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# PLANNING SALINE RESERVOIR STORAGE DEVELOPMENTS – THE IMPORTANCE OF GETTING STARTED EARLY

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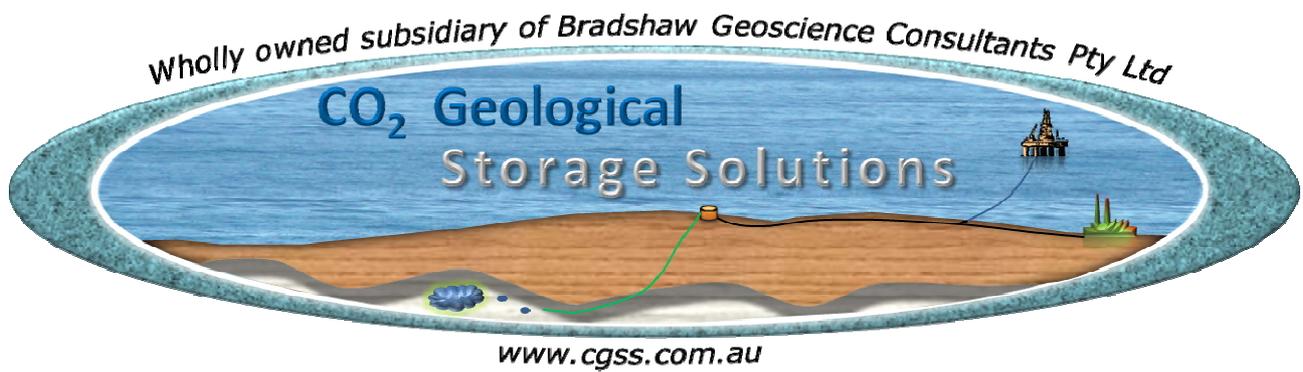
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## Abstract

Finding suitable storage sites and securing industry participation in geological storage of carbon dioxide (CO<sub>2</sub>) is critical to the successful development of every integrated carbon dioxide capture and storage (CCS) project, although there is often poor understanding by stakeholders of the process, time, costs, and business risks involved in the assessment and development of geological storage sites, especially for saline reservoirs. A systematic stage gate process, methodology and work programme for the storage life cycle is presented. A major consideration for saline reservoirs is the requirement for new exploration and appraisal activities at the site identification and characterisation stages to prove sites in a practical sense. This may involve seismic reprocessing, 2D/3D seismic acquisition and drilling new wells, coring and injection tests. The amount of time required from initial screening to the project investment decision could take more than ten years for some sites depending on data availability, the status of licensing and regulatory frameworks and the pace of stakeholder approvals. The costs may also be substantial with expenditure up to millions of dollars. CO<sub>2</sub> capture and transportation investments will need to progress in parallel, but it will be prudent for a geological storage site to be proven with high certainty prior to physically locating any capture plant or pipeline system. A significant risk is that a viable site may not be confirmed by such site assessment work and the entire CCS chain development could be put at risk. This is analogous to exploration and appraisal risk for oil and gas exploration. Although the quantification of storage exploration risk has not yet been calibrated, there are examples from ongoing geological storage activities where site characterization activities have not yielded positive results that meet the anticipated outcomes of earlier screening studies. Providing storage solutions for CCS deployment and capture by major emitters is widely described as a new business opportunity for potential investors. New business models for geological storage will need to be developed providing remuneration for the storage provider from CCS value chains, commensurate with the additional risk involved. A number of technical, business, policy and regulatory risks impact the risk/reward balance and attractiveness of geological storage as a business opportunity. These include the uncertain and long term nature of monitoring obligations and carbon policies, uncertainties around long-term liabilities, exploration risk in saline reservoirs and potentially low returns. These considerations provide further justification for developing policies for CO<sub>2</sub> storage. Because of the potentially extended timescales, it is essential to get an early start on saline reservoir storage opportunities and for the risks to be appropriately addressed by policymakers and by carbon emitters who require storage services.

## 1. Introduction

Finding suitable geological storage sites and securing industry participation in CO<sub>2</sub> storage is critical to the successful development and implementation of every integrated CCS project. However there is often poor understanding by project developers and stakeholders of the work programme, project stages, time, costs, technical and business risks involved in geological storage site assessment and development [1, 2]. Saline reservoir formations are considered the most capacious type of storage option for large-scale long-term storage in many parts of the world [3]. However, initial geological understanding is more limited for this option than for oil and gas reservoirs, and less data are likely to be available. Because of these issues, detailed assessment will be required to identify, select, validate and characterise storage sites and new exploration and appraisal activities will generally be required. There is a risk that a proportion of storage sites identified in screening studies will be confirmed by these activities as actually not being suitable for storage, and thus additional exploration for suitable sites will be required; which has received little attention in the literature to date and often ignored in economic assessments for CCS.

This paper outlines a systematic framework for the overall work programme for storage assessment work in different stages of the project life cycle which includes a generalised description of activities and time frames. It presents a discussion on exploration activities including examples of activities and costs. It proposes definitions for storage-ready and discusses issues relating to exploration and business risk that

will be important considerations for industry investment. The aim of the geological storage assessment activity is to become “storage ready” by identifying, proving and securing a geological storage site that is capable of having commercial quantities of CO<sub>2</sub> injected and stored in the deep subsurface on a sustainable basis, whilst maintaining high geological integrity in the geological structures and formations both during and after the injection and storage period. But to become “storage ready” with a high level of certainty requires significant investment of time, finances and human resources, amidst the current back drop of the competing timelines of the necessary action on climate change mitigation. It is the knowledge about the scope, commercial and technical aspects and associated uncertainty with “storage ready” activities that this paper attempts to redress; for which companies that are not accustomed to dealing with subsurface matters are not ordinarily aware [4].

## 2. Stage Gate Framework for Storage Activities

A systematic stage gate framework for storage work programme activity for saline reservoirs has been developed as part of a project to develop CCS-Ready Guidelines for the Global CCS Institute in 2009-10 [1]. This is framed as part of the overall CCS and storage asset lifecycle which may last 60-70 years from initial screening to stewardship. It is based on a stage gate process used by industry for large scale energy project development. The assessment is divided into nine stages, five of which cover activities up to the major investment and development decision that must include project approval and permitting by all stakeholders. The stages are divided by the major project milestones that are expected to include a) storage exploration permitting/licensing, b) site selection, c) storage project approval and permitting, d) injection start-up, e) closure and f) transfer of responsibility and liability. The stages of the storage assessment process are 1) Regional Prospectivity studies, 2) Catalog of Potential Sites, 3) Site Screening and Selection, 4) Characterisation of Selected Sites, 5) Storage Site Design, 6) Site Development, 7) Injection and storage, 8) Closure and Post-Closure Monitoring and 9) Long-term Stewardship.

The overall project goals, the generalised scope of activities involved, and time required are presented for each stage in Figure 1, together with the major milestones. Storage activities such as site characterisation, selection, and monitoring plans as required in emerging regulatory frameworks are incorporated, along with drilling and seismic activities. Through the successive stages the technical objective is to reduce or better quantify geological uncertainty and risk associated with the prospectivity assessment of the storage site capacity, injectivity, containment and integrity. A major consideration for saline reservoirs is the requirement for new exploration and appraisal activities to address the technical and environmental objectives for site characterisation and project approval and injection permitting by regulators and to provide the confidence required to commit to long term CO<sub>2</sub> offtake/ storage contracts that will underpin the upstream capture and transport investments.

The timeframes for each stage are based on the types of activity involved and include experience from existing projects. The timeframes in Figure 1 are generic in nature, and actual timeframes for specific projects will depend on the site characteristics, scope of activities required, regulatory frameworks and the industry environment as well as public attitudes to the project and how long it takes to gain public acceptance. The storage activities and project development timeline will need to be fully integrated with and to proceed in step with capture and transportation. The two initial stages of screening are now well advanced for many sedimentary basins in areas where CCS is currently of interest. Once permitting and licensing regimes for saline reservoirs are in place and exploration permits are awarded, between 3 and 8 years may be required ahead of project approval. This period would include exploration and appraisal and detailed site characterisation activities. Few sites have progressed through the detailed site selection process, at which based on analogies with oil and gas exploration, a significant percentage are likely to fail, and thus new sites will need to be considered. Site development may take 1-3 years before injection begins. The injection period may last up to 50 years. The post injection phase is usually expected to be divided into two stages based on regulatory frameworks, and transfer of liabilities from the operator to the regulator. The duration of these stages is uncertain at present. In Europe the CCS Directive specifies that this period should normally be no shorter than 20 years, unless the first conditions required for transfer have been met before the end of that period.

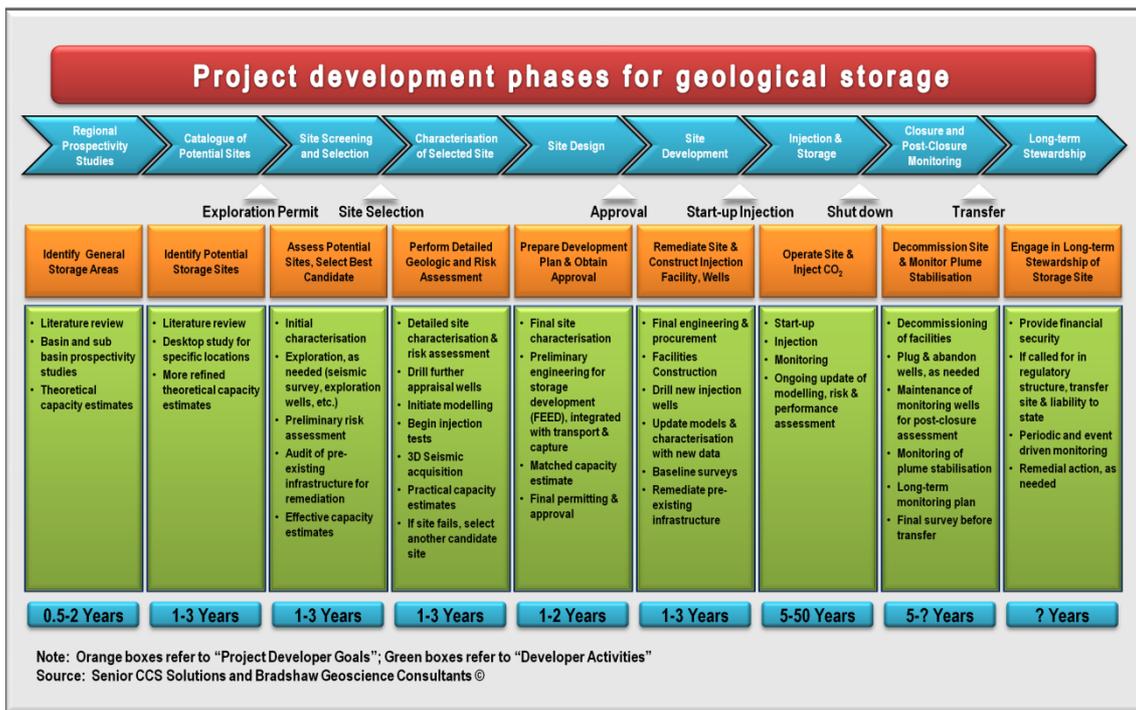


Figure 1: Stage Gate Framework for Storage activities in Saline Reservoirs [from 1]

### 3. Screening Activity

The initial activities and first two stages involve geological screening studies to identify potential storage areas and make preliminary capacity assessments ahead of exploration permitting. These will generally be desk-top studies using pre-existing data. In many areas these types of studies have been conducted with some public support and are publically available ahead of licensing and competitive processes for exploration permitting. Such pre-competitive activities are required to assist industry in the assessment of storage sites, although industry is likely to make their own independent assessments. Screening activity will progressively focus from country to regional to local (prospect) scales, with a mixture of government and industry funded activities. Examples of likely costs and work years effort are shown in Figure 2 based on experience from work completed in Australia covering both onshore and offshore basins. This presents a specific practical example of the work years (effort), costs and duration to complete a series of precompetitive data assessments from the world scale to the local scale. Note: the brackets (e.g.200) indicate pre-existing work effort that allowed the storage site assessments to occur more rapidly; for instance pre-existing petroleum prospectivity data sets and knowledge.

ASSESSMENT SCALE /CATEGORY	WORLD	COUNTRY	PROVINCE (STATE)	BASIN	SUB-BASIN
WORK YEARS	0.5 (200)	6 (120)	8	2	4
COST	\$50K	\$1 Mill	\$2 Mill	\$1 Mill	\$0.75 Mill
LEVEL	BASIN	BASIN	BASIN / PLAY	PLAY / SITE	PLAY / SITE (SCREENING)
GOVERNMENT, INDUSTRY	GOVERNMENT	GOVERNMENT	GOVERNMENT	GOVERNMENT, INDUSTRY	INDUSTRY
DURATION (YRS)	0.25	2	1	0.5	1

Figure 2: Storage Screening Studies - Duration, Effort and Costs at Different Scales in Australia

#### 4. Exploration and Appraisal

Due to the limited data and geological understanding available during the initial screening for most saline reservoir CO<sub>2</sub> storage opportunities, such sites are likely to require additional exploration and appraisal activities. These activities may be required for any type of storage option although they may not be necessary for storage options in oil and gas fields, unless further data are needed for storage assessment and site characterisation. The exploration and appraisal activities could include seismic reprocessing, 2D and/or 3D seismic acquisition, processing and interpretation, drilling new wells (with comprehensive sampling, coring and logging) and injection testing. These activities are assigned to take place during the site screening/selection and characterisation stages. In many areas, including the EU and Australia, storage exploration permits or licences are required before such activities take place.

An exploration programme will almost always be required for saline reservoirs and this is assigned to the site screening and selection stage which at a generic level could take up to 3 years with expenditure of millions of dollars. This would involve data acquisition to prove sites in a practical and technical sense, and not in theory and is likely to require seismic reprocessing and acquisition and drilling new wells which acquire significant core material in the target geological formations. Coring is likely to involve both the reservoir and seals (unlike oil and gas operations where this does not usually occur). Appraisal wells, 3D seismic and injection tests may be required in the subsequent site characterisation stage. Detailed characterisation of the storage site and storage complex is an essential and vital step ahead of the permitting of a site for storage development and injection operations. This phase involves extensive detailed studies by the operator to define the geological framework of the site and surrounding complex, and to model it in three dimensions through initial versions of static and dynamic models and to conduct detailed risk assessment. Additional studies may be needed to look at leakage risk from any pre-existing wells that may penetrate the storage complex.

The amount of time required from initial screening to the project investment decision could take more than ten years for some sites depending on the quality and amount of pre-existing data that is available, the status of licensing and regulatory frameworks and the pace of stakeholder approvals. The costs involved may be substantial. Generic cost estimates, solely for drilling and seismic costs, based on industry experience in Australia are presented in Figure 3. Dependent on the complexity of the potential storage site, and the amount of pre-existing data and knowledge, then based on the example in Figure 3, the costs to find and prove a storage site could range from AU\$19 to AU\$85 million (onshore) to AU\$58 to AU\$270 million (offshore). Additional costs for technical studies and office based personnel and support costs, could add another 50% to the overall exploration and appraisal drilling and seismic costs. The poorer the reservoir injectivity and the larger the volume of CO<sub>2</sub> to be injected and stored, then the greater the overall costs. The storage assessment for the ZeroGen project in south east Queensland in Australia commenced in the onshore Bowen Basin in 2005, after preliminary planning in 2004. To date 12 wells, including an injection well, have been drilled and over 5,000 m of core acquired over six years.

Storage costs should not only include the costs of performing the storage at a proven site, but also the exploration and development costs. Many assessments for costs of storage do not allow for the “finding” costs in their estimates, or grossly underestimate the likelihood of such costs. As such, any published costs for storage need to be carefully scrutinized to determine whether assessment, data, exploration and appraisal costs are included. When considering large industrial-scale injection of CO<sub>2</sub> over a 30- to 50-year period, and where geological uncertainty needs to be resolved to allow substantial financial investment for construction of a power plant and pipeline, geological storage exploration may be similar to exploration in the oil and gas industry as discussed further below. If exploration occurs in a well-proven mature sedimentary basin with a large number of existing wells and good spatial seismic coverage, the likelihood of geological uncertainty in the exploration phase will be lower than in an immature unexplored basin with complex reservoir characteristics. Geological uncertainty can substantially increase finding costs, as well as result in the need to obtain a large amount of data prior to reaching a level of probability that is sufficient for financial and planning purposes. However, whilst higher geological certainty may occur in mature oil and gas provinces, geological storage of CO<sub>2</sub> in such areas can introduce other uncertainties such as the

impacts associated with conflict of use of the subsurface, and the likelihood of leakage through abandoned wells that are not compliant for CO<sub>2</sub> storage.

Anticipated costs for geological storage in saline reservoirs		Item	Number		Cost (\$mill AUS)		Total (\$mill AUS)		Comment	
			From	To	From	To	From	To		
Onshore	Exploration	Well	1	5	3	5	3	25		
		Seismic 2D	1	1	3	5	3	5		
							Sub-Total	6	30	
	Appraisal	Well	2	10	5	5	10	50	Dependent on the location, many more wells may be required	
		Seismic 3D	1	1	3	5	3	5	More localised, and/or higher resolution seismic survey	
							Sub-Total	13	55	
						TOTAL	19	85		
Offshore	Exploration	Well	1	5	15	30	15	150		
		Seismic 2D	1	1	3	5	3	5		
		Seismic 3D	1	1	5	15	5	15		
							Sub-Total	23	170	
	Appraisal	Well	2	3	15	30	30	90	Dependent on the location, many more wells may be required	
		Seismic 3D	1	1	5	10	5	10	More localised, and/or higher resolution seismic survey	
						Sub-Total	35	100		
						TOTAL	58	270		

Figure 3: Potential exploration and appraisal drilling and seismic generic costs to prove a storage site in saline reservoirs (\$AUS)

## 5. Investment Issues and Risks

Ensuring that a chosen site will allow for safe and secure storage is a pre-requisite for any site that will be used for storage, and is a key aspect of the assessment programme. The activity must also address the regulatory and stakeholder requirements in the specific jurisdiction which may include site characterisation, modelling, monitoring, corrective measures, transfer obligations, etc. In this section we also consider how these and other issues and uncertainties impact the business case for investing in storage.

A key risk that has not been adequately considered is the risk that a viable storage site is not proved up by site evaluation and characterisation activity, including exploration and appraisal activities. Possible reasons this may occur could be because suitable trapping, seal and reservoir conditions are not confirmed and therefore storage integrity risk, capacity or injectivity is inadequate for the proposed project. Alternatively technical uncertainty may be too high. This can be considered broadly analogous to exploration and appraisal risk for oil and gas exploration, typically between 1 in 3 and 1 in 10 for commercial discoveries of oil and gas [5]. To date the quantification of storage exploration risk has not yet been developed or calibrated, although it may be significant if it is comparable to oil and gas exploration risk. An example of this risk is beginning to emerge from proposed CCS projects where desktop screening fails to identify a suitable site (i.e. it has low geological integrity) even though pre-existing studies suggested potential storage capacity was available; just as happens in the oil and gas exploration industry. One significant difference between storage and oil and gas exploration risks is the continuing seal risk throughout the injection and post-injection stages of a storage project, unlike oil and gas exploration where seal risk is essentially proven by a discovery.

Another major consideration is the business and regulatory risk for the storage investor. Providing storage solutions for CCS deployment and capture by major emitters is widely described as new opportunity for the oil and gas industry or new entrants. New business models will need to be developed providing remuneration for the storage provider's investment from CCS value chains. There are sources of value from existing oil and gas assets, local geological data and knowhow, skills and capabilities. The oil industry's

control of assets and data may impact the availability of storage sites, other stakeholder's ability to conduct assessments, costs and access and therefore wider deployment of CCS and opportunities for new entrants. In all cases developers will need to build confidence in the primary source of revenue from carbon abatement which is underpinned by Government policy.

However, there are a number of issues that impact the risk/reward balance and attractiveness of these as a business opportunity. These include the uncertainty surrounding climate change policies in various key countries, uncertain and long term nature of monitoring obligations, uncertainties around the management and transfer of long-term liabilities, exploration risk in saline reservoirs and potentially low or negative returns. There are also risks that storage sites will become unavailable as they are prioritised for other uses, such as gas storage or discovery of hydrocarbons, or for non-technical reasons. There will continue to be a significant risk for the storage provider during the operational and closure stages of any project, after any injection revenues cease. This will result from continued technical uncertainty and risk about exactly how the CO<sub>2</sub> will behave in the reservoir and overburden, integrity risk and the impact of injection on surrounding resources and operations. These result in continued business risk and highlight the possible need for policy interventions. Insurance schemes for long term storage are at a very early stage of development and some companies doubt these will be a suitable alternative to managing the risk through the balance sheet or risk sharing with government. Finally there may be issues around public acceptance of storage and specific projects, which have arisen as potential barriers for projects in other countries. Some regulatory risk will continue up until the final transfer of liability.

Overall, the business risk for storage investments by the private sector may be considered high. Furthermore, the overall risk profile and uncertainties are greater for saline reservoir prospects than oil and gas fields, however saline reservoirs offer a very much larger storage resource potential. For an integrated development of a power plant with capture, transport of the CO<sub>2</sub>, and geological storage, the need to prove a geological storage site first is both prudent and paramount to a successful outcome. Whilst most of the cost for a CCS project is with the capture and power plant, almost all of the risk of success and the uncertainty is in the storage, in the subsurface. Proving a storage site will take several years, and just like oil and gas exploration there will be false starts and failure to prove a site; requiring new exploration activity. The oil and gas industry handle these outcomes by management of a portfolio of drilling opportunities in a range of sedimentary basins and countries, with a joint venture arrangement to share/spread the financial risks of geo-technical failure. For integrated CCS projects, pre-existing power plants suitable for retrofit obviously can't move, and locating new power plants require substantial time for specific site planning and approvals, as do pipeline developments. Thus becoming "storage ready" as soon as possible in a project is critical for the timely and successful deployment of CCS. At the same time, the potential commercial returns are unclear for geological storage of CO<sub>2</sub>, and it is likely the returns may be significantly lower than the oil and gas business. In summary, developing storage sites may be an uncertain, potentially time-consuming, costly and risky business opportunity.

## 6. Storage Ready

The concept of "CCS Ready" is intended to avoid the risks relating to carbon lock in for carbon-emissions-intensive plants while technical, economic, regulatory, and policy barriers are addressed. CCS Ready policies are intended to facilitate a smooth transition to CCS deployment. CCS ready policies have been introduced in some jurisdictions, including UK and EU. In 2010, ICF conducted a review of literature and proposed definitions of CCS Ready on behalf of the GCCSI. Most of the early literature on this topic ignored storage considerations, although some literature mentions the need for identifying appropriate storage sites and transportation routes, without addressing storage requirements in detail. In 2005, the G8 invited "the IEA to work with the CSLF to study definitions, costs, and scope for 'capture ready' plant and consider economic incentives." Following this request, the IEA Greenhouse Gas R&D Programme proposed a definition of capture ready which included the need for identification of reasonable route(s) to storage of CO<sub>2</sub> [6].

The ICF report [1] recognised the imbalance between capture and storage considerations in existing CCS Ready definitions and developed alternative definitions of a Storage Ready plant in more detail. These are especially important for saline reservoirs because of the potential time and costs in the assessment, selection and characterisation of storage sites as explained in this paper. The report presented a preferred definition of storage ready, along with three alternatives representing increased levels of definition and stringency for consideration by policymakers. The preferred definition for a CO<sub>2</sub> Storage Ready plant would be where it satisfies all or some of the following criteria:

- One or more storage sites have been identified that are technically capable of, and commercially accessible for, geological storage of full volumes of captured CO<sub>2</sub>, at an acceptable economic cost;
- Adequate capacity, injectivity, and storage integrity have been shown to exist at the storage site(s);
- Any conflicting surface and subsurface land uses at the storage site(s) have been identified and/or resolved;
- All required environmental, safety, and other approvals have been identified;
- Public awareness and engagement activities related to potential future storage have been performed;
- Sources for equipment, materials, and services for future injection and storage operations have been identified; and
- Storage Readiness is maintained or improved over time as documented in reports and records.

The ICF report strongly suggested that policies for CCS Ready, and in particular storage readiness, be put in place as soon as possible in order to reduce the potential for carbon lock-in.

## 7. Conclusions

The systematic framework for storage activities presented in this paper can be used to improve understanding of the work programme, project stages, time, costs, technical and business risks involved in geological storage site assessment and development. This illustrates the timeframes that may be required for saline reservoirs taking account of exploration and appraisal activity. The initial stages of screening activity for saline reservoirs, both of which will generally be required ahead of exploration permitting, may take between 1.5 and 5 years. Once permitting and licensing regimes for saline reservoirs are in place and exploration permits are awarded, a further 3 - 8 years may be required ahead of project approval and storage permitting. Exploration and appraisal activities are likely to be required for most saline reservoir CO<sub>2</sub> storage opportunities due to the limited data and geological understanding after initial screening. These could include 2D and/or 3D seismic acquisition, processing and interpretation, drilling new wells (including coring) and injection testing. In addition to taking several years, these represent a substantial cost. An emerging issue is the funding of exploration and appraisal activities. Industry may be reluctant to meet these costs and public support may be required. There are further concerns for storage in saline reservoirs that include exploration risk, policy and regulatory risk and potentially low returns. In view of these issues the storage aspects of CCS Ready are of particular importance due to the long timeframe and necessary investment in geological assessments. In summary, in the current policy environment developing storage sites may be an uncertain, potentially time-consuming, costly and risky business opportunity. If CCS is to be deployed at industrial scale to mitigate climate change, these limitations will need to be rapidly resolved by policy makers and so provide industry with the appropriate incentives to proceed. Delay in implementing these policies and incentives will hamper the development of a commercial storage industry, further putting CCS technology development at risk.

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