MMV activities are affordable, these occur over the long term (>50 years) with the frequency of measurement significantly higher than for a typical O&G monitoring project. Environmental impact scores a 2 because there is some footprint with the presence of infrastructure such as permanent monitoring arrays and monitoring stations. MMV scores a rating of "mid-long term" (2.4).

3.7 Geosequestration - Overall Technology Rating

The overall rating for Geosequestration at 2.3, as detailed above, suggests a medium to high probability of success as a commercial-scale CO_2 storage option. This is consistent with recent trends in CO_2 geosequestration, as well as published government and industry experience.

4. Conclusions

We have developed and presented a new methodology to assess and compare multiple CCS technologies and barriers to adoption. We have defined a general evaluation criteria and ranking/scoring system for CCS projects and then applied the methodology to the specific CCS technology of Geosequestration as a case study example. Our analysis suggests that Geosequestration has a medium to high probability of success as a commercial-scale CO_2 storage option. The methodology can be applied to multiple alternative CCS technologies in both a general and site-specific comparative manner, allowing the ranking of competing or complementary technologies across a company project portfolio. Our new methodology should be both practical and useful for CCS portfolio analysis of commercial-scale CO_2 storage activities.

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