SRMS
Guidelines

Guidelines for Applications of the CO_2 Storage Resources Management System

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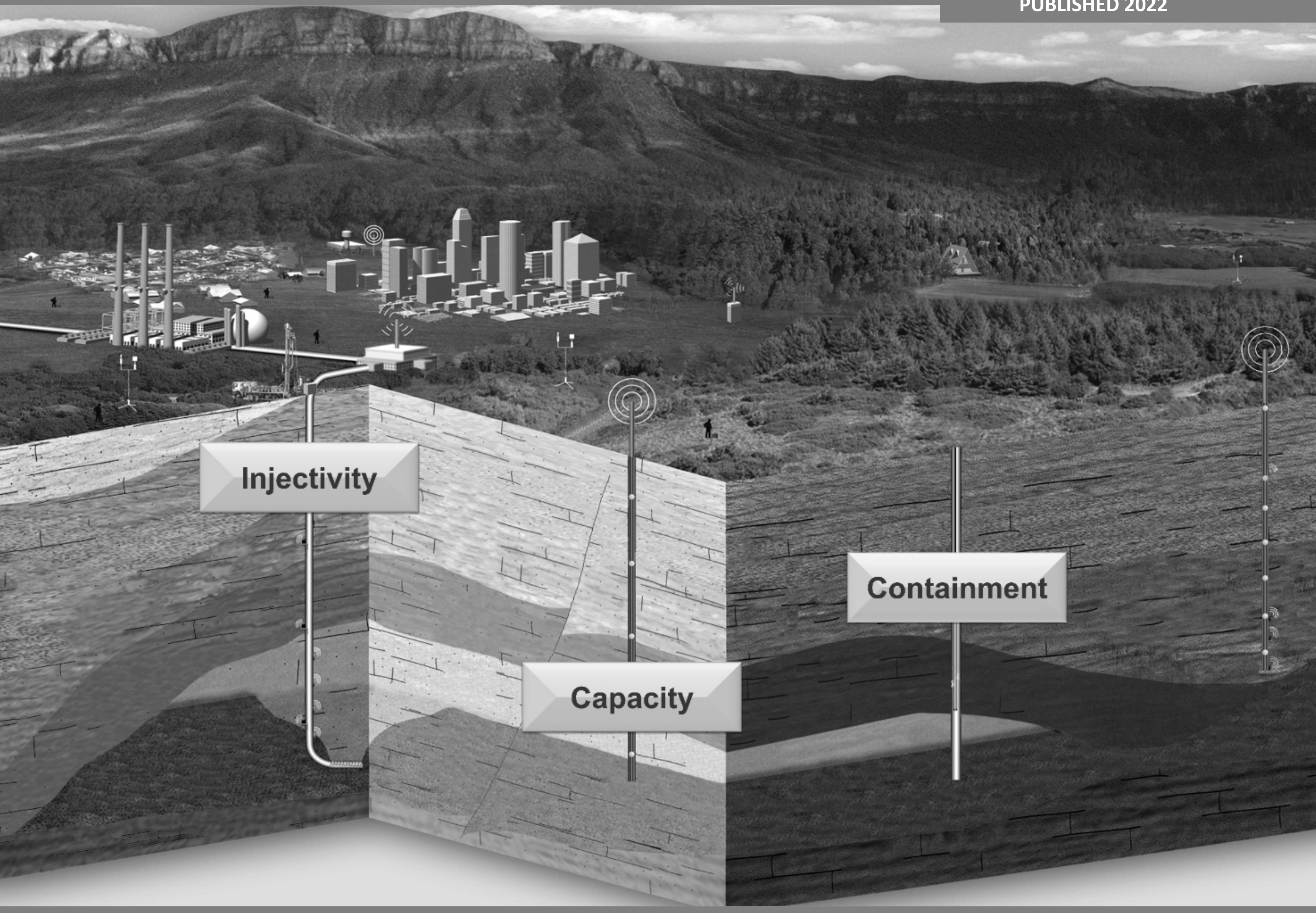

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(Accepted October 2021)

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1.0 Introduction

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1.1 Rationale for Applications Guidelines

The precedent of the *PRMS Guidelines for Application of the Petroleum Resources Management System* (2011; hereafter referred to as "PRMS Guidelines") to supplement the *Petroleum Resources Management System* (2007; hereafter referred to as "PRMS") highlighted the importance of guidelines to the *CO_2 Storage Resources Management System* (2017; hereafter referred to as "SRMS"). The SRMS, a project-based system, is independent of implementation and, therefore, does not provide advice. The SRMS guidelines include suggestions for the application of the SRMS with the intent of including details of the processes of quantification, categorization, and classification of storable quantities so that the subjective nature of subsurface assessments can be consistent between storage resource assessors. As more experience is gained in how commercial project frameworks will be developed, the SRMS and these guidelines will be updated.

1.2 Complementarity of the PRMS Guidelines

The SRMS was modelled on the PRMS. This was a deliberate choice aimed at making the development of storage resources clearer by drawing parallels with the well-known and understood process of maturing petroleum resources. Although a voluntary system, the intent is that regulators, government departments, and financiers will be able to draw upon the experience of managing petroleum resources to advise on the management of storage resources.

1.3 Key Concepts in CO_2 Storage

The aim of geologic storage is separation of CO_2 from the linked ocean-atmosphere system and containment for a significant period of time (e.g., thousands of years) with the expectation of permanence. CO_2 can be stored in geologic structures (e.g., an anticline) or in regionally extensive dipping geologic formations. Inherent in storage is that displaced fluids (e.g., brine or hydrocarbons) are managed. The storage mechanisms are geologic (structural and stratigraphic), residual, solubility, and mineral trapping. In the context of the SRMS and these guidelines, CO_2 storage is used throughout and is synonymous with sequestration.

As clearly stated in the SRMS (2017, Introduction), a CO_2 storage resource is defined as the quantity (mass or volume) of CO_2 that can be stored in a geologic formation. The key point in the definition is the phrase "can be stored," as this implies a future action, quantification, and containment. The need to show that injected CO_2 can be contained in a geologic formation is the key difference between exploring for CO_2 storage resources and exploring for petroleum accumulations. Additionally, for active projects, Stored CO_2 or the storage process may have collateral effects (e.g., induced seismicity) that may cause changes or cessation to the project, which affect the estimate of storable quantities.

1.4 Basic Principles and Definitions

1.4.1 Project-Based Resources Evaluations. The SRMS is a 2D array of (1) project maturity (*classification*) and (2) certainty of storable quantities estimates (*categorization*). There are two broad project maturity–based CO_2 storage classifications: undiscovered and discovered storage resources. *Prospective Storage Resources* are undiscovered, while *Contingent Storage Resources* are discovered until a project has financial commitment to commence injection. After this level of project maturity, the storable quantities estimate is called the *Storage Capacity*. The *Resources* and *Capacity* classifications are specific to the potential to store CO_2, while the classification *Stored* is CO_2 previously injected and contained. *Categorization* of certainty of a storable quantities estimate is made within each classification: low, best (or most likely), and high estimates.

The nature of a classification system will always be subjective. However, the universal application of a classification system must have some definitive criteria for each classification so that clear and understandable guidelines can be applied. For example, separating discovered from undiscovered storage resources is the availability of a well with adequate data for estimating storable quantities.

Like the PRMS, the SRMS will develop and evolve as stakeholders use the system. At this time, the SRMS will provide a classification system that is familiar to those in subsurface hydrocarbon assessments and investments, which should encourage more carbon capture and storage (CCS) projects.

1.4.2 Storage Resources Classification Framework. The SRMS combines certainty in the estimate of storable quantities with maturity of a project intended ultimately to inject and store CO_2. The use of terms to represent various, but specific, combinations of certainty and project maturity is intended not only to improve notable differences between CO_2 storage estimate methods and certainty of storage estimates but also communications between stakeholders that will promulgate CO_2 storage.

The subjective nature of assessments of storable quantities is based on the simple fact that these assessments are all projections into the future of development projects and subsurface processes. The ranges and distributions of specific values that quantify geologic terms (e.g., formation thickness) can be used to estimate low, most likely, and high estimates (or, probabilistically, P90, P50, and P10) of storable quantities for an area or region associated with a project or a development plan.

Confidence in storable quantities estimates increases with quantity, quality, and data types available at the time of the assessment. Generally, more data becomes available as a project matures (e.g., before and after a potential CO_2 injection well is drilled or before and after an injection test). Additionally, the inclusion of project maturity reflects the commitment of an entity to provide adequate resources such that a project will meet the development project's specifications. This provides a relatively strong indication of the entity's confidence in the storage resource assessment.

As an example, low maturity or notional project may be a regional or basin assessment of a single geologic formation for CO_2 storage, which might be a site screening process leading to a site selection for drilling a well. A high-maturity project may be an assessment of the geologic formation penetrated by a single injection well and single monitoring well that is fully characterized and awaiting completion of surface pipeline to deliver CO_2 to the injection well. A third party's (e.g., financier) confidence in the storable quantities should be much higher in the case of the project with higher maturity.

1.5 SRMS Guidelines Scope

The SRMS is intended to be used for CO_2 storage in brine aquifers and abandoned oil and gas reservoirs. While the SRMS may be applicable to CO_2 injection with the intended purpose of enhancing oil production, the SRMS was not developed for this application.

In this document, Chapter 2: Classification and Categorization Guidelines develops ideas for labeling storage estimates and CO_2 storage projects in the context of the SRMS framework, while Chapter 3: Project Evaluation and Reporting Guidelines provides economic considerations. Chapter 4: Estimating Storable Quantities provides methods to make calculations based on the data available at the time the storage estimate is made.

Chapter 5: Analogy and Differences of SRMS to PRMS contrasts and compares the PRMS and SRMS. Chapter 6: Data Used to Characterize a Geologic Formation for a Storage Project includes data typically required to characterize a site in the context of categorizing and classifying storage resources. Three examples are given in Chapter 7: Case Studies and Examples of Storage Resource Classifications. Chapter 8: Glossary has terms unique to the SRMS Guidelines and does not repeat terms found in the SRMS.

2.0 Classification and Categorization Guidelines

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2.1 Resources Classification

2.1.1 Introduction. The SRMS is a fully integrated system that provides the basis for classifying and categorizing storable quantities of CO_2. The system encompasses the entire resource base and is focused on estimates of Capacity (i.e., commercial storable quantities), as well as Prospective and Contingent Storage Resources. Because storage resources cannot be used for storage without the installation of (or access to) appropriate transportation and injection facilities, the SRMS is based on an explicit distinction between (1) a development project that has been (or will be) implemented to store CO_2 from one or more facilities generating CO_2 and, in particular, the chance of commerciality of that project (i.e., classification), and (2) the range of uncertainty in the storable quantities that are forecast to be injected and stored from that development project (i.e., categorization).

Within each of the three main resource classes, the range of uncertainty (shown left to right in **Fig. 2.1**) in the estimated storable quantities resulting from a specific project is categorized with the intent to use at least three scenarios (e.g., different development scenarios within a specific project and/or geologic uncertainty associated with each scenario) of the potential outcome: low, best, and high (or P90, P50, and P10). Within each class, low, best, and high are represented as 1, 2, and 3, with the letter P, C, or U following each number symbolizing Capacity (P), Contingent Storage Resources (C), and Prospective Storage Resources (U).

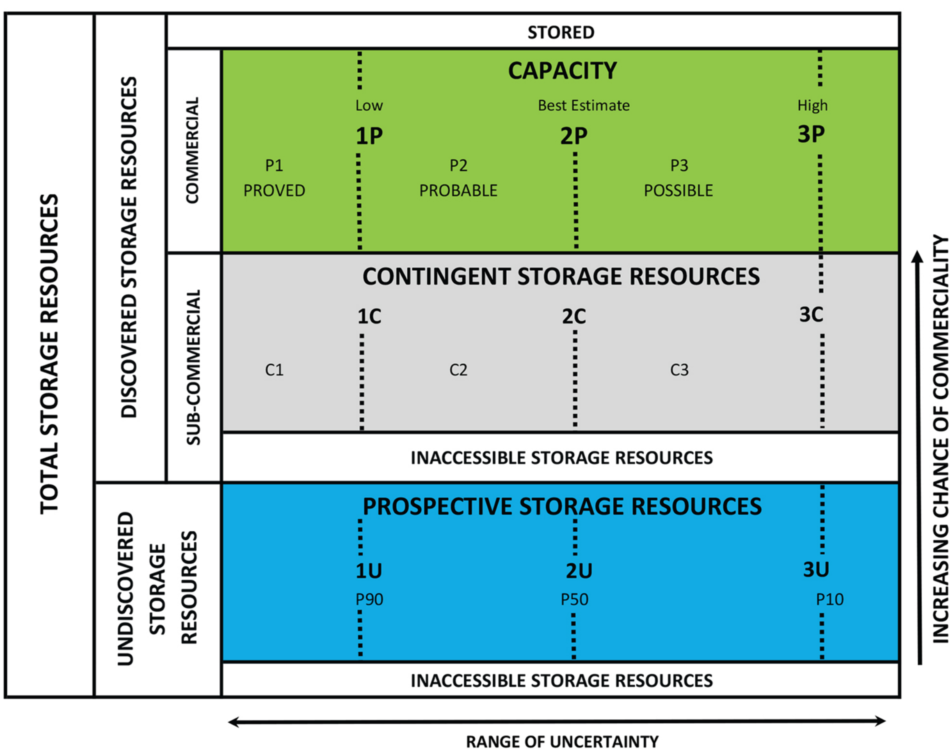

Fig. 2.1—Resources classification framework. Image taken from SRMS (2017).

Projects represent the link between storable quantities and the project-related decision-making process, including (but not limited to) permitting, engineering, construction, and budget allocation. A project may, for example, constitute the development of a single geologic formation, or an incremental development of several geologic formations with integrated development of several storage sites and CO_2 generating facilities with a common ownership. In CO_2 storage, a notional project can simply represent the assessment of a regional storage resource. In general, an individual project will represent a specific maturity level at which a decision is made as to whether to proceed (i.e., further invest or allocate resources), accompanied by an associated range of storable quantities.

Capacity is assigned to storable quantities for projects that satisfy commerciality requirements. The three cumulative Capacity categories of commercially storable quantities are designated as 1P (Proved), 2P (Proved plus Probable), and 3P (Proved plus Probable plus Possible). The equivalent categories for storable quantities of projects classified as Contingent Storage Resources are 1C, 2C, and 3C, while 1U, 2U, and 3U are used for storable quantities of projects with Prospective Storage Resources (i.e., Undiscovered). Capacity can be categorized and reported as incremental quantities (instead of cumulative): Proved (P1), Probable (P2), and Possible (P3). The same principle applies to Contingent Storage Resources; for instance, a best or 2C estimate is the sum of the incremental quantities C1 and C2. Mathematically, this is shown as follows:

Capacity:

- 1P = P1
- 2P = P1 + P2
- 3P = P1 + P2 + P3

Contingent Storage Resources

- 1C = C1
- 2C = C1 + C2
- 3C = C1 + C2 + C3

Prospective Storage Resources

- 1U = U1
- 2U = U1 + U2
- 3U = U1 + U2 + U3

The relationship between the cumulative quantities and incremental quantities is illustrated in the following example:

If:

- 1P = Low estimate scenario or Proved Capacity = 1 Mtonne CO_2
- 2P = Best estimate scenario or Proved + Probable Capacity = 1.5 Mtonne CO_2
- 3P = High estimate scenario or Proved + Probable + Possible Capacity = 1.75 Mtonne CO_2

Then:

- P1 = Proved Capacity = 1P = 1 Mtonne CO_2
- P2 = Probable Capacity = 2P – 1P = 0.5 Mtonne CO_2 (increment between 1P and 2P)
- P3 = Possible Capacity = 3P – 2P = 0.25 Mtonne CO_2 (increment between 2P and 3P)

Resource classification requires that criteria be established for the discovery of storable quantities, and, thereafter, criteria for the distinction between commercial and subcommercial projects (i.e., Capacity and Contingent Storage Resources). Implicit in the assessment of storable quantities is the assessment of containment of the Stored CO_2, as defined by the project.

This chapter describes how to classify storable quantities based on the maturity of the evaluated project(s) (the vertical axis, **Fig. 2.2**), and how to categorize storable quantities to show the range of uncertainty (the horizontal axis, Fig. 2.2).

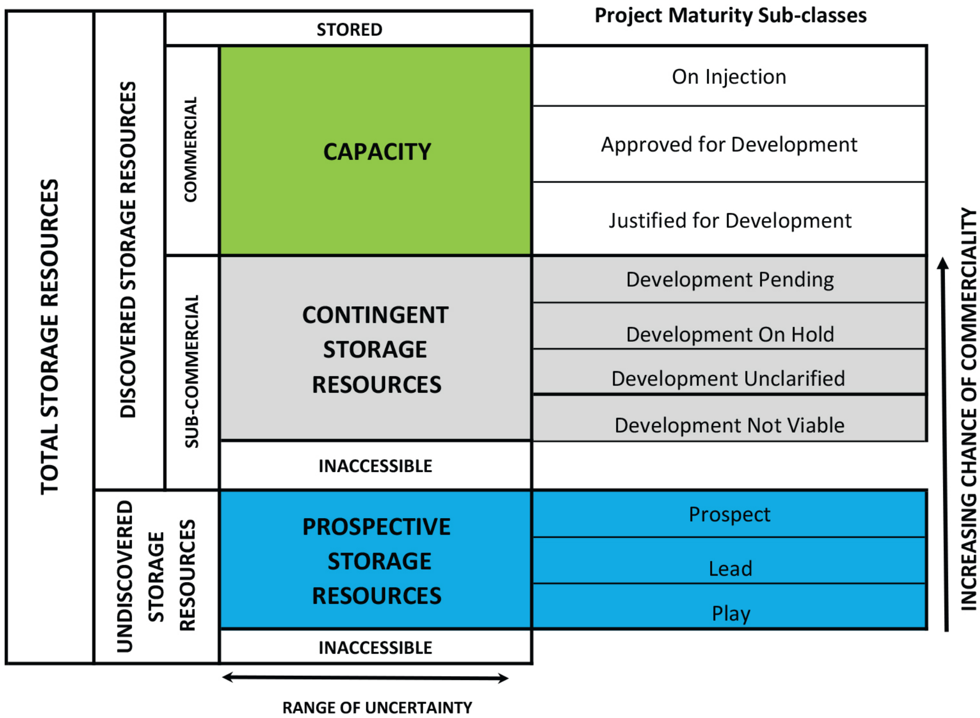

Fig. 2.2—Storage resources classes and subclasses based on project maturity. Image taken from SRMS (2017).

2.1.2 Determination of Discovery Status. A discovery is defined as one geologic formation, or several geologic formations collectively, for which the existence of "significant" storable quantities for the proposed project has been established from one or several wells (that may be offset to the project) through well testing, core analyses, and/or logging. (Seismic data may be necessary if lateral existence of the geologic formation is unknown.) For a geologic formation to be deemed to have storable quantities, it must (1) have pore volume accessible to CO_2 (quantity and sustained injection rate commensurate with the project requirement) and (2) be suited for containment (e.g., existing wellbore and caprock integrity) of the Stored CO_2 over a time period established by the project.

For storable quantities to be classified as Discovered Storage Resources, the geologic formation must be established as being suitable for injection and containment of injected CO_2. The following are examples of this:

- Core data, log data, and seismic data providing direct and convincing evidence (from the geologic formation) of a significant pore volume of permeable formation, and suitable caprock that will provide containment.
- A well test (production or injection) of any test fluid within all or a subinterval of the geologic formation at relevant flow rates that support the expectation that the planned number of injection wells can achieve the annual quantity of CO_2 injection, and that this injection can be sustained over the life of the project.

- A reasonable expectation that Stored CO_2 will not migrate vertically or laterally out of the specified area and geologic formation(s).

The evaluation of a storable quantities discovery is always at the level of the geologic formation(s), but the assessment of storable quantities in a geologic formation must be based on a defined (or at least notional) project.

The requirement for "direct and convincing evidence" (i.e., testing, core analyses, and/or logging) is met if at least one well penetrating the geologic formation (or group of formations) demonstrates "significant" storable quantities. In this context, "significant" implies that there is evidence of sufficient storable quantities to justify maturing a project assessing commerciality (Section 2.1.4.4 Maturation of Storage Projects).

Drilling of an exploration prospect represents an immature project that could become a commercial development (Section 2.1.4.4 Maturation of Storage Projects). A project's specifications may change over time and can aggregate or subdivide. For example, an exploration project may initially be defined on the basis that, if a discovery is made, the storable quantities will be developed as a standalone project and classified as a Discovered Storage Resource. However, if the discovery of storable quantities is smaller than expected and perhaps unable to support storage facilities (per the project's specifications), the project might be classified as Contingent Storage Resources, subclass Development On Hold, and delayed until, for instance, another discovery is made or other conditions change, making a development commercially viable. Then the two discoveries could be aggregated and developed as a single project that is able to justify the cost of development of both discoveries. The subsequent investment decision is then based on proceeding with a development plan that includes the two sites as a single project using shared facilities. Again, the key is that the project is defined based on which investment decision is made.

Similarly, Discovered Storage Resources may initially be considered as a single development opportunity and then subsequently be subdivided into two or more distinct projects. For example, the level of uncertainty (e.g., in storable quantities) may make it prudent to implement a pilot project first. The initial concept of a single formation development project then becomes two separate projects: (1) the pilot project and (2) the subsequent development of the remainder of the formation, with the latter project contingent on the successful outcome of the former.

Storable quantities in a discovery are classified as Contingent Storage Resources until a defined project satisfies all the criteria necessary to reclassify some or all the storable quantities as Capacity. In cases where the discovery is, for example, adjacent to a planned or existing CO_2 generating facility, and a commercially viable development storage project is immediately evident and planned, the storable quantities may be immediately classified as Capacity. More commonly, the storable quantities for a new discovery will be classified as Contingent Storage Resources while further appraisal and/or evaluation is carried out. Discovered Storage Resources that are not usable for future storage development projects may be classified as Discovered Storage Resources–Inaccessible.

2.1.3 Determination of Commerciality. The criteria for commerciality (and hence assigning Capacity to a project) are outlined in Section 2.1.2 Determination of Discovery Status and Section 3.1 Commercial Evaluations in these guidelines. All active storage projects must have, at a minimum, capital committed to meet expenses. From an assessment perspective, the storage project can be defined as integrated or standalone (Section 3.1.1 Introduction). Furthermore, each project's specifications will define commerciality metrics for use in estimating storable quantities and maturing projects.

A project may be considered as an investment to determine the value of the storage resource and project decisions reflect the selection or rejection of project opportunities from a portfolio based on consideration of financial metrics, including the total investment funds available, the amount of the specific investment, and the expected outcome (in terms of resource determination) of that investment. The project is characterized by its "itemized" expenses (i.e., adequate description so that it is clear what part of the project the expense can be assigned) and provides the fundamental basis for portfolio management and decision making. In some cases, projects are implemented strictly based on strategic drivers (e.g., proof of concept of a technology or demonstrated commitment to a project) but are nonetheless defined by financial metrics. The critical decision is whether to proceed with a project and the estimated storable quantities associated with that project.

2.1.4 Project Status and Maturation. Storable quantities for any project must be assigned to one of the three classes: Capacity, Contingent Storage Resources, or Prospective Storage Resources. Further subclassification and subdivision are optional. The subclassification and subdivision systems can be used together or separately. The project maturity–based subclassifications are available for all three classes; however, further subdivision based on active storage operations is limited to the Capacity class and referred to as *Capacity Status*.

2.1.4.1 Project Maturity Subclasses. As illustrated in Fig. 2.2, development projects (and their associated storable quantities) may be subclassified according to project maturity, based on the associated actions (i.e., business decisions) required to mature a project toward commercial storage. This approach supports managing portfolios of opportunities at various stages of exploration and development and may be supplemented by associated quantitative estimates of a project's chance of commerciality using risk analyses. The boundaries between different levels of project maturity may align with internal (corporate) project decision criteria, thus providing a direct link between the decision-making process within a company and management of its portfolio through resource classification. This link can also act to facilitate the consistent assignment of appropriate quantified risk factors affecting the chance of commerciality.

If the SRMS subclasses are not suitable for a specific project, alternative subclasses and project maturity modifiers may be adopted (and must be properly defined and documented as part of the evaluation process) to align with the decision-making process, but advancing projects toward commercial injection (i.e., increasing the chance of commerciality) should remain the impetus for applying the alternative classification system and supporting portfolio management. Note that, in quantitative terms, the "chance of commerciality" arrow shown in Figs. 2.1 and 2.2 is not intended to represent a linear scale, nor is it necessarily wholly sequential in the sense that, for example, a Contingent Storage Resource project that is classified as Development Not Viable could have a lower chance of commerciality than a different project classified as Development Unclarified. In general, however, quantitative estimates of the chance of commerciality will increase as a project matures from an exploration concept to a storage site with active injection.

If the subclasses in Fig. 2.2 are adopted, the following guidelines should be considered in addition to those in Table 1 of the SRMS:

1. **On Injection** is self-explanatory. The project must be able to inject and store CO_2 at the effective date of the evaluation. Although implementation of the project may not be 100% complete at that date, and some of the Capacity may still be undeveloped, the project must have all necessary approvals and contracts in place and capital funds committed. If a part

of the project development plan is still subject to approval and/or commitment of funds, that part should be classified as a separate project in the appropriate maturity subclass.

2. **Approved for Development** requires that all approvals/contracts are in place and capital funds have been committed. Construction and installation of project facilities should be underway or due to start imminently. Only a completely unforeseeable change in circumstances that is beyond the control of the developers would be an acceptable reason for failure of the project to be developed within a reasonable time frame.
3. **Justified for Development** is used after the developers agree that the project is commercially viable and decide to proceed with development under an agreed upon development plan (i.e., there is a "firm intent"). This agreement is before a final investment decision has been made by the developers to commit the necessary capital funds and may be before regulatory and other approvals and contracts are in place. If the storage project is dependent on a capture site that is separate from the storage project, then all decisions for the capture site must have the same maturation subclass. The benchmark is that development would be expected to be initiated within five years of assignment to this subclass (refer to Section 2.1.2 Determination of Commerciality in the SRMS for discussion of possible exceptions to this benchmark).
4. **Development Pending** is limited to projects that are actively subject to project-specific technical activities, such as appraisal drilling or detailed evaluation designed to confirm commerciality and/or to determine the optimum development plan. It may include projects that have nontechnical contingencies, if these contingencies are being actively pursued by the developers and are expected to be resolved positively (i.e., such that development can commence) within a reasonable time frame. Such projects would be expected to have a high probability of becoming a commercial development (i.e., a high chance of commerciality).
5. **Development On Hold** comprises two situations. Projects classified as Development On Hold would generally be those that are considered to have at least a reasonable chance of commerciality but also have major nontechnical contingencies (e.g., local stakeholder opposition) that must be resolved before the project can move toward development. The primary difference between Development Pending and Development On Hold is that in the former case, the only significant contingencies are ones that can be (and are being) directly and actively pursued by the developers (e.g., through negotiations), whereas in the latter case, the primary contingencies are subject to the decisions of others over which the developers have little or no direct influence, and both the outcome and the timing of those decisions are subject to significant uncertainty.
6. **Development Unclarified** includes projects that are still under evaluation (e.g., a recent discovery) or require significant further appraisal to clarify the potential for commercial development, and for which the contingencies have not yet been fully defined. In these cases, the chance of commerciality may be difficult to assess with any confidence.
7. **Development Not Viable** includes technically viable projects that have been assessed as having insufficient potential to warrant any further appraisal activities or any direct efforts to remove commercial contingencies. Projects in this subclass are expected to have a low chance of commerciality. Storable quantities may not remain within this classification once it is determined that no project will be matured that can use these storable quantities. At that time, these storable quantities may be reclassified as Discovered Storage Resources–Inaccessible.

It is important to note that while the aim is always to move projects toward higher levels of maturity, and eventually to On Injection, a change in circumstances (e.g., disappointing well results or change in financial metrics) can lead to a project's storable quantities being classified to a less mature subclass due to the decreasing chance of commerciality. It is also important to consider all elements of a storage project needed for its successful operation for it to mature from one subclass to the next. For example, if a project is planning to use brine extraction as a means of pressure control and increase storage efficiency, the development plan must include water management.

One area of possible confusion is the distinction between Development Not Viable and Discovered Storage Resources–Inaccessible. A key goal of portfolio management should be to identify all possible incremental development options for a geologic formation; it is strongly recommended that all technically feasible projects that could be applied to a geologic formation are identified, even though some may not be economically viable at the time of the evaluation. Such an approach highlights the extent to which identified development projects would achieve a level of storage efficiency that is at least comparable to analogous geologic formations. Conversely, if analogous geologic formations are achieving levels of storage efficiency significantly better than the geologic formation(s) under consideration, it is possible that there are development options that have been overlooked.

A project is classified as Development Not Viable if it is not seen as having sufficient potential for eventual commercial development at the time of reporting to warrant further appraisal. However, the storable quantities classified as Development Not Viable assigned to the project should be recorded so that the potential development opportunity will be recognized in the event of a new technology and/or commercial conditions.

If no project is identified that could lead to active injection, the storable quantities should be classified as Discovered Storage Resources–Inaccessible. A portion of these storable quantities may become storable in the future due to the development of new technology or a change in commercial conditions. The remaining portion may never be used due to physical/chemical constraints represented by subsurface interaction of fluids and reservoir rocks. This classification should also be applied to storage resources that underlie environmentally, culturally, or socially sensitive areas such as national parks, monuments, and communities.

The Contingent Storage Resources classification is also used for projects that are dependent on a technology that is under development. It is recommended that the following guidelines be used to classify storable quantities as Contingent Storage Resources (vs. Discovered Storage Resources–Inaccessible):

- The technology has been demonstrated to be commercially viable in an analogous geologic formation.
- The technology has been demonstrated to be commercially viable in other geologic formations that are not analogous, and a pilot project is planned and budgeted to demonstrate commerciality for this geologic formation.
- The technology has not been demonstrated to be commercially viable but is currently under active development, and there is sufficient, direct evidence (e.g., from a test project) to indicate that it may reasonably be expected to be available for commercial application within a defined time. (While five years is recommended as a benchmark, a longer time frame could be applied when, for example, development of economic projects are deferred at the option of the operator for, among other things, market-related reasons or to meet contractual or strategic objectives.)

2.1.4.2 Capacity Status. Storable quantities associated with projects that fully satisfy the requirements for Capacity may be subdivided according to the project's operational status and necessity for future investment. Subdivision by Capacity status includes the following status levels: Developed Injecting, Developed Noninjecting, and Undeveloped. These subdivisions can be applied to all categories (i.e., Proved, Probable, and Possible) and classifications of Capacity, but do not apply to Prospective or Contingent Storage Resources. When developing a storage project, the Capacity should refer to the defined economically viable project. The remainder of the storable quantities, if any, will be Contingent Storage Resources.

Because these subdivisions, categorizations, and subclassifications are to some degree independent of one another, they can be applied together. Such an approach requires some care, as it is possible to confuse the fact that project maturity subclasses are linked to the status of the project as a whole, whereas Capacity status considers the level of implementation of the project's operations essentially on a well-by-well basis. Unless each well constitutes a separate project, Capacity status is a subdivision of Capacity within a project. Capacity status is *not* project-based, and hence there is *no direct relationship between capacity status and chance of commerciality,* which reflects the level of project maturity.

The relationship between Capacity status and project maturity subclasses may be best understood by considering all possible combinations, as illustrated in **Table 2.1.** A project that is On Injection could have Capacity in all three capacity status subdivisions, whereas all of a project's Capacity is Undeveloped Capacity if the project's maturity classification is Justified for Development. A project may be Approved for Development (i.e., may have Capacity associated with installed equipment that is ready to start injecting), in which case Developed Noninjecting Capacity is applicable. The same project may have additional capacity subdivided as Undeveloped Capacity.

Project Maturity Subclass	**Capacity Status Subdivisions**		
	Developed Injecting Capacity	**Developed Noninjecting Capacity**	**Undeveloped Capacity**
On Injection	Proved Developed Injecting Capacity Probable Developed Injecting Capacity Possible Developed Injecting Capacity	Proved Developed Noninjecting Capacity Probable Developed Noninjecting Capacity Possible Developed Noninjecting Capacity	Proved Undeveloped Capacity Probable Undeveloped Capacity Possible Undeveloped Capacity
Approved for Development	–	Proved Developed Noninjecting Capacity Probable Developed Noninjecting Capacity Possible Developed Noninjecting Capacity	Proved Undeveloped Capacity Probable Undeveloped Capacity Possible Undeveloped Capacity
Justified for Development	–	–	Proved Undeveloped Capacity Probable Undeveloped Capacity Possible Undeveloped Capacity

Table 2.1—Capacity Status. Note that Proved, Probable, and Possible represent the uncertainty in the estimated quantities, so all relevant combinations of subclasses and capacity status subdivisions can have all three categories associated with them.

Applying Capacity status (see Table 2.1) in the absence of project maturity subclasses can lead to the conflation of two (or all three) different statuses of Undeveloped Capacity and may hide the fact that they may be subject to different levels of project maturity. For example, Capacity may be Undeveloped simply because implementation of the approved, committed, and budgeted development project is ongoing, and drilling of the injection well(s) is still in progress at the date of the evaluation. Another example is Capacity that is undeveloped because the final investment decision for the project has not yet been made and/or other approvals or contracts that are expected to be confirmed have not yet been finalized. Both examples are Undeveloped Capacity, but at different stages of project maturity.

For portfolio analysis and decision-making purposes, it is important to be able to distinguish between the three statuses (or alternatively the three subclassifications) of Undeveloped Capacity. Using project maturity subclasses, a clear distinction between a project that has been Approved for Development and one that is Justified for Development, but not yet approved, can be made.

While estimates of Capacity will frequently change with time, including during the period before injection startup, it should be rare for an entire project that had been assigned to the Capacity class to be subsequently reclassified to the Contingent Storage Resources class. Such reclassification should occur only as a consequence of an unforeseeable event that is beyond the control of the developers undertaking the project; for instance, an unexpected political or legal change that causes development activities to be delayed beyond a defined time (e.g., five years) or changes to availability of the CO_2 stream. Even so, if there are identifiable concerns regarding receipt of all the necessary approvals/contracts for a new development, it is recommended that the project's storable quantities remain in the Contingent Storage Resources class until such time that the specific concern has been addressed.

2.1.4.3 Commercial Risk. It is important to distinguish between uncertainty in the storable quantities and the chance of commerciality for a project. Storable quantities cannot be classified as Capacity (of any category) unless a project satisfies all the commerciality criteria for the Capacity classification. Thus, for Capacity, a project should be subject to very little, if any, commercial risk. The Capacity categories (i.e., Proved, Probable, and Possible) are used to characterize the range of uncertainty in storable quantities from that project.

Commercial risk can be expressed quantitatively as the chance of commerciality, which is defined as the product of the "chance of discovery" and "chance of development":

- *Chance of discovery:* The chance that a project's Undiscovered Storage Resources can be established as suitable for injection and storage and become Discovered Storage Resources.
- *Chance of development:* The chance that a project's Discovered Storage Resources will be commercially developed.

Because Capacity and Contingent Storage Resources are only assigned to Discovered Storage Resources, and hence the chance of discovery is 100%, the chance of commerciality becomes equivalent to the chance of development. Therefore, for a project's Discovered Storage Resources to be classified as Capacity, there should be a very high chance of development and very little, if any, commercial risk.

However, for projects with Contingent or Prospective Storage Resources, the commercial risk may be quite significant and should always be carefully considered and documented. The chance of discovery for Prospective Storage Resources is assessed based on the probability that storable quantities are present. Separately, an evaluation of the potential quantity that can be stored is undertaken, which may be based on deterministic or probabilistic methods, as discussed in Section 2.2 Resources Categorization.

For anything to exist in the highest maturity classification—that of Capacity—the project must satisfy all the criteria for Capacity.

2.1.4.4 Maturation of Storage Projects. Defining the term "project" unambiguously is difficult because its nature will vary with its level of maturity. A mature project may be defined completely by a comprehensive development plan that includes full details of all the planned injection wells and their locations, specifications for the surface facilities, discussion of environmental considerations, staffing requirements, market assessment, estimated capital, operating, site rehabilitation and post-closure monitoring costs. In contrast, drilling of an exploration prospect could define a very immature storage project that could lead to a commercial development if the well is successful.

Projects that assess the regional resource potential through analysis of available information (e.g., the creation of storage atlases, Section 3.1.4 Regional Storage Resources Assessments Using Notional Projects) are even less mature. Resource assessments may be considered a project in the context of the SRMS because it may involve an investment in maturing the resource through the assessment project. The evaluation of the economic viability of the regional assessment or of an exploration project will require a view of the likely development or notional project, but the development plan for the notional project will be specified only in very broad conceptual terms. This notional project's development plan represents the project (or collection of potential projects) on which both the Undiscovered Storage Resource classification (project maturity classification) and the uncertainty in the storable quantities (1U, 2U, and 3U) are based. To rephrase this, *a regional resource assessment project needs to have notional development concepts* that would be required to exploit the resource (i.e., to mature the notional project). These concepts will determine a range of storable quantities related to the identified geologic formations and the notional project and will give an indication of the notional costs and potential project development challenges (e.g., induced seismicity).

The decision to proceed with an individual project requires a projection of future costs to determine the expected financial return from that investment. In this context, the future costs include all the necessary injection, processing, and transportation facilities to enable injection of storable quantities for the individual project. Once a specific injection location is identified, it is these development facilities that define the project because it is the planned investment of the capital costs that is the basis for the financial evaluation of the investment and hence the decision to proceed (or not) with the project. Evaluation of the storable quantities and the range of uncertainty will also be key inputs to the financial evaluation, and these can only be based on a mature, defined development project.

There are three different subclasses for Prospective Storage Resources: Play, Lead, and Prospect. Detailed descriptions of all three subclasses can be found in Table 1 of the SRMS (2017).

When a geologic formation becomes a future drilling target, the storable quantities associated with the geologic formation are classified in the Lead subclass. A Lead is typically a project that is still poorly defined and may require more data acquisition and/or evaluation to be matured to a Prospect. After such additional data and evaluation are acquired with favorable outcome to consider drilling a well (or fully characterizing an existing well), the storable quantities associated with the geologic formation can be classified as Prospective Storage Resources: Prospect. Through the Prospective Storage Resources maturation process, part of the storable quantities may be subclassified as Prospect and another part as Lead; the remaining part of the Prospective Storage Resources may remain in the Play subclass. The Prospective Storage Resource is the sum of all the quantities in the subclasses.

Maturing a project from Play to Lead to Prospect is linked to decision criteria, where the goal is to identify prospects that can be drilled to discover storable quantities that can be classified as Discovered Storage Resources. These decision criteria may vary across different companies, as each has a unique decision-making process and method for prioritizing considerations for reclassifying a project into a more mature subclass. Not all projects subclassified as Play and/or Lead are matured, in which case these storable quantities may be classified as Inaccessible Prospective Storage Resources or kept in these subclasses for future projects.

Once a discovery is made and a project fulfills the requirements for classification as Discovered Storage Resources, it can be classified as Contingent Storage Resources (Section 2.1.2 Determination of Discovery Status), which can be subclassified using the four available project maturity subclasses outlined in Fig. 2.2. Detailed descriptions of these subclasses can be found in Table 1 in the SRMS (2017).

Once a final decision to commence project implementation and development of a storage site is made, the storable quantities that will be developed as a result of project implementation can be classified as Capacity. If part of the storable quantities is not included in the final decision to implement a project and develop a storage site, this portion of excluded storable quantities will remain in the Contingent Storage Resources class but may ultimately be developed through future incremental projects.

2.2 Resources Categorization

2.2.1 Introduction. The range in uncertainty in the storable quantities in a geologic formation (or group of geologic formations) associated with a specific, defined project is represented by the horizontal axis in Figs. 2.1 and 2.2. The project's specifications (not its maturity) will affect its storable quantities. Additionally, because assumptions are required to estimate storable quantities (e.g., storage efficiency, thickness, area, and porosity), to forecast (with time) a project's injection rates, and to complete project economics, inherent uncertainty (and perhaps a range) of storable quantities exists. Moreover, the variability in the data used leads directly to uncertainty. Categorization of storable quantities is not related to the project classification based on project maturity, but in uncertainty related directly to the estimate of storable quantities.

A critical distinction between classification and categorization is that the classification of storable quantities as Capacity, Contingent, or Prospective Storage Resources is *based solely on an assessment of the **maturity** of a specific project*. In contrast, the categorization of Capacity into 1P, 2P, and 3P (or the equivalent incremental quantities P1, P2 and P3) is *based solely on considerations of uncertainty in storable quantities resulting from the **definition** of a specific project* (and similarly for Contingent/Prospective Storage Resources). For any project being evaluated, there will often be a low estimate, a best estimate, and a high estimate of storable quantities. However, depending on the purpose of the study, a single estimate may be made and categorized as either low, best, or high. In the case that very specific circumstances exist, a single value estimate may be appropriate to describe the Capacity; in this case, the single value estimate would be the "best" estimate of storable quantities. This might be most applicable when the storable quantity is based on the scheduled annual injection using purchased equipment and the projected life of the project and not limitations of the geologic formation to store CO_2.

2.2.2 Range of Uncertainty. The range of uncertainty is categorized by three specific storable quantities reflecting low, best, and high estimates for the defined project. The terminology and nomenclature are different depending on the classification, but the underlying principle is the same regardless of the level of project maturity. For Capacity, the low, best, and high storable quantities are designated in cumulative quantities as Proved (1P), Proved plus Probable (2P), and Proved plus Probable plus Possible (3P), respectively. The equivalent cumulative quantities for Contingent Storage Resources are 1C, 2C, and 3C, while 1U, 2U, and 3U are used for Prospective Storage Resources.

These three categories of storable quantities may be based on deterministic or probabilistic methods. The relationship between the two approaches is highlighted in these guidelines (Section 2.2.3 Considerations for Estimating the Range of Uncertainty in Storable Quantities) and the SRMS (Section 2.2.1 Range of Uncertainty).

As follows,

> "Uncertainty in resource estimates is best communicated by reporting a range of potential results. However, if it is required to report a single representative result, the *best* estimate is considered the most realistic assessment of storable quantities. It is generally considered to represent the sum of Proved and Probable estimates (2P) when using the deterministic scenario, or the P50 when using probabilistic-assessment methods. It should be noted that under the deterministic-incremental (risk-based) approach, discrete estimates are made for each category, and they should not be aggregated without due consideration of their associated risk" (SRMS 2017, Section 2.2.2 Category Definitions and Guidelines).

2.2.3 Considerations for Estimating the Range of Uncertainty in Storable Quantities. While estimates may be made using deterministic or probabilistic methods, the underlying principles must be the same if comparable results are to be achieved with both methods for the same project or different projects. It is useful, therefore, to consider certain characteristics of the probabilistic method when applying a deterministic approach.

- The range of uncertainty relates to the uncertainty in the storable quantities for a specific project. Conceptually, the full range of uncertainty extends from the minimum storable quantities for the project through all potential outcomes up to the maximum storable quantities. Because the absolute minimum and absolute maximum outcomes (e.g., P00 and P100) represent extreme storable quantities, it is considered more practical to use low and high quantities to represent the range of uncertainty. Where probabilistic methods are used, the P90 and P10 outcomes are typically selected for the low and high quantities.
- In the probabilistic method, probabilities correspond to ranges of outcomes rather than to a discrete scenario (within a specific project). P90, for example, corresponds to a 90% probability that the storable quantities will be equal to or exceed the low storable quantities. Consequently, there is a corresponding 10% probability that the storable quantities will be equal to or exceed the high storable quantities. In a deterministic context, "a high degree of confidence that the quantities will be stored" does not mean that there is a high probability that the exact quantity categorized as Proved Capacity will be the actual CO_2 stored (SRMS 2017, Appendix A, Proved Capacity). Rather, it means that there is a high degree of confidence that the stored quantities will be equal to or exceed the Proved Capacity.
- In this uncertainty-based approach, a deterministic estimate is a single discrete scenario that should lie within the range that would be generated by a probabilistic analysis, although the storable quantities do not have associated quantitatively defined probabilities. The range of uncertainty reflects our inability to calculate exactly the actual storable quantities for a project, and the 1P, 2P, and 3P Capacity estimates are simply single discrete scenarios that are representative of the extent of the range of uncertainty. In the SRMS,

there is no attempt to consider or establish separate ranges of uncertainty for each of the 1P, 2P, or 3P estimates or the Proved, Probable, and Possible Capacity estimates because the objective is to estimate the range of uncertainty in the storable quantities from the project as a whole.

Typically, there will be a significant range of uncertainty, hence there will be low, best, and high storable quantities (or a full probabilistic distribution) that characterize the range. However, there are specific circumstances that can lead to having only discrete values for low, best, and/or high storable quantities. These are described in Section 2.2.1 Range of Uncertainty of the SRMS (2017).

There are several different methods to estimate the range of uncertainty in storable quantities for a project. These methods, such as Monte Carlo simulation, largely relate to volumetric methods but are also relevant to other methods. In this context, "deterministic" is taken to mean combining a single set of discrete parameter estimates (e.g., gross rock volume and average porosity) that represent a specific estimate of storable quantities. Such a combination of parameters represents a discrete scenario. On this basis, even the probabilistic method is scenario-based. Irrespective of the approach used, the uncertainty in storable quantities is associated with the project, while the risk of the project (e.g., chance of commerciality) is defined by its assignment to a resource class or subclass. It is important to recognize that the level of uncertainty of the estimated quantities remains the same, regardless of the method used.

Both deterministic and probabilistic may be applied to a specific project, especially for more complex developments. For example, three deterministic scenarios (for a specific project) may be selected for the deterministic method after reviewing a Monte Carlo simulation of the same project. The primary methods in current use are described here in the context of the SRMS uncertainty categories.

- **Deterministic-Scenario Method.** In this method, for a given project, three discrete scenarios are developed that reflect low, best, and high storable quantities. These scenarios must reflect realistic combinations of parameters to ensure that a reasonable range is used for the uncertainty in rock property averages (e.g., low, average, and high porosity) and that interdependencies of rock properties are considered (e.g., a large gross rock volume estimate may have a low average porosity associated with it). It is generally *not appropriate* to combine the low estimate for each input parameter to determine a low storable quantity estimate outcome, as this would *not* represent a realistic low-case scenario (it would be closer to the absolute minimum possible outcome).
- **Deterministic-Incremental Method.** This method uses discrete, describable scenarios, and is applicable to all classifications; here it is exemplified for the Capacity classification subdivisions. For example, storable quantities projected to be Stored by the defined scenario (within a given project) would be assigned Proved Developed Capacity; Proved Undeveloped Capacity would be assigned to adjacent storable quantities for which there is high confidence in continuity of the geologic formation and the storable quantities. Probable Capacity and Possible Capacity would be assigned to more remote storable quantities, indicating progressively less confidence. These incremental quantities (e.g., Probable Capacity) are estimated discretely as opposed to defining a 2P (Proved plus Probable) Capacity scenario. Consequently, scenario descriptions of a project should accompany storable quantities reported using this method. Additionally, this method should ensure that all uncertainties are appropriately addressed.
- **Probabilistic Method.** Commonly, the probabilistic method is implemented using Monte Carlo simulation, which defines the uncertainty distributions of the input parameters and

the relationships (correlations) between them. This method derives a distribution of storable quantities based on combining the input parameter distributions. Unlike deterministic methods, no discrete scenario is defined. Instead, each (internal) iteration of the Monte Carlo simulation is a single, discrete deterministic scenario. In this case, the Monte Carlo simulation numerically determines the combination of parameters for each iteration that defines internally each scenario. ("Internally" is used because the combination of input parameters defining each scenario is internal to the simulation and is not explicitly defined.) Each simulation has many different possible combinations (usually several thousand) to develop a full probability distribution of storable quantities from which three representative outcomes are selected (i.e., P90, P50, and P10). Stochastic reservoir modeling methods may also be used to generate multiple realizations of storable quantities.

- **Multi-Scenario Method.** The multi-scenario method is a combination of deterministic-scenario and probabilistic methods. In this method, a significant number of discrete deterministic scenarios are developed (perhaps 100 or more) and a probability is assigned to each scenario's storable quantities. Each scenario has a single deterministic value of storable quantities, and the probabilities for each of the input parameters are combined to give a probability for that scenario. With sufficient scenarios, it is possible to develop a probability distribution from which the three specific deterministic scenarios that lie closest to P90, P50, and P10, for example, may be selected.

2.2.4 Containment Assessment and Project Maturity. The containment assessment for storable quantities should progress so that the evaluation is consistent with the maturity of the project and the financial commitment is associated with the project's development plan (**Table 2.2).** The containment assessment will be updated during the process of project maturation as additional containment-related data become available and future investment requires management of containment risk. Both the impact and probability of containment failure should be evaluated and incorporated into ongoing investment decisions at each project maturity classification, based on data available at the time of the assessment.

Classification	Containment: Wellbores	Containment: Geological
Prospective Storage Resources–Play	Identify wellbores that penetrate the assessment area.	Identify caprocks (primary and secondary), all major faults and structures, and geologic formation limits.
Prospective Storage Resources–Lead	Use wellbore proxies (e.g., depth, age, historical usage, number of wellbores) to determine the likelihood of containment.	Use geologic proxies (e.g., thickness and lithology) and analog data to infer caprock containment.
Prospective Storage Resources–Prospect	Obtain and check well records and operator's standard operating practices for the stated wellbore plug depths, cement tops behind casing, and material types. Evaluate containment for each well (based on records), specifically with regard to barriers and the caprock.	Conduct geologic and geomechanical assessment of fault seal using available data; investigate containment, specifically pressure buildup and migration, using a simple dynamic model.
Contingent Storage Resources	Assess barriers' (integrity and depth relative to geologic containment) effect on storable quantities. If remediation is necessary, add remediation strategies and cost estimates to project development plans.	Update geologic containment assessments using additional data and evolving project description.
Capacity	Demonstrate acceptable containment risk for storable quantities (including demonstration to regulatory authorities).	

Table 2.2—Guidelines for containment assessment for storable quantities classes.

For a regional storage resource assessment, a notional project may require an area that includes thousands of wellbores and numerous faults. The use of proxies to indicate wellbore containment potential can provide a more fit-for-purpose containment assessment given the immaturity of a notional project (Prospective Storage Resources–Play or Lead). Well density and depth are poor proxies alone but may be the only data available. Data for hydrocarbon shows and target formations are often available and might be used as geologic containment proxies. For example, to avoid vertical movement of low-density hydrocarbons, hydrocarbon-bearing formations may be more carefully isolated with cement compared to normally pressured brine aquifers that have less risk of vertical flow. Other wellbore containment proxies could include the time (e.g., decade) of the plugging operations, the regulations in place at time of the procedure, or the operator who performed the activities. Application of proxies for well containment requires an understanding of historic local regulations and practices.

The Prospective Storage Resources–Prospect subclass is used for storable quantities for a drillable project or characterization of an existing well using available data only. For wellbore containment, it is recommended to review well records for plug lengths and depths and behind-casing cement tops for comparison with formation tops. Depending on the exploration investment, or for initial prospect ranking, the available data might be taken “as-is.” However, before deciding to drill a well, it is recommended that each well’s barriers should be more critically assessed (e.g., how was the cement placed, was the string centralized, was it rotated, did the “plug bump,” were all permeable zones plugged).

To assess the geological containment potential (constrained by migration and/or pressure) of a project’s Prospective Storage Resource, it is recommended to use analogs or simple models (e.g., Frailey 2013, 2014) to estimate migration distance, displaced fluid movement, or pressure reaching faults or caprock limits. The impact of all identified containment risk features, both geological and wellbore, should be incorporated into the assessment of containment risk and, hence, the project’s storable quantities. For example, if the project is a structural trap with a wellbore or mapped fault at the crest of the structure, then a containment assessment could result in storable quantities near zero (significant impact on the project potential) without a remediation or monitoring plan that was included in the project development plan specific to the wellbore or fault at the crest of the structure. However, if the wellbore or fault intersects the structural trap mid-flank, then the storable quantities associated with the pore volume updip of the wellbore or fault locations would have significantly reduced containment risk compared to storable quantities associated with the downdip of the wellbore or fault locations. Additionally, a wellbore or fault might influence the maximum containment pressure (applying a pressure constraint below the caprock fracture pressure) and, hence, the storable quantities estimate.

Once the project’s storable quantities are classified as a Contingent Storage Resource and actively under maturation for development, the containment risk should evaluate the impact of containment failure or constraints at wellbores or geologic features and determine if any remedial activities should be part of the project’s development plan. A diagram that overlies well isolation components (casing cement, plugs) onto the geologic formation tops (i.e., porous and permeable zones) and places each well in the target formation into context with neighboring wells and geologic features (e.g., faults) may be useful. In the context of the project’s CO_2 plume, pressure footprint, and displaced brine, using such a diagram facilitates identification of potential leak paths along the wellbores and faults, including more complex leak paths incorporating crossflows between wells and/or faults.

To mature a project's storable quantities from Contingent Storage Resources to Capacity requires all wellbores and identified potential geologic leak paths in the containment assessment area to have either (1) evidence of containment or (2) monitoring and mitigation plans for wells that do not have evidence of containment. Risk assessment methods (e.g., bowtie methodology; Tucker 2018; Tucker et al. 2013) should be applied to evaluate containment. An overall risk management approach should include all remedial actions, along with monitoring and corrective measures (remedial actions triggered by the monitoring), in an integrated whole to demonstrate that the project can contain the requisite storable quantity.

For active storage projects, loss or reduction in containment could reduce Capacity estimates. Therefore, operational monitoring that includes measurements of properties indicative of containment should be considered.

2.3 Incremental Projects

If, at any time during the development or operation of a storage site, incremental projects are designed to increase the Stored CO_2, storage efficiency, and/or to accelerate injection, such projects should be classified according to the same criteria as the initial development project. Related increments in storable quantities attributable to the incremental projects are similarly categorized on certainty of storable quantities. The storable quantities can be included in the estimated Capacity when the incremental project's maturity is such that the project will be developed and placed On Injection within a reasonable time frame.

Examples of such incremental projects include an increase in the number of injection wells, either within the same area as the existing project or in an extended area; changes to the installed facilities allowing for higher rates of injection; implementing brine extraction; and development phases beyond the originally envisaged time frame (contract extension).

2.4 Examples of Project Descriptions

Because the SRMS requires project maturation, a project description is required. However, a less mature project's description is not always obvious. For example, a project may involve the assessment of the storage potential of a region, the development of a single geologic formation or group of formations, or there may be more than one project implemented on a single geologic formation. The following are some examples of project descriptions in the context of the SRMS:

- The development of a regional storage assessment (e.g., an atlas) for identifying potential geologic formations and estimating the storable quantities for an identified regional development concept (i.e., project) may be a combination of real and notional projects. The "project" is deemed to be economical if it delivers on strategic objectives of the regional development concept that enable the maturation of storage projects. The results of the assessment can be used to inform future investment in a storage project; for example, if there is no storage potential for a region, an investor might be less likely to consider a project capturing the CO_2 in that region because the project's transport cost to another region will increase the cost of the project.
- Where a detailed development plan is prepared for a partner and/or government approval, the plan itself defines the project. If the plan includes some optional wells or facilities that are not subject to a further capital commitment decision and/or government approval, these will *not* constitute separate projects, but rather would form part of the assessment of the range of uncertainty in potentially storable quantities from the project (i.e., an incremental project).

- Where a development plan is based on initial storable quantities (i.e., the initial development plan), and storage resources are still available, additional development opportunities (i.e., an incremental project) will be subject to a separate capital commitment decision and/or approval process at the appropriate time and will constitute a separate project. In this scenario, there may also be impacts on the original project, perhaps lengthening the project life and increasing storable quantities, which should be taken into consideration when evaluating the new, separate project.
- Where decision making is entirely on a well-by-well basis (as may be the case in mature projects) and there is no overall defined development plan (but in this case a separate development plan for each well will be necessary) or any capital commitment beyond the current well, each well constitutes a separate project.
- In the assessment of an undrilled prospect, an economic evaluation of risk will be made to underpin the decision whether to initiate injection. This evaluation must include consideration of a notional project defined by a conceptual development plan to derive cost estimates and storable quantities (Prospective Storage Resources) based on an assumed successful outcome from the exploration well (Section 2.1.4.3 Commercial Risk). The project is defined by the exploration well and the conceptual development plan.
- In some cases, an investment decision that involves a combination of exploration, appraisal, and/or development activities may be required. Because the SRMS subdivides resource quantities on the basis of three main classes that reflect the distinction between these activities (i.e., Capacity, Contingent Storage Resources, and Prospective Storage Resources), it is appropriate in such cases to consider that the development plan is based on implementing a group of projects, whereby each project can fit uniquely into one of the three classes.

A key strength of using a project-based system like the SRMS is that it encourages the consideration of all possible technically feasible projects to maximize storage, even though some projects may not be economically viable when initially evaluated. These projects are still part of the portfolio and identifying and classifying them ensures that they remain visible as potential future investment opportunities. The storable quantities that are classified as Inaccessible Resources should be limited to those that are currently not technically or commercially accessible or are precluded from development because they underlie environmentally, culturally, or socially sensitive areas such as cities, national parks, and monuments. A proportion of these Inaccessible Resources may, of course, become accessible in the future as a consequence of new technology development or changes in social or commercial circumstances.

Technology refers to the applied technique by which Capacity is developed. Some guidelines on the relationship between the status of technology under development and the distinction between Contingent Storage Resources and those storable quantities that are currently considered Contingent Storage Resources–Inaccessible are provided in Section 2.3 Incremental Projects.

Finally, it is imperative to clearly understand the distinction between the subclassification by project maturity and the assignment of Capacity based on Capacity status as described previously (Table 2.1). The SRMS explains that storable quantities "may be subdivided by Capacity Status independent of subclassification by project maturity" (SRMS 2017, Section 2.1.3.2 Capacity Status). Thus, Capacity status is a subdivision of associated storable quantities *within* a project and does not directly reflect a project maturity subclassification unless each well is validly defined as a separate project. If this is the case, then each separate well project is developed once the well is drilled.

3.0 Project Evaluation and Reporting Guidelines

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3.1 Commercial Evaluations

3.1.1 Introduction. The evaluation process serves to determine the monetary value of the resources assigned to a specific project from a given date forward. In the context of CO_2 storage projects, the commercial evaluation of a storage resource ultimately yields a return on investment (e.g., net present value or NPV) for the development or maintenance of a storage project. For the purposes of evaluation and reporting described in this chapter, a storage project may be integrated or standalone. An integrated storage project evaluation includes revenue and expenses from the facility generating the CO_2, such that the CO_2 storage project will be a capital and operating expense to the facility. A standalone storage project may be an independent business offering storage services or owned by the facility (or co-owned by several facilities) but valuated separately from the facility's revenue and expenses. Regardless, investment criteria such as NPV are used to make investment decisions with respect to commitment and allocation of funds for the commercial development of storage resources.

The SRMS serves to promote and ensure consistency in the process by which the investment value of CO_2 storage projects is determined and, consequently, the presentation of commercial evaluations. The commercial evaluation of a project establishes both injection and associated cash-flow schedules; the time integration of these schedules yields an estimate of storable quantities and associated future net revenue of a project (i.e., NPV calculated using a range of discount rates; see Section 3.1.2 Cash-Flow-Based Commercial Evaluations). Estimates of storable quantities as well as associated future net revenue (or NPV) are subject to uncertainties, including the uncertainty inherent in estimating injection rates, CO_2 storage credits or prices, capital and operating costs, and timing of implementation. Thus, estimates of storable quantities and NPV should reflect a range of probable outcomes.

Storage resource evaluation requires the integration of multidisciplinary technical and commercial expertise. Therefore, project evaluations should be conducted by multidisciplinary teams using all available information, data, and analyses relevant to the project being evaluated.

This chapter considers two types of projects:

1. A standalone CO_2 storage project providing storage services to third parties in exchange for a payment (or tax credit).
2. An integrated project that includes CO_2 storage with a CO_2 generating facility. The storage development and operations are funded (at least in part) by the associated facility.

To classify storable quantities as Capacity for either type of project, economic evaluation is required. This evaluation could follow the same method for either project type, however the source(s) of revenue and project boundaries should be clearly defined.

3.1.2 Cash-Flow-Based Commercial Evaluations. Investment decisions are based on the assessment of future commercial conditions that may affect a project's feasibility (and, ultimately, commitment to develop) on the basis of injection rates and associated cash-flow schedules. Projected commercial conditions reflect the assumptions made pertaining to economic scenarios (e.g., costs, prices, fiscal terms, taxes) as well as other factors (e.g., marketing, legal, environmental, social, governmental).

The value of a CO_2 storage development project can be assessed in several different ways, including the use of a benchmark per-unit storage value (e.g., a carbon price) that is based on analogous projects or forecasts and analyses of future trends. For a standalone storage project, the economic terms of the storage agreement between the CO_2 generating facility and the storage project are used. For an integrated project (e.g., ethanol facility, which has a revenue source, and the storage facility), an economic limit and NPV calculations should include the complete integrated project. The economic evaluation for less mature project subclasses necessarily requires the use of assumptions specific to development costs, CO_2 source (e.g., composition and transport), and the value generated per unit CO_2 stored. These assumptions should be clearly stated when reporting results of the evaluation. (Additionally, as noted in Chapter 2 Classification and Categorization Guidelines, economic assumptions contribute to quantifying the uncertainty in storable quantities for the low, best, and high categories.) However, as articulated in the SRMS, the guidelines herein apply only to evaluations based on discounted cash-flow analysis.

The NPV calculations should reflect the following information and data:

- Injection schedules (i.e., the expected quantities of CO_2 stored over the identified time period) for a standalone project (or integrated project if using a transfer CO_2 storage price).
- Estimated costs [i.e., capital expenditures (CAPEX) and operating expenditures (OPEX)] associated with the project to develop, inject, and monitor the quantities of CO_2 stored at the defined Reference Point (Section 3.2 Injection Measurement and Operational Issues), including environmental, abandonment, post-closure monitoring, and reclamation costs, based on the assessment of expected future costs. In addition, estimated costs must include any CAPEX and OPEX associated with brine production and disposal if the project uses pressure management through brine extraction. A fully integrated project's NPV calculation would also require CAPEX, OPEX, and product forecasts associated with the non-storage parts of the project.
- Estimated revenues from the stored quantities of CO_2 based on the assessment of the future prices, subsidies, tax credits, and/or sales of associated products (i.e., for a fully integrated project).
- Any projected revenue-related taxes or royalties expected to be paid.
- A project life that is limited to the period of entitlement, inferred by the legal agreement, which allows access to the storage resource (or reasonable expectation thereof; Section 3.3 Resources Entitlement and Recognition), the permitted maximum storable quantities, storage contract limitations, or the economic limit, whichever is the most constraining.
- The application of an appropriate discount rate that reasonably reflects the weighted average cost of capital or the minimum acceptable rate of return established and applicable at the time of the evaluation.

A project's net cash-flow (NCF) projections can be generated under both current and future economic conditions. In terms of meeting the threshold of an "economic" project, it is important to restate the following from the SRMS: "While each entity may define specific investment criteria, a project is generally considered to be economic if its best-estimate case has a positive NPV under the organization's standard discount rate, or if it at least has a positive undiscounted cash flow" (SRMS 2017, Section 3.1.1 Cash-Flow-Based Resources Evaluations).

3.1.3 Economic Criteria: Development and Analysis of Project Cash Flows. Some of the major components of a storage project's cash flow are annual CO_2 stored and related revenue (e.g., tax credits), capital and operating costs, and ownership interests, royalties, and fiscal agreements. These components may vary over time.[1]

3.1.3.1 Revenues and Product Prices. For storage project evaluation, the CO_2 price refers to the revenue generated per unit of CO_2 stored (e.g., USD per tonne or USD/t). It is important to use the appropriate CO_2 prices, while considering the specific terms of any CO_2 storage contract, qualifying regulations for any CO_2 storage subsidies or tax credits, and other factors where appropriate (e.g., injection gas composition). The revenue generated per unit of CO_2 stored, as defined by any commercial storage contract or government subsidy/tax credit scheme, would be the primary source for CO_2 price forecasts.

The revenues allocable to CO_2 storage depend on the storage project type:

1. A standalone CO_2 storage project's economic evaluation follows a standard approach: After-tax cash flow and NPV calculated based on the revenues and project costs.
2. An integrated CO_2 storage project may not have commercial revenues per se and may be an expense to the CO_2 generating facility. Therefore, the revenue generated would be solely that of the industrial facility.

In cases of integrated projects, transfer prices (internally between the facility and the storage parts of the project) might be calculated (addressing any royalty treatment, regulatory guidance, and accounting) to provide revenue for cash-flow analysis of the storage project. It is recommended that a Custody Transfer Point (i.e., the Reference Point; see Section 3.2 Injection Measurement and Operation Issues) be notionally assigned for the determination of the transfer price. This transfer price may vary with the price of the product manufactured by the integrated project (e.g., ethanol). Consequently, the product prices should then be forecasted from historical price data or contractual terms. Otherwise, it is best to use empirical CO_2 price data (i.e., revenue generated per tonne of CO_2 stored) to predict future CO_2 prices. If suitable historical data is unavailable, uncertainty regarding future CO_2 prices should be assessed within the constraints of any contractual terms and incorporated into the evaluation of a project.

Transportation costs for CO_2 storage may be included as a reduction of the CO_2 storage unit price (direct impact on revenue calculation) and, if so, should be clearly stated as such. Otherwise, transportation costs should be identified as part of the operating costs [Section 3.1.3.3 Project Operating Expenses (OPEX)] when they are part of the project (which depends on the Reference Point).

3.1.3.2 Project Capital Expenses (CAPEX). CAPEX for a CO_2 storage project include land acquisition, exploration, drilling and well completion (including any brine production and disposal wells), remediation or recompletion of wells (e.g., to ensure containment), surface facilities development (i.e., gathering infrastructure, process plants, water disposal, and pipelines), and site abandonment. [See the PRMS Guidelines (2011) Section 7.4.1 for more guidance regarding capital costs categories and depreciation or amortization.]

Chronologically, the development process of a storage project encompasses four pre-injection phases: (1) initial planning and evaluation, (2) conceptual engineering design, (3) detailed engineering design, and (4) pre-injection construction. These phases could take several years to complete. A decision to proceed to the next project phase includes cost estimates to determine

[1] Where the definitions of different cash-flow terms are identical for PRMS and SRMS, they have not been repeated here. For more information, please refer to the PRMS Guidelines (2011), subchapter definitions and development of project cash flows regarding definitions of essential terms for cash-flow analysis, or the definitions and development of project cash flows.

economic viability. The detail and accuracy of the CAPEX estimate required is determined by the intended use (of the cost estimate) and the project maturity (pre-injection development phase).

The American Association of Cost Engineers (Humphreys and Katell 1981) recommends three basic categories of project cost estimates, which are defined as follows:

- *Order-of-magnitude estimate* is considered accurate within –30% to +50%. This cost estimate is based on cost-capacity[2] curves and ratios made during the initial planning and evaluation phase. This cost-estimate category is used for investment screening purposes.
- *Preliminary estimate* is considered accurate within –15% to +30%. This semi-detailed cost estimate is based on flow sheets, layouts, and equipment details made during the conceptual-design stage of a project. This cost-estimate category is used for budget proposal and expenditure approval purposes.
- *Definitive estimate* is considered accurate within –5% to +15%. This estimate is based on detailed and well-defined design and engineering data (with complete sets of specifications, drawings, equipment data sheets, etc.) made during the detailed engineering and construction stage of a project. This category of cost estimate is used for procurement and construction.

Abandonment, decommissioning, and restoration (ADR) costs are CAPEX that represent the capital cost required to finish a project after the period of project injection or operation. Abandonment activities will typically include decommissioning of surface facilities and wells and transforming the surface site to the condition stipulated by the applicable regulations and lease or permit terms. Any relinquishment process (i.e., for the property transferred from the storage project operator to another party, normally a state/governmental body) for a storage site is likely to include a post-closure (post-injection) period, during which site monitoring will continue and may last for several decades. These costs should be incorporated into the storage project's abandonment cost evaluation.

3.1.3.3 Project Operating Expenses (OPEX). Estimates of OPEX (in money of the day or real terms) are generally based on analogous operations adjusted for the storage injection rate, manpower, and appropriate cost-escalation (or cost-component specific inflation) rates. OPEX are generally determined on a per unit CO_2 stored (e.g., mass or volume) or time (e.g., monthly or annual) basis. Similar to CAPEX, the assignment of OPEX to various categories for estimation and treatment could also be important.

OPEX are generally recognized under five categories (Humphreys and Katell 1981).

1. *Direct costs* are incurred only during active injection operations and include variable and semi-variable components. These may include costs associated with power and labor, any brine handling and disposal operations, and monitoring activities (before the post-closure period). During temporary or intermittent injection shutdowns (e.g., for routine maintenance), direct costs are generally represented at a reasonable minimum basis of approximately 20% or greater of the semi-variable costs estimated for a site operating at its scheduled injection rate.
2. *Indirect costs* are those incurred independent of active injection operations; they include general and administrative expenses (or overhead expenses) or costs incurred that are not specific to project operations but are required to support the project and typically associated

[2] Note that capacity here does not refer to SRMS storage Capacity, but to the main cost drivers of the equipment, such as the pressure ratings, rate, weight, and volume. High-level cost estimates might be extrapolated from historic cost data, assuming a relationship to the main cost drivers.

with home office or headquarters management. This category includes salaries and expenses of company officers and staff, central engineering, research and development, and marketing costs.

3. *Distribution costs* are operating and manufacturing costs associated with transporting CO_2 from the Reference Point (Section 3.2.3 Reference Point) to the injection site (e.g., pipelines, rail, truck, and ship). These costs include the cost of pipeline operations, terminals, and temporary, aboveground storage tanks. In some cases, transport costs may be incorporated as a reduction of CO_2 storage price (Section 3.1.3.1 Revenues and Product Prices).
4. *Contingencies* constitute an allowance made in an operating cost estimate for unexpected costs or for error or variation likely to occur in the estimate. The contingency allowance might include costs for remediation activities (e.g., additional monitoring activities or drilling activities triggered by storage site response contrary to expectations).

3.1.3.4 Other Key Terms and Definitions. The ownership of the storage resource (i.e., entity with the legal rights to develop the geologic formation for CO_2 storage) should be legally defined (Section 3.3.2 Regulatory Frameworks and Pore Space Ownership). Ownership interest represents the share, right, or title in the storage resource (i.e., a lease, concession, or license), project, asset, or entity. The most common types of economic interests (or ownership) for subsurface, natural resource–related projects are working interest, net working interest, mineral interest, carried interest, back-in interest, and reversionary interest. These interests are applicable to CO_2 storage projects. Ownership of the storage resource may be through purchase or lease.

The storage project may not have ownership of the storage resource and may lease the rights to store CO_2 from the owner. The owner of the storage rights may be an individual, business, or government. There is no standard approach to acquiring access to a storage resource. Depending on the terms of the storage lease or rental contract or applicable regulatory framework, any payment made for the rights to store CO_2 in the subsurface may be treated as a royalty, a tax, or an expense. For some projects, no payment to a storage resource owner for the right to inject and store CO_2 may be required. In some instances, there may be a lump sum payment, annual fees, a fee based on CO_2 stored and/or injected, or a fee based on projected Capacity or estimated ultimate storage for the storage project (analogous to saltwater disposal).

If a payment for resource usage is considered a royalty, then the royalty is free of cost obligations except for any taxes that may be imposed on the storage project that are directly related to the type of ownership payment (e.g., royalty payment that is based on Stored CO_2). The royalty owner may be paid "in kind" through direct receipt of storage revenues (e.g., tax credits or subsidies), or a project could monetize any quantities injected and/or stored under royalty on behalf of a storage resource owner. Regardless of how the royalty is monetized, Stored quantities must be deducted from the lessee's entitlement to the Capacity and gross revenue. If a payment for resource usage is considered an expense (analogous to saltwater disposal in some regions), then this payment should be included in the OPEX and will not impact resource entitlement. If a royalty has attributes closer to that of a tax (generally specified in the lease agreement), the interest may be treated as a tax for resource entitlement calculation (Section 3.3 Resources Entitlement and Recognition).

3.1.3.5 Analyzing Project Cash Flows and Establishing Value. The SRMS states that "a project is generally economic if its best-estimate case has a positive net present value (NPV) under the organization's standard discount rate, or if it at least has a positive undiscounted cash flow." For brevity herein, these guidelines reference positive NPV only. [See the PRMS Guidelines (2011) Section 7.4.2 for further information regarding the calculation of NPV and NCF.]

Economic criteria directly impact the classification and categorization of storage resources. A project's Discovered Storage Resources are considered economic, and its storable quantities may be classified as Capacity, when an economic evaluation has established a positive NPV and there are no unresolved contingencies to prevent timely development. If the NPV is negative and/or there are unresolved contingencies preventing project implementation within a reasonable time frame, Discovered Storage Resources must be classified as Contingent Storage Resources.

In addition to NPV, there are other important measures of profitability (e.g., internal rate of return, profitability index, profit investment ratio or dollar generated per dollar initially invested, and payout time or payback period of the capital investment) that are routinely used in economic evaluations (Campbell et al. 2001; Higgins 2001; Newendorp and Schuyler 2000; Seba 1998; *COGEH* 2007).

Economic Limit. The assessment of economic limit is based on a project's forecasted NCF and could significantly affect the estimate of Capacity. Economic limit is defined as the injection rate beyond which the NCFs (net revenue minus direct operating costs) from a project are deemed uneconomic to continue storage operations. (Direct operating costs include property-specific fixed overhead charges if these are actual incremental costs attributable to the project and any property taxes.) The assessment should ensure that the economic life of the storage project does not exceed the economic life of existing facilities required to sustain the project's operations (e.g., where CO_2 transport is routed via another offshore platform or shared pipeline).

OPEX are defined and described in detail in the PRMS Guidelines (2011, Section 7.4.1). They should be based on the same type of projections (and time frame) as those used to predict the CO_2 price for a project's revenue forecasts. OPEX should include only those costs that are incremental to the storage project for which the economic limit is being calculated. In other words, only the incremental costs that would be eliminated if the CO_2 storage project ceased. OPEX should include fixed site-specific overhead expenses (those incurred even when injection is on hold) if they are incremental costs attributable to the project (in addition to any property taxes); however, depreciation, abandonment and reclamation costs, income tax, and any overhead costs outside those required to operate the project itself should be excluded from OPEX. OPEX may be reduced, and thus project life extended, by various cost-reduction and revenue enhancement approaches, such as sharing transport and injection facilities, pooling maintenance contracts, or marketing costs. Interim negative NCF may be accommodated in short periods of low product prices or during temporary major operational problems, provided that the longer-term forecasts still indicate positive cash flows.

The value of a storage project's Capacity is the NPV, defined as the projected, cumulative, discounted NCF over the project's economic life. NPV is discounted at the minimum acceptable rate of return desired for and expected from an investment project, which generally reflects the weighted average cost of capital [different principle-based methods used to determine an appropriate discount rate can be found in Campbell et al. (2001) and Higgins (2001)].

The following guidance is provided as relevant to the Capacity valuation process:

- Presentation and reporting of valuation results should not be construed as replacing guidelines for subsequent public disclosure under guidelines established by external regulatory and government agencies and any current or future associated accounting standards. Consequently, Capacity valuations conducted for internal use may vary from those used for external reporting and disclosures due to variance between internal business planning assumptions and regulated external reporting requirements of governing agencies.

Therefore, internal valuations may be modified to accommodate criteria regarding external disclosures imposed by regulatory agencies.

- There may be circumstances in which the project meets the criteria to be classified as Capacity using the forecast case but does not meet the external criteria for Proved Capacity (1P). In these specific circumstances, 2P and 3P estimates may be recorded without separately recording the 1P estimate. If, as development proceeds, the low estimate satisfies external requirements, storable quantities can be categorized as Proved Capacity.
- Project financing confirmation is not required prior to classifying storable quantities as Capacity. However, financing may be an external requirement for classifying as Proved Capacity. In general, if there is not a reasonable expectation that loans or other forms of financing (e.g., farm-outs) can be arranged such that the development will be initiated within a reasonable time frame, then the storable quantities should be classified as Contingent Storage Resources. If financing is reasonably expected but not yet confirmed, and financing is an external requirement for reporting in that jurisdiction, the project may be internally classified as Capacity (Justified for Development), but no Proved Capacity may be reported.

3.1.4 Regional Storage Resources Assessments Using Notional Projects. While not designed specifically for regional assessments (e.g., government studies to create national storage atlases) of storable quantities, these types of assessments can follow the SRMS by specifying notional projects and order-of-magnitude costs. Without a specific project defined, economic evaluation of the storage resource is challenged by a lack of known CO_2 price, a limited project description (e.g., well numbers and type), and uncertainties regarding transport to the injection site. Nevertheless, the notional project should be supported by an injection forecast (e.g., injection only or injection plus brine extraction), the number and type of wells necessary, the basic facilities required (e.g., offshore platforms), and the cost of installing and operating the required wells and facilities. Where the storable quantities are estimated assuming active management of reservoir pressure through brine extraction, then brine extraction wells, brine handling, and technically feasible disposal must be included in the specifications of the notional project description. An economic project is generally defined as being NPV positive for the base case revenue and cost forecast that represent reasonable and foreseeable commercial conditions and technology. Where the storage resource will not be associated with a defined CO_2 source and an associated CO_2 price (required to calculate NPV), an economic indicator [see Section 3.1.4.1 Unit Technical Cost (UTC)] could be used.

Resources that are assigned to Contingent or Prospective Storage Resources subclassifications have diminished requirements for economic evaluation. Alternately, an expectation of commercial viability might be inferred from comparison with a suitable (more mature) analog storage project. The methodologies and thresholds for establishing the economic viability of a project should be reported.

The following section describes how a unit technical cost (UTC) is calculated and could be used to provide an economic evaluation for immature resource classifications for which the CO_2 price is unknown.

3.1.4.1 Unit Technical Cost (UTC). The storage resource UTC represents the break-even unit CO_2 price, which represents the minimum unit CO_2 price (e.g., tax credit, subsidy, storage contract price, or assigned transfer price within an integrated project) necessary to make the CO_2 storage operation breakeven (on a pretax basis). A UTC is frequently used for screening or ranking less defined (i.e., notional) development projects. When using notional projects, it is generally recommended that the UTC be calculated using real costs, with equivalent inflation and deflation factors applied, such that the UTC calculated will not be impacted by the assumed development date. Whatever assumptions are made, the units and economic basis (reference year, escalation, and discount rate) should be clearly reported (e.g., USD per tonne of CO_2 stored, real-term costs, NCF, and NPV). The following equation is an example of UTC definition:

$$\text{UTC PV} = \frac{[\text{PV } CO_2 \text{ storage project costs (CAPEX+OPEX+ADR)}]}{(\text{PV } CO_2 \text{ quantity stored})}. \quad \text{(3.1)}$$

An example of generating a UTC calculation to a notional project is described in Section 3.4.1 Example of Project Evaluation Using UTC.

The UTC should be compared to economic threshold(s) to determine economic viability of the resource. The threshold(s) should represent a reasonable maximum UTC for an economic storage project in the region.

Thresholds should be defined and reported for the region in which the storage resource is located and the applicable regulatory system to assign potential for future commercial development. The threshold definition should be subject to qualified assurance comparable to the assurance of storable quantities. The UTC assumptions will be different for integrated and standalone projects.

As described in Section 2.1.4.3 Commercial Risk, a prospective resource is reported in terms of "chance of discovery," and "chance of development." The chance of development reflects the evaluation of the Prospective Storage Resources' development if discovered (i.e., the chance that a discovery would result in an NPV positive development). See Section 3.4.2 Chance of Development Evaluation Using UTC for an example of applying a UTC Prospective Storage Resources evaluation to estimate a prospect's "chance of development."

A UTC calculation to support the evaluation of economic potential for a Prospective Storage Resource may not include costs associated with exploration activities (e.g., drilling wells and acquiring seismic data). A developer's exploration budget may be separate from that of the development of a specific project and associated storable quantities.

3.2 Injection Measurement and Operational Issues

3.2.1 Introduction. Storable quantities with their respective classification will be reported with the projection of revenue from Stored CO_2 from the specific development project at the Reference Point. (The term Stored CO_2 refers to CO_2 that is already injected and contained; a "forecast of Stored CO_2" is a projection of CO_2 to be injected in the future.) The quantity of CO_2 at the Reference Point will be based on a metered quantity of the CO_2 in the CO_2 stream[3] in the transportation system. The intent is to quantify Stored CO_2 and to forecast Stored CO_2, which may be called estimated ultimate storage. This section provides guidance on defining the Reference Point, non-CO_2 constituents in the CO_2 stream, surface CO_2 losses, and shared ownership.

3.2.2 Background. The quantity of Stored CO_2 is established through metered flowlines leading to injection wells, estimates of CO_2 stream composition, and interpretations and indications by means of monitoring that CO_2 is contained in the geologic formation(s) specified in the development plan. Consequently, the following discussion provides context for application of

[3] The term CO_2 stream refers to the fluid that is in the transportation system at the Reference Point, which is expected to be primarily CO_2, but may have other constituents present.

SRMS guidelines regarding the relationships between metered quantities, stored quantities, storable quantities, and storage resource estimates associated with a CO_2 storage project.

Storable quantities can be reported as either mass or volume at a specified standard temperature and pressure. A storage project may have limits on the composition of the CO_2 stream (e.g., injection permit may set restrictions on the quantity of non-CO_2 constituent). All quantities (stored and storable) should be specified by composition (e.g., mol% component), with a comparative subsurface conversion to stored quantities (of CO_2) such that the development and use of storable quantities can be categorized and classified (see Section 3.2.7 Non-CO_2 Constituents in the CO_2 Stream).

3.2.3 Reference Point. Storage resources and stored quantities are reported in association with a defined Reference Point. Ideally, the Reference Point is a defined location(s) where the CO_2 stream is metered or assessed, which must directly relate to the Stored quantities. The Reference Point and Custody Transfer Point may be the same location. The Custody Transfer Point is a physical location in the transportation system where the CO_2 stream ownership is transferred from the CO_2 generating facility or transportation system to the storage project. In the case of an integrated project, there may not be a formal exchange of ownership.

Fig. 3.1 illustrates three possible locations of Reference Points and Custody Transfer Points in the context of a specified project (defined by the dashed boxes), which provide the basis for discussion in the following section. Fig. 3.1a illustrates a standalone project that does *not* include processing the CO_2 stream (i.e., the composition of the CO_2 stream at the Reference Point is the same as the composition at the Custody Transfer Point). Fig. 3.1b is a standalone project that includes a facility that captures and processes the CO_2 stream. Fig. 3.1c illustrates an integrated project, where the CO_2 generating process (source) is also included in the defined project and no exchange of CO_2 ownership occurs.

The Reference Point location and the Custody Transfer Point location need not be the same location. However, in each of these examples (Fig. 3.1), if only one meter is used and it is located at the Custody Transfer Point, the Reference Point and Custody Transfer Point would be at the same location. In the case of the project illustrated in Fig. 3.1b, the stream transferred to the project (at the Custody Transfer Point) will differ from the stream at the Reference Point (both in composition and quantity). If the Reference Point was also located at the Custody Transfer Point, then the reported "injection quantity" would not align with actual injected quantity.

Consequently, if a storage project includes gas processing, it is recommended that the Reference Point be defined downstream from the gas processing facility (i.e., capture, compression, and/or separation), such that the composition and quantity of the injected CO_2 stream remains unchanged from the Reference Point to the injection wellhead. A storage project that includes gas processing between the Reference Point and Custody Transfer Point must report the Stored quantities downstream of the processing facility. Reporting Stored quantities and forecasted Stored quantities for a project in terms of a Reference Point upstream of the processing facility is incorrect.

In addition to metering the CO_2 stream for estimating Stored CO_2, metering may be required for fiscal purposes. If the project revenue is directly tied to the Stored quantity (e.g., government subsidies or tax credits), fiscal metering should be immediately upstream of the injection wellhead. If the project revenue is generated through the sale of CO_2 storage services, fiscal metering should be at the Custody Transfer Point between the CO_2 generating facility (or pipeline operator) and the storage project. If the project revenue is generated as part of an integrated project (revenue generated from the sale of a CO_2 generating product), fiscal metering of the CO_2 is not required.

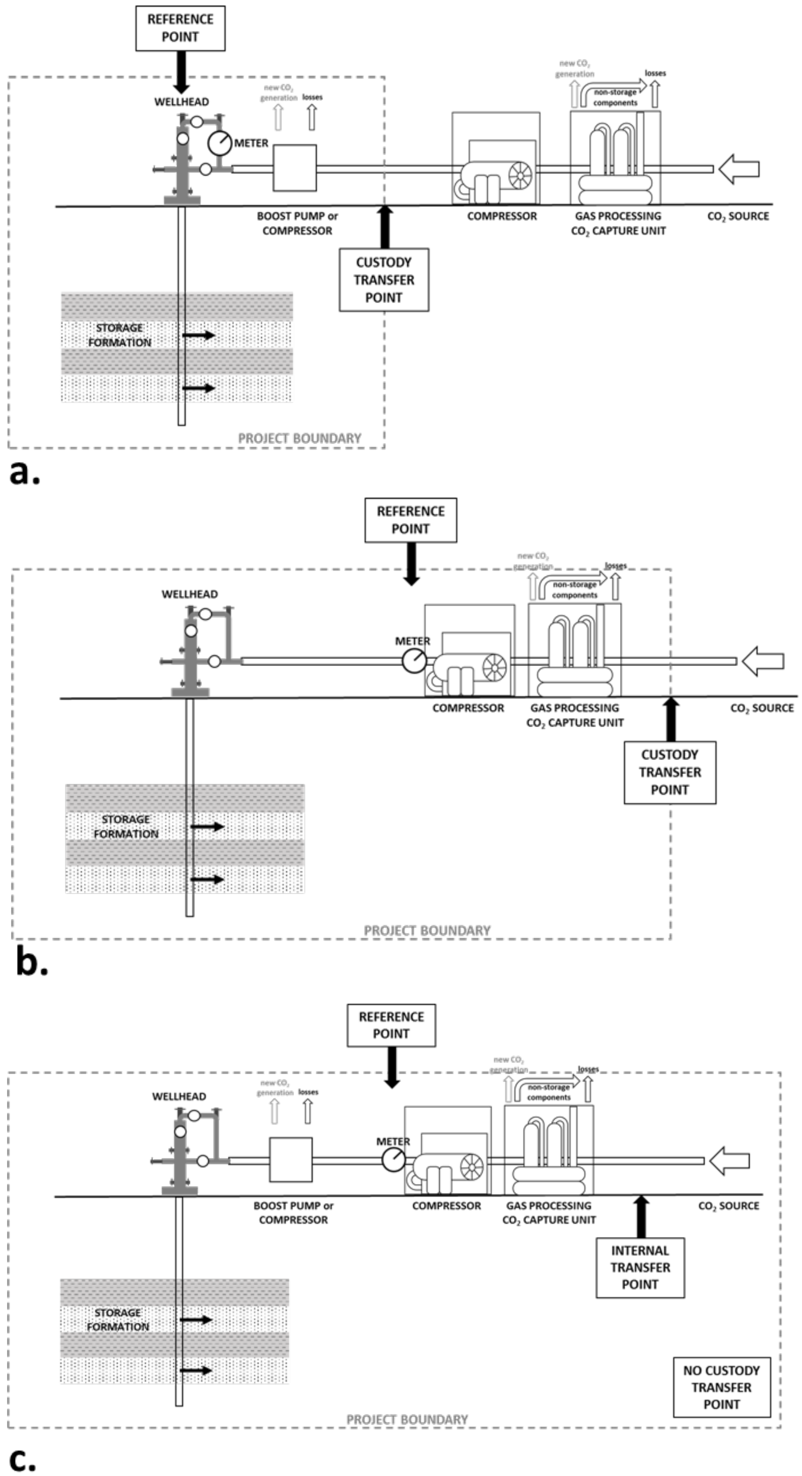

Fig. 3.1—Schematic illustrating three possible storage projects (as defined by the dashed box). (a) The storage project illustrated does not include gas processing, which occurs before the Custody Transfer Point. (b) The storage project illustrated includes CO_2 capture and gas processing; the Custody Transfer Point occurs upstream of the capture unit. (c) An integrated storage project that includes the CO_2 generating facility and storage project. In this example, there is no custody transfer. The Reference Points illustrated for each example are assigned as part of the evaluation. The meters could be placed at the Custody Transfer Points and the Reference Points might be the same location.

3.2.4 Surface Losses. Between the Reference Point (i.e., meter) and the injection wellhead, minor losses of CO_2 may occur from leaks in the surface equipment (e.g., facilities, flowlines, and wellheads). Site monitoring should provide data to quantify and forecast these losses such that the Stored CO_2 can be quantified. The minor losses may be small and not measurable; in these cases, approximations may be required.

If a storage project generates CO_2 emissions that are not captured, the emissions are not directly associated with estimating, classifying, or categorizing storable quantities. However, if there are costs (e.g., penalties or fees) resulting from these emissions, these costs should be incorporated into the project valuation.

3.2.5 Injection Balancing. Where a single storage project involves multiple working interest owners, or where a geologic formation is subject to development by several different projects, an imbalance in CO_2 injection for each project can occur. Such imbalances result from the owners having different operating or marketing arrangements for selling storage resources and equal ownership of the storage resources. One or more parties' storage resources then become over/underutilized. For example, one owner may be selling CO_2 storage resources and may be waiting on a storage contract or pipeline installation. That owner's storage resources will become underused, while the other owners have active projects with Stored quantities. These imbalances must be monitored and part of the project's forecast of Stored quantities.

3.2.6 Shared Transport or Processing Facilities. Several CO_2 storage sites may receive CO_2 from the same transport system (and/or the same processing facility). Where a company has an equity interest in one or more of the storage projects, the transport system, and/or the processing facility, the allocation of each project's Stored quantity and Capacity and each owner's interest in the CAPEX, OPEX, and revenue can be complex. These allocations should be tied to the Reference Point using composition and quantity of metered CO_2 (Section 3.2.3 Reference Point).

By measuring the quantity and constituents of the CO_2 stream stored at each storage project, based on the equity share in the subsurface ownership, an entity can calculate its share of the revenues resulting from the storage of CO_2 from the common transport system (and/or processing facility). If there is no equity interest in the common transport system (and/or processing facility), Stored CO_2 and Capacity are simply estimated in terms of the CO_2 delivered to the storage project. The allocation of revenues is subject to the contractual agreement among the equity owners and common transport system (and/or processing facility) owners.

3.2.7 Non-CO_2 Constituents in the CO_2 Stream. All quantities (stored and storable) should be specified by composition (e.g., mol% component), with a comparative subsurface conversion to Stored quantities (of CO_2) such that the development and use of storable quantities can be categorized and classified. Reporting of storage resources in terms of equivalent CO_2 storable quantities would allow for meaningful aggregation of the storage resources associated with several separate projects (which may or may not include different resource classes) to provide a combined portfolio, basin, or country estimate, for example. Reporting equivalent CO_2 storable quantities for each project maturation subclass will facilitate quantifying the range of uncertainty as the project matures. Specifically, the storage of non-CO_2 constituents likely reduces the storage resource available to CO_2. Therefore, when aggregating storable quantities, especially within specific categories and classifications, the impact that non-CO_2 constituents have on the resources should be included in all assessments.

If a storage project includes removal of constituents present in the CO_2 stream downstream of the Custody Transfer Point, the quantities of Stored CO_2 and Capacity include only CO_2. However, for making forecasts of revenue and expenses, it may be appropriate to use the CO_2

stream, especially if additional revenue and expenses occur because of the storage project's removal of non-CO_2 constituents prior to injection or because of injection and storage of non-CO_2 constituents. Revenue generated by the sale of the separated non-CO_2 constituents (which are excluded from the CO_2 stream) may be used to offset project operation expenses.

3.3 Resources Entitlement and Recognition

3.3.1 Introduction. This section discusses storage resource entitlement based on a set of principles by which the resource entitlement might be inferred. It is critical that Stored CO_2, the forecast of Stored CO_2, and Capacity are clearly reported in terms of storable quantities. A developer might report only the Capacity and Contingent Storage Resources to which they are entitled; however, the *entire* project's Capacity and Contingent Storage Resources should also be reported excluding any losses between metering and injection point (see Section 3.2.3 Reference Point and Section 3.2.4 Surface Losses).

3.3.2 Regulatory Frameworks and Pore Space Ownership. Although several countries have drafted storage regulations and standards for geologic CO_2 storage, there are currently numerous countries without a legal framework to support commercial evaluation or development of storable quantities that would require storage licenses and/or permits to develop the storage project. If there is no reasonable expectation of a developer being able to obtain permits or if a regulatory framework is not available in the foreseeable future, then the storage resource should be classified as Discovered or Undiscovered Storage Resource–Inaccessible. Note that while a legal framework for specific CO_2 storage activities may not be defined, existing regulations (e.g., governing subsurface injection for other purposes or hydrocarbon development regulations for development with fluid injection for improved oil recovery or enhanced oil recovery) might be applicable as a basis for a reasonable expectation of future development of storage resources.

Adequate information must be included that demonstrates ownership of, or entitlement to develop, the geologic formation required for the project (specifically duration and storable quantity). A storage project's subsurface impact has two components: (1) the subsurface location of the Stored CO_2 and (2) the area of elevated pressure as a result of the Stored CO_2. Both have areal and vertical dimensions that change with time as a result of CO_2 migration, dissipation of the pressure, and large-scale aquifer water movement. Typically, the elevated pressure component is considerably larger than the Stored CO_2 component (unless active pressure management is used). If the storage project's subsurface impact exceeds the project's subsurface ownership, the assignment of storable quantities to the project will be affected unless additional adjacent pore volume rights can be acquired. These restrictions may apply only to the physical subsurface location of Stored CO_2, or to both the CO_2 and area of pressure impact (i.e., footprint), depending on the applicable pore-space-ownership agreement and injection project permitting regulations. Likewise, nearby storage projects may affect the assessed project's assigned Capacity and Contingent Storage Resources, if the area of elevated pressure associated with the neighboring projects impacts the pore space targeted by the assessed project. Moreover, local regulations may prescribe the means by which Capacity or Contingent Storage Resources can be assigned to subsurface pore space owners with respect to adjacent projects and may restrict the extent of the CO_2 and/or pressure components in relation to the project's accessible pore space.

3.3.3Storage Capacity and Resources Recognition. In general, agreements and contracts for resource development cover a wide spectrum of fiscal and contractual terms established by private pore space owners and host countries to best meet their needs. Currently, there are few commercial storage projects to guide the likely range of contract types that may become relevant and no established practice for determining when a developer might recognize entitlement to Capacity or Contingent Storage Resources under these contracts. Therefore, resource entitlement is discussed here in terms of principle rather than specific to different contract types, and in the context of petroleum resources.

The right to extract petroleum, the exposure to elements of risk, and the opportunity for reward are key elements that provide the basis for recognizing entitlement to claim petroleum reserves and resources. These principles could also be applied to assign an expectation of Capacity or storage resource entitlement. Hence, entitlement is inferred when the project lease and contracts include the following:

- The right to store CO_2
- The right to share in the proceeds from the revenues from Stored CO_2
- The exposure to market and technical risk
- The opportunity for reward through participation in storage activities

Specific elements that do not support an economic interest, and hence do not support the recognition of an entity's entitlement to Capacity and Contingent Storage Resources, include the following:

- Participation that is limited only to the right to purchase storage resource usage
- Storage resource brokerage arrangements
- Agreements for services to a storage project, or funding of a storage project, that do not contain aspects of risk and reward or convey an interest in the pore space

The exposure of an entity to the risks and rewards associated with storage projects is a key indicator of Capacity and storage resource entitlement. Risks include any technical uncertainty of the ability to store CO_2 and economic risks, which are dependent on the economic environment over the life of the project. Economic risks will fluctuate with the prevailing CO_2 cost structures and price or subsidy/tax credit where these are not fixed by contract for the duration of the project. The ownership of, or entitlement to, the storable quantities should be clearly stated when reporting the estimated quantity, uncertainty, classification, and categorization.

3.3.3.1 Impact of Taxes, Royalty, and Geologic Formation Rental Fees. In general, net working interest Capacity and storage resources recognize that there is an economic interest, after deduction for any royalty. The net working interest does not deduct resources associated with taxes [see PRMS Guidelines (2011), Sections 10.4.1 and 10.4.2]. If a payment is made to the legal owner of the property for the use of the pore volume, then the developer's entitlement to the storage quantities may be reduced if the payment is considered a royalty.

If the obligation has attributes of a tax rather than a royalty (e.g., is based on project profitability rather than a defined interest), then there is no deduction to the resource entitlement of the developing developer. If the obligation is a rental fee, it may be considered part of the project's OPEX.

3.3.4 Contract Storage Resources Entitlement. This section focuses on the specific elements of agreements that enable recognition of storage resources classification; it does not focus on categorization. This section is highly speculative in the context of SRMS because too few contracts exist and are available for developing SRMS guidelines. Therefore, the analogies to petroleum and mineral production are used.

3.3.4.1 Concessions, Mineral Leases, and Permits. Historically, leases and concessions have been the most commonly used agreements between oil or mining companies and mineral owners (which may be a private owner, government, or Crown). In such agreements, the mineral owner grants the developer the right to explore for, develop, produce, transport, and market hydrocarbons or minerals within a specified area for a specific amount of time. Applying these types of contracts to storage projects' leases requires the following to support resource entitlement:

- The developer bears all risks[4] and costs for exploration, development, and storage.
- The developer can monetize the revenue generated by the resource development within the area and time covered by the lease.
- The revenue generated through storage in the concession may be subject to rentals, royalties, bonuses, and taxes.
- Ownership of the storable quantities is retained by the host government or mineral owner, but the developer(s) can claim entitlement to all resources that will be used while the agreement is in effect.

3.3.4.2 Injection-Sharing Contracts. The oil and gas industry frequently applies production-sharing agreements between a contractor and a host government. Applying this type of contract to storage leases requires that:

- The developer bears all risks and costs for exploration, development, and storage.
- The developer can monetize the storage resource to recover costs (through subsidies, tax credits, or sale of CO_2 storage services) followed by an additional share of the revenue generated by the storage resource development (as defined by the terms of the Storage-Sharing Contract).
- Ownership of the storable quantities is retained by the leaser (typically host government), but the developer(s) can claim entitlement to the share of the storage resources that they will monetize under the terms of the agreement.

Mirroring the principles applied to a petroleum production-sharing contract, storage resources might also be recognized for future development phases under an Injection-Sharing Contract, where project maturity is not sufficiently advanced, or for possible extensions to the contract term where project maturity would not be a matter of course.

3.3.4.3 Contract Extensions or Renewals. In general, the right to exploit a resource is subject to a fixed-term contract or agreement. As these contracts or agreements approach maturity, they can be extended by negotiation for contract extensions, by the exercise of options to extend, or by other means.

Capacity should not be assigned to those storable quantities that will be stored beyond the end date of the current agreement unless there is reasonable expectation that an extension, a renewal, or a new contract will be granted. Such a reasonable expectation may be based on the historical treatment of similar agreements by the license-issuing jurisdiction. Otherwise, forecasting Stored CO_2 beyond the contract term should be classified as Contingent Storage Resources–On Hold. Moreover, it may not be reasonable to assume that the fiscal terms in a negotiated extension will be comparable to existing terms. Similar logic should be applied where the storable quantities will be monetized by means of a CO_2 storage sales agreement or government subsidies and/or tax credits that are defined in a fixed-term contract or agreement.

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[4] The transfer of risk back to the storable quantities owner post-closure will be determined by the lease contract or agreement, storage permit, and local regulations.

3.4 Project Evaluation Examples

3.4.1 Example of Project Evaluation Using UTC. The following is an example of using a UTC estimate for a notional CO_2 storage project in an offshore geologic formation in the United Kingdom, North Sea (after Pale Blue Dot Energy and Axis Well Technology 2016a)[5]. The project was defined to develop an offshore, open-structure storage site in the North Sea, located in a brine aquifer between two gas fields. Once injected, the CO_2 was predicted to migrate updip, but ultimately remained within the project-defined area. The project evaluation was performed as part of a government-sponsored study by a contracting company (non-developer) to investigate the feasibility and cost of CO_2 storage in the North Sea. The study evaluated several potential storage sites, previously identified by a regional resource screening exercise, with relatively detailed notional projects (including cost estimates for development of each site) and storage resource uncertainty assessments. This example is based on the Captain-X site (also discussed in Section 7.2.4 Captain-X Project: A Development-Scale Site-Specific Open Brine Aquifer), which describes injection of CO_2 into an open-structure brine aquifer formation (no local trap) at an offshore location (Pale Blue Dot Energy and Axis Well Technology 2016b).

The notional project has continuous injection of 3 Mtonne/year over 20 years. The evaluation incorporates only those costs associated with storage activities, including transport to the site from a regional gathering and distribution system; therefore, the standalone assessment described above is followed in this UTC example. Note that this cost estimate does not include capture costs.

1. CAPEX for key development items (wells, pipelines, platforms, and well pads) and costs required to develop the resources were estimated from industry benchmarks and analogous data. The evaluation assumes that petroleum industry costs would be applicable. To develop the resource, the following CAPEX would be required:
   - Offshore facilities (well jacket and topside)
   - Three injection wells (two for primary injection and the third for spare/monitoring)
   - A new pipeline to link the injection facilities to an existing regional pipeline
   - Development costs (including feasibility studies) and costs for permit applications
2. OPEX were estimated from petroleum industry analogs and applied as a cost per year of operation. Costs for facilities and transport were estimated as a percentage of CAPEX. Costs for additional OPEX for specific activities [metering, monitoring, and verification (MMV); tariffs; workovers] were estimated individually. To develop the resource, the following OPEX are required:
   - MMV
   - Maintenance costs for pipeline, wells, and facilities
   - Additional costs for remediation activities
   - Tariffs
3. ADR costs include (estimated from petroleum industry analogs):
   - Decommissioning (for facilities, wells, and pipeline)
   - Post-closure MMV
   - Final handover of site

[In this example, handover is the time in the project life at which injection has stopped and the developer has closed the site to meet the regulatory agency's or government's requirements. In

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[5] Information taken from the Strategic UK CCS Storage Appraisal Project, funded by DECC, commissioned by the ETI, and delivered by Pale Blue Dot Energy, Axis Well Technology, and Costain. The information contains copyright information licensed under an *ETI Open License*.

terms of cash-flow projections, the developer is no longer responsible for normal operations (monitoring and remediation OPEX) and will incur no additional operating expenses because a regulatory agency or government has accepted long-term custody and liability of the stored CO_2 for the defined project.]

Following handover, any ongoing monitoring and remediation costs associated with the site were not part of the project. **Table 3.1** summarizes these three costs. Pre-injection CAPEX were distributed over five years, and OPEX were evenly distributed over a 20-year injection period. The ADR costs were highest in the two years following CO_2 injection cessation (abandonment of wells and surface facilities) and the final year of post-injection monitoring (per contractual agreement with relevant regulatory agency or government). For the other years, ADR costs (regular post-closure monitoring activities) were evenly distributed. **Fig. 3.2** plots both the undiscounted cost forecast (CAPEX, OPEX, and ADR costs) and injection forecast defined for this notional project. (Note that the agency or government, to whom the site liability was returned, may perform additional monitoring activities beyond the handover date. For this example, these activities are not considered part of the project and are not directly financed by the project. However, these activities may be financed by funds paid during the project operation and post-closure phases by the project. In this example, the costs of these monitoring activities should be included in cash-flow calculations at the date on which they occurred.)

	Costs	Million USD
CAPEX	Feasibility studies	43
	Transport	49
	Facilities	154
	Wells	86
OPEX		550
ADR	*Decommissioning*	*137*
	Post-closure monitoring	90
	Site handover	41
TOTAL		**1,149**

Table 3.1—Summary of example CO_2 storage project costs by category.

For storable quantities of 60 Mtonne (over the 20-year project life), this project would yield an undiscounted UTC of USD 19.15/t. The inflation and deflation factors were considered equivalent; therefore, the estimated costs (estimated at the time of valuation) are equivalent to a real-terms-cost UTC estimate. This is defined as the undiscounted or PV0 UTC.

The discount rate was applied to both the CAPEX and OPEX forecast and the Stored CO_2 forecast **(Fig. 3.3).** The UTC PV10 (2014) was USD 28/t, and the discounted storage quantity was 13 Mtonne.

Hence, if the economic UTC threshold[6] is USD 28/t, then for this notional project, the 60 Mtonne storable quantities would not be economically viable but could still be developed by a different project with an economic threshold of USD 28/t or greater.

[6] The published evaluation did not give an economic threshold. It is proposed that a developer might define their own economic thresholds based on historic and projected CO_2 prices (analogous to screening oil price assumptions) by which the economic viability of storage resources might be assessed. These thresholds could vary by CO_2 source-type and/or site location.

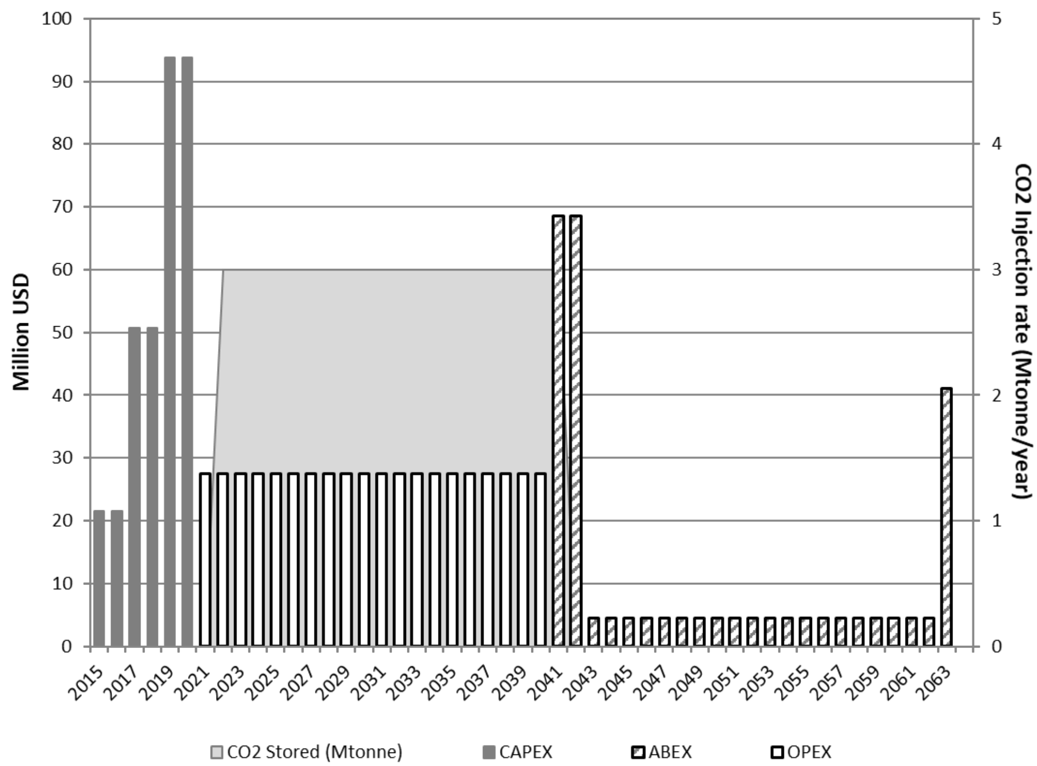


Fig. 3.2—Bar chart provides the example storage project's CAPEX, OPEX, and ADR costs forecast. Costs are from 2014 when the project was valuated. The area chart provides the Stored CO_2 forecast.

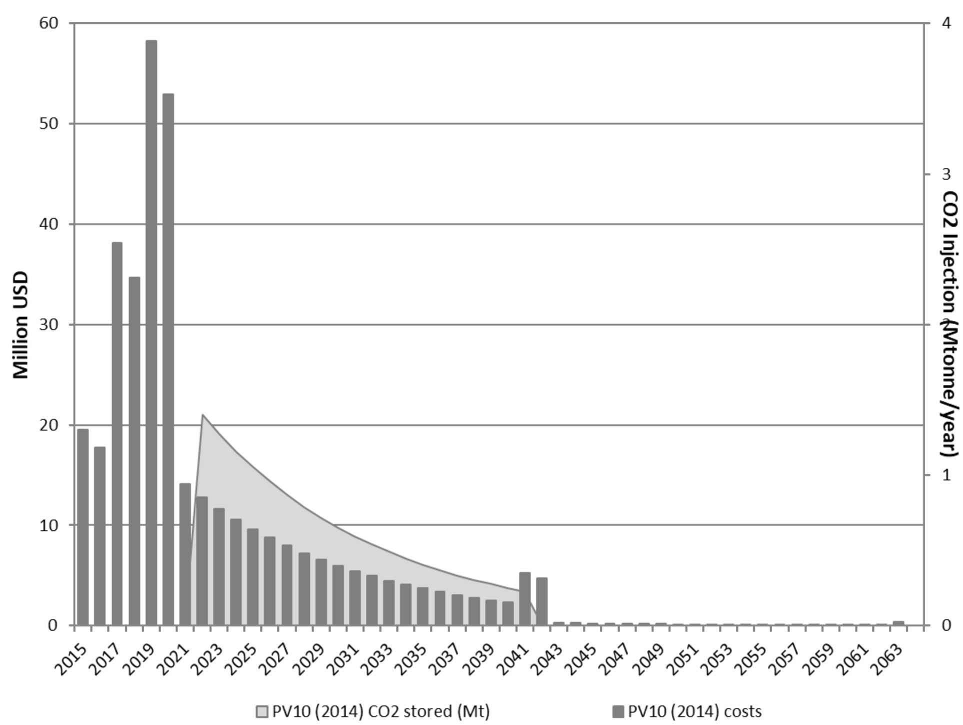


Fig. 3.3—Bar chart provides the example storage project's discounted cost forecast. Costs are PV10 (2014). The area chart provides the example storage project's discounted Stored CO_2 forecast [PV10 (2014)].

3.4.2 Chance of Development Evaluation Using UTC. For Prospective Storage Resources, a chance of development and an associated cutoff for the technical storage resource estimate is required (Section 2.1.4.3 Commercial Risk). The chance of development is estimated based on the valuation of the discovered resources in comparison to the project's defined economic criteria. (The published UK example did not provide adequate information for a specific numeric example for this section; nevertheless, the use of UTC for chance of development is presented here.)

A notional project valuation could be applied to the assessed technical resource quantity range (using the technical resource quantity evaluations described in Chapter 4 Estimating Storable Quantities; evaluation of notional project is described in Section 3.1.4 Regional Storage Resources Assessments Using Notional Projects). The costs associated with discovering the resource (e.g., discovery wells) are excluded from any evaluation of resource economic viability (the assessment represents the resource once Discovered; exploration expenditures will become a sunk cost at this point). The valuation exercise results in a plot of economic indicator vs. resource quantity (or quality) vs. economic indicator such as the UTC (as shown **Fig. 3.4a**). Applying a maximum UTC threshold (or other economic indicator), as described in Section 3.1.4 Regional Storage Resources Assessments Using Notional Projects, provides an estimate of the minimum resource quantity (or quality) discovery required to support a future commercial project. Combining this with the resource quantity (or quality) probability assessment (Fig. 3.4b) indicates the chance of discovering a resource that could result in an NPV positive project.

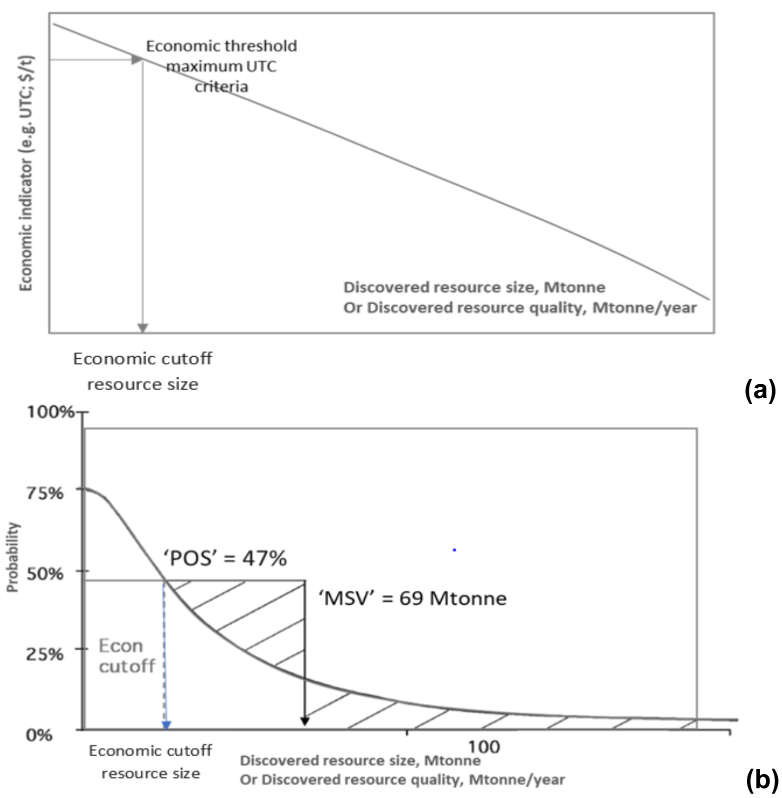


Fig. 3.4—(a) Plot of UTC (or other economic indicator) vs. exploration outcome (storage resource quantity or quality) was used to define a minimum "economic" discovery cutoff. (b) Plot of resource size (or quality) vs. cumulative probability was then used to estimate the probability of discovering a developable resource and the mean developable resource quantity or mean success volume (MSV). Note: The distribution does not start at 100%, but at the "chance of discovery" (75% in this case), as defined in Section 2.1.4 Project Status and Maturation.

4.0 Estimating Storable Quantities

Sylvain Thibeau, George Koperna, Roland Okwen, Subhash Thakur, David Riestenberg, Tip Meckel, Isis Fukai, Steve Whitaker, Owain Tucker, and Scott M. Frailey

4.1 Introduction

Central to the classification and categorization of storage resources is storable quantities. Therefore, this chapter provides guidelines for estimating storable quantities, a requirement of storage resource assessments. The equations in this chapter are for units of mass; however, a standard volume may be calculated by dividing mass by CO_2 density at a standard pressure and temperature.

Although storable quantities can be calculated independent of a project, in the context of the SRMS, the description of a project (even if notional) is necessary to estimate storable quantities. Moreover, for the same geologic formation, projects with different specifications may have different storable quantities. Containment is explicit in the definition of storable quantities, and therefore must be integral to the estimate of storable quantities. To this end, the geomechanical assessments of containment may limit the storable quantities estimate (e.g., establishing a maximum storage pressure or maximum injection pressure).

4.1.1 Principles. For CO_2 storage, there are four major trapping (storage) mechanisms: geologic, residual, solubility, and mineral (IPCC 2005).

- Geologic (structural and stratigraphic) trapping causes CO_2, as a buoyant fluid (in the presence of brine), to accumulate below a caprock (e.g., a very-low-permeability shale or salt beds) at high CO_2 saturation (the maximum being one minus the irreducible water saturation: $1 - S_{wirr}$). CO_2 is stored as a free and mobile phase (i.e., as a unique, identifiable fluid at saturations exceeding the residual CO_2 saturation). Heterogeneity trapping describes CO_2 that gets trapped in very small-scale stratigraphic or structural traps (e.g., Saadatpoor et al. 2009).
- Residual trapping occurs in aquifers where CO_2 migrates over long distances. When CO_2 is stored in an aquifer, it displaces brine and migrates buoyantly upward until it reaches the caprock. During this migration (either locally or after injection stops), brine imbibes into the pores until free-phase CO_2 is immobile at its residual saturation. This may occur on regional dip (outside of the presence of a geologic trap[7]) or at the base of very thick formations, where significant vertical movement of CO_2 is present (even within a geologic trap).
- Solubility trapping occurs when CO_2 progressively dissolves into the brine, which may continue until the brine is fully saturated with CO_2. Because brine saturated with CO_2 has a slightly higher density than brine only, a very slow convective process can take place with CO_2-saturated brine sinking and being replaced with native brine (void of CO_2); however, this normally happens on time scales that are longer than the life of a project so convection may be deemed negligible in most resource assessments.
- Mineral trapping follows the dissolution of CO_2 into brine, which modifies the chemistry of the brine. This can lead to the dissolution of some existing minerals and the precipitation

[7] IPCC uses the term "structural and stratigraphic traps"; however, SPE labels these traps "geologic traps."

of new minerals. CO_2 will contribute to the formation of carbonate minerals and will be trapped as mineral, a solid phase. Generally, the geochemical reactions that are part of mineral trapping are very slow in the context of a project's life and may be negligible for most resource assessments.

Stored CO_2 displaces brine from the geologic formation and exploits various storage mechanisms. For certain storage mechanisms and resource assessments, it may be assumed that a reservoir volume of stored CO_2 displaces an equal reservoir volume of brine. For geologic formations limited in size, if brine (or other fluids) is not extracted, the injection of CO_2 will increase the pressure in the geologic formation. The pressure increase must be compared to the integrity of the caprock; therefore, pressure is a fundamental constraint on the storable quantities estimate. For large, open aquifers, the pressure increase may occur only during active injection.

4.1.2 Approaches to Estimating Storable Quantities. Estimating storable quantities requires determination of the boundary of the geologic formation (open or closed) and the dominant trapping mechanism (geologic or "residual and solubility"), as shown in **Fig. 4.1.**

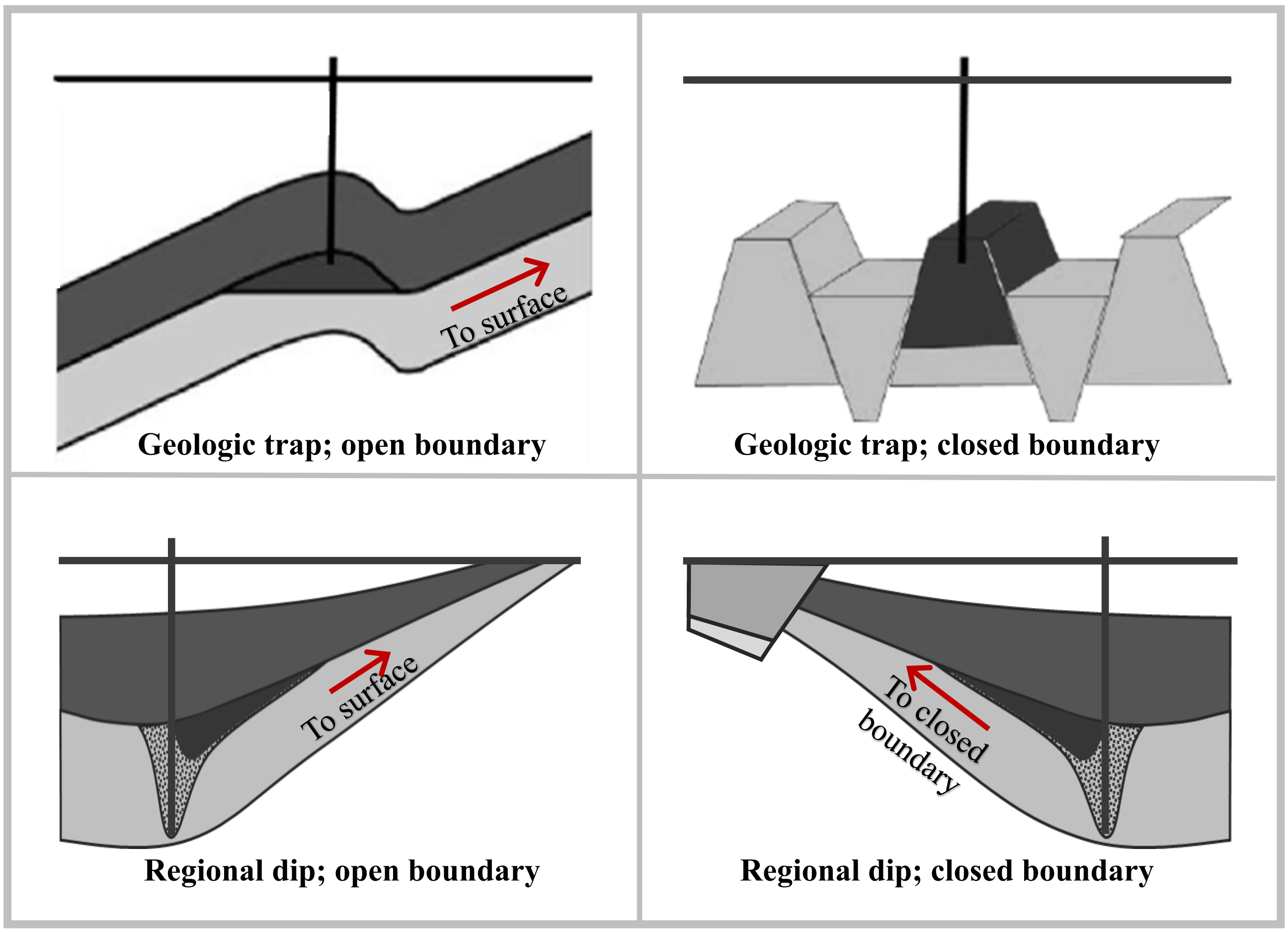


Fig. 4.1—Combinations of geologic trap and regional dip with closed and open boundaries.

Methods to estimate storable quantities that are included in this chapter are described as follows.

- *Analog-based estimates* of storable quantities require an analogous, mature storage project that includes the subsurface and surface components of the project. The project should have Stored CO_2 and data to make a reasonable projection of storable quantities that is adequate to build an analog. Simple ratios may be used to scale storable quantities from the analog project to the project being assessed.
- *Volumetric method–based estimates* of storable quantities are based on storage efficiency applied to a reference volume [e.g., the pore volume or the Total Storage Resources (TSR)]. The volumetric method is valid when the storage efficiency is representative of the storage mechanism of a specific geologic formation or project specifications (e.g., well count). However, if the same value of storage efficiency is applied on a regional scale without a critical examination of the nature of any potential projects needed to achieve such an efficiency, the approach can yield estimates that are unachievable in the context of a project.
- *Traditional and enhanced material balance method–based estimates* of storable quantities are a variation on the volumetric method that rely on the connected pore volume by means of production and/or injection history. Instead of using storage efficiency, a maximum pressure is used. Hence, the storable quantities are defined at the maximum in-situ reservoir pressure at which there is risk of losing containment.
- *Reservoir simulation–based estimates* of storable quantities honor the boundary conditions of a project and the project specifications (e.g., well numbers, injection rates, brine extraction and disposal, and pressure constraints).
- *Performance-based estimates* of storable quantities can be based on historical injection, radial flow equations (e.g., well testing), and analogs. After there is adequate injection rate and pressure data for CO_2 storage in a geologic formation (from an active or an analogous project), then performance-based estimates can be used. A special case in CO_2 storage is the reuse of a depleted oil or gas field. In these cases, there can be decades of production and pressure performance data that can be applied to the estimation of storable quantities.

4.2 Containment Assessment

Containment of CO_2 in a geologic formation is fundamental to CO_2 storage and can be compromised by geologic features and wellbores. In addition to CO_2, storable quantities must coincide with containment or management of all displaced in-situ fluids (e.g., brine from a brine aquifer and oil and gas from depleted oil and gas reservoirs). (Note that containment of CO_2 and displaced brine must be defined and described in the project development plan and include an area and all geologic formations in which CO_2 may be stored and brine displaced.) Therefore, in this section it is implicit that the containment assessment area is the entire area impacted by the CO_2 plume and pressure footprint *and* the displaced in-situ fluids. The containment assessment area may exceed the area in which storable quantities are estimated.

A project definition will have a prescribed annual storage estimate and project life defining the storable quantities required. After the identification of the volume of a geologic formation in which the storable quantities are estimated and the storage mechanisms determined, the assessment area can be estimated. Within this area, all geologic features and wellbores that might impact containment should be identified. Additionally, specifically for depleted oil and gas reservoirs, the geologic formations' historical development (e.g., minimum and maximum reservoir pressure and subsidence) and well completions (e.g., hydraulic fracture stimulation) should be included in the containment assessment. The following sections describe how to assess aspects of geology and wellbores in the context of containment of storable quantities.

4.2.1 Wellbore Containment Assessment. In this section, it is implicit that wellbores included in the assessment are limited to the containment assessment area defined by the project and penetrate the caprock(s) providing geologic containment. Nevertheless, all wellbores, regardless of status (e.g., active and producing or injecting or inactive, plugged, abandoned, and remediated) or original purpose of the well, must be part of the assessment. Therefore, cement depth behind pipe and depth and number of plugs (e.g., cement or mechanical plugs) inside of casing (or proxies) are part of the containment assessment (e.g., Khalifeh and Saasen 2020). [In this section, wellbore barrier is used to represent all types of physical barriers, including fluid between barriers (e.g., mud) to keep in-situ fluids from moving above the caprock.]

To assess wellbores for containment, it is recommended to divide wells along two axes, as illustrated in **Fig. 4.2.** The horizontal axis represents the current containment assessment of the wellbores. The horizontal axis can include the quality and availability of the well records and evidence for the integrity of the well construction and plugs. The vertical axis describes the feasibility of repairing a well (including accessibility) such that it will provide containment. Each axis may include probability of success. Wellbores with attributes plotting near the origin represent wellbores with significant containment challenges, while attributes plotting near 1.0 on either axis have no known containment challenges. In general, risk decreases as the attributes increase to the upper right on this graph. (Note the curves on this graph showing low and high risk are generalizations only; specific assessments may have different relationships than those shown here.)

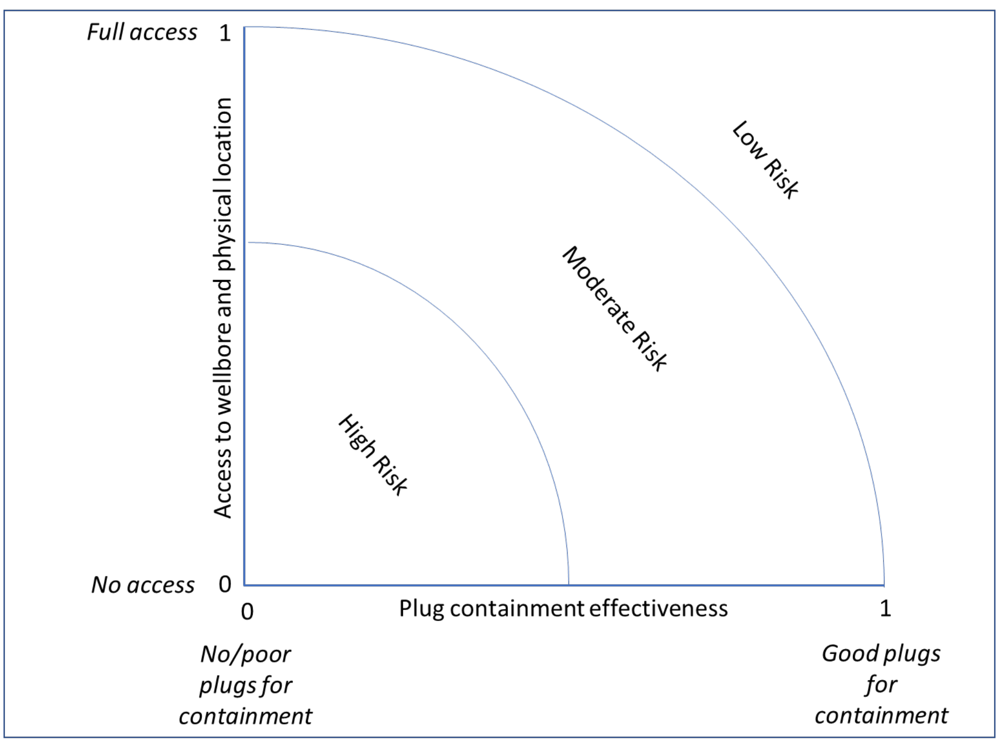


Fig. 4.2—Wellbore containment tool.

When evaluating wellbores within the confinement assessment area, there are five possible scenarios with regard to well records and wellbore accessibility:

1. Wellbore has excellent completion and abandonment records, which show that a wellbore is likely to provide containment (e.g., a suitable combination of well casing, cement, completion, and plugs). These wellbores are unlikely to constrain a project's storable quantities estimate. (This would be near 1.0 on the *x*-axis and 0.0 on the *y*-axis.)
2. Wellbore has excellent completion and well abandonment records that describe a wellbore that will *not* likely provide containment and is *accessible* for remediation to provide containment. These storable quantities can include the wellbores within the containment area if the project plan includes workovers or monitoring of these wellbores to ensure wellbore containment. If the project maturation plan does not include wellbore improvements to provide containment, then the storable quantities must reflect the impact of the wellbores that are unable to provide containment. (This would be near 0.0 on the *x*-axis and 1.0 on the *y*-axis.)
3. Wellbore has excellent completion and well abandonment records that describe a wellbore that will *not* likely provide containment and is *inaccessible* for remediation to provide containment. Some reasons for inaccessibility might be:
   - Side-tracks that cannot be re-entered because of a permanent whipstock
   - Wells where the surface casing has been cut off below the seabed
   - Wells where the surface casing has been removed
   - Wells where the surface location is no longer accessible because of other developments
   - Wellbores with obstructions, which means the lower portion cannot be reached

   If it is not possible to ensure containment with existing wellbores, then the storable quantities will be constrained to an area that does *not* include these wellbore(s), so that the storable quantities, displaced in-situ fluids, and pressure do not reach these wellbore locations. [This would be near the origin (0,0).]
4. Wellbore has inconclusive or incomplete completion and/or well abandonment records that describe a wellbore that will *not* likely provide containment and is *accessible* for remediation to provide containment. The guidelines for this scenario are the same as those in Scenario 2 above.
5. Wellbore has inconclusive or incomplete completion and well abandonment records that describe a wellbore that will *not* likely provide containment and is *inaccessible* for remediation to provide containment. The guidelines for this scenario are the same as those in Scenario 3 above.

In some cases, completion and well abandonment records may be incomplete, but available records would indicate containment to occur; these wells may be inaccessible or accessible. Regardless, these wells will fall in the middle of each axis or in the middle quadrant in Fig. 4.2. The modest risk of these wells would need to be compared to potential impact on storable quantities to continue the project development or enhance the development plan.

In the absence of completion and well abandonment records, drilling records (e.g., loss circulation) may be proxies for effective primary cement in the wellbore containment assessment. Examples of inconclusive or incomplete completion and well abandonment records include:

- Missing well location (e.g., wells drilled during wars, extremely old wells, unpermitted wild cat wells, wells drilled for purposes other than mineral or hydrocarbon exploration, fires or floods at the record office)
- Missing or incomplete records indicating presence and quality of isolation plugs is incomplete (e.g., not logged or tested, cement recipe undocumented)
- Records of well repair activities may not be successful
- Records of isolation plugs not set within the caprock

The project's storable quantities and uncertainty must reflect the wellbores' containment uncertainty.

4.2.2 Geologic Containment Assessment. An evaluation of a geologic formation for storage must include an evaluation of the seal to establish that it provides geologic containment of the storable quantities to meet the project's specifications. For depleted oil and gas reservoirs, the historical pressure increases or decreases (including subsidence) should be part of the caprock evaluation. As a project matures, the uncertainty associated with geologic containment should be progressively reduced through targeted data acquisition and analyses. This process will support the project's storable quantities and resource classification.

Characteristics of the caprock that should be determined include lithology, thickness, and lateral continuity. Large-scale lateral and vertical variations in these parameters within and potentially beyond the project's specified area should be evaluated to establish indications of containment supportive of the maturity of the project. This evaluation should include the identification of fault zones and structural features that could impact containment. To aid in risk management and monitoring operations, all potential geologic leakage pathways and their potential to transmit fluids should be identified.

The evaluation of the primary caprock should address its integrity (whether it is fractured, faulted, or thin), porosity, permeability, and mineralogical framework. Capillary entry pressure estimations should be determined. Chemical compatibility between CO_2 and CO_2-brine mixtures with the caprock should be assessed.

Methods for obtaining the information for this evaluation will evolve with the project's maturity and include regional mapping and construction of cross sections across the project area. Regional wells may provide core or cuttings that can be evaluated for lithology, mineralogy, and petrophysical characteristics. Regional 2D seismic lines can provide information regarding lateral continuity and presence of cross-cutting faults or presence of other structural features. 3D seismic may provide additional information on faults and fractures, including orientation, distribution, and density. Wells drilled to evaluate the geologic formation and caprock should collect core from the caprocks (full diameter and/or sidewall) and collect a comprehensive suite of geophysical logs that allow for evaluation of the integrity of the caprocks. The suite of logs should include image logs across the primary and any secondary caprocks. In-situ well tests can be performed to evaluate caprock strength and flow characteristics. Geomechanical testing can provide information on the strength of the caprock. A geomechanical earth model that includes in-situ stresses can be generated using these data to evaluate the performance of the containment strata and faults under the conditions expected during storage operations.

Geologic models and reservoir simulations used to assess geologic containment should incorporate caprocks and their relevant characteristics (e.g., mechanical properties and in-situ stresses). These simulations will identify the extent of the CO_2 plume, displaced brine, and pressure increase within the geologic formation. The range of CO_2 plume and pressure footprint sizes transposed onto the mapped reservoir-caprock area will allow the evaluation of the containment risk of proposed injection well locations and identified potential geologic leakage pathways (e.g., fault zones or lateral caprock limits). The role that progressive reduction in uncertainty of geologic containment has in the classification of storable quantities is discussed in Section 2.2.4 Containment Assessment and Project Maturity.

4.3 Estimation of Storable Quantities Using Volumetric Method

4.3.1 Analog. Analogs can be useful for estimating storable quantities and injection rates. A key principle of an analog is that it should be directly applicable to the development project and the geologic formation. Operations and development specifications should also be compared to ensure a past or ongoing project is analogous to the current project. These specifications may include well pattern, well architecture, and brine extraction.

Geologic and reservoir characteristics, such as depth, thickness, porosity, permeability, structure, and stress regime, can significantly impact the estimate of storable quantities. Therefore, due diligence should be taken to ensure the analogy is suitable for the project. At the simplest level, if the geologic structure and reservoir properties are similar, an analogous storage efficiency can be used from the analog project to estimate the storable quantities. Due to the simplicity in this approach, this type of analogy may lead to a wide range of uncertainty for a given project.

4.3.2 Volumetric Equation. The volumetric method estimates storable quantities based on the pore volume ($A \times h \times \phi$) of the geologic formation(s) and a storage efficiency coefficient (E):

$$M_{\mathrm{CO_2}} = A \times h \times \phi \times \rho_{\mathrm{CO_2}} \times E, \quad \text{(4.1)}$$

where $M_{\mathrm{CO_2}}$ is the mass of CO_2; A is the area of the geologic formation considered for storage; h is the average net thickness of the geologic formation (total thickness may be used if E accounts for the net-to-gross thickness ratio); ϕ is the average effective porosity of the net thickness of the geologic formation (total porosity may be used if E accounts for the ratio of effective to total porosity); and $\rho_{\mathrm{CO_2}}$ is the density of CO_2 at the average pressure and temperature of the portion of a geologic formation projected to store CO_2.

Estimates of storable quantities should consider Stored CO_2 and pressure footprints (in the context of the area and thickness used in Eq. 4.1) that might adversely affect the storable quantities estimate. Projects that may lead to excessive pressurization could jeopardize containment and the estimate of storable quantities. Excessive pressurization could be reflected by the choice of E or the magnitude of A and h.

When pressure buildup is expected (e.g., in a closed system), the following equation may be used:

$$M_{\mathrm{CO_2}} = A \times h \times \phi \times \rho_{\mathrm{CO_2}} \times C_t \times \Delta P, \quad \text{(4.2)}$$

where C_t is the total compressibility, and ΔP is the average pressure increase resulting from the Stored CO_2.

Eq. 4.2 will provide a low estimate of storable quantities (compared to Eq. 4.1) because there is no fluid movement out of the geologic formation during active injection. The increased pressure (ΔP) should be defined by the project. The estimation of ΔP should be located at the weakest location of the geologic formation (e.g., fault locations) and based on the threshold activation pressure of natural fracture or fault, entry pressure of a caprock, and fracture initiation pressure at the injection well(s). Moreover, ΔP is likely to be depth-dependent because rock stress is depth-dependent and may be constrained by the risk of inducing seismicity. (This is not intended to preclude fracture stimulation intended to increase injectivity without compromising containment.)

Due to the limited data required for the volumetric method, it is often applied at an early stage of a development project and notional projects.

4.3.3 Storage Efficiency Coefficients for Aquifer Storage on Regional Dip or at Basin Scale. Several organizations and authors have developed methodologies to estimate storable quantities and storage efficiency coefficients at basin and formation scales[8]. The applicability of different estimation methods depends on factors such as boundary conditions, reservoir type(s), CO_2 trapping mechanism(s), and data availability. A study by Goodman et al. (2013) found that regional-scale estimates derived from the volumetric method established by the Carbon Sequestration Leadership Forum (CSLF), US Department of Energy National Energy Technology Laboratory (US-DOE-NETL), and US Geological Survey (USGS) are statistically indistinguishable when applied to open-boundary aquifers using the same geologic input. The volumetric method developed by the US-DOE-NETL and CSLF require minimal data (i.e., area, reservoir properties, CO_2 properties, and storage efficiency). The volumetric methodology developed by the USGS accounts for residual CO_2 trapping mechanisms as well as buoyant trapping in structural and stratigraphic traps. The USGS method requires the same general input as the US-DOE-NETL and CSLF methods with the addition of permeability data that will impact storage efficiency.

Many basin-scale estimation methods define the storage efficiency as the ratio of CO_2-occupied pore volume relative to a total pore volume (e.g., Bachu 2015); however, each method uses slightly different procedures for arriving at that fraction of CO_2-occupied pore volume. For example, the USGS buoyant trapping storage efficiency, defined as the mobility of CO_2 relative to ambient formation fluids and irreducible water, is similar to the US-DOE-NETL displacement storage efficiency, with values from the USGS methodology based on experimentally derived relative permeability data and US-DOE-NETL values based on numerical reservoir simulations using oil- and gasfield data (IEA-GHG 2009; Brennan et al. 2010; Goodman et al. 2016). Probabilistic distributions are intended to be used for each parameter in the USGS method. Deterministic and probabilistic approaches can be applied to the US-DOE-NETL method by use of average values or probability distributions as input for storage efficiency coefficients. An inter-comparison of methods was performed during an International Energy Agency (IEA) workshop (IEA 2013). Ranges of published storage efficiency coefficients are presented in **Table 4.1.**

Case	US-DOE-NETL Atlas V	Mount Simon Sandstone (Illinois Basin), USGS	Norwegian Petroleum Directorate Atlas (Offshore Norway), Open/Closed	Bachu (2015); Closed Aquifers, Alberta Applications	EU Geocapacity Project (Paris Basin), Open/Closed
Low	0.51%	2.9%	3.0%/0.4%	0.4%/km depth	2.0%/0.1%
Medium	2.0%	3.5%	–	–	–
High	5.5%	6.875%	5.5%/0.8%	0.6%/km depth	6.0%/6.0%

Table 4.1–Storage efficiency comparison.

[8] Bachu et al. (2007); Blondes et al. (2013); Bonijoly et al. (2003); Bradshaw et al. (2011); Brennan et al. (2010); Chadwick et al. (2008); CSLF (2007); Goodman et al. (2011); Liu et al. (2014); Norwegian Petroleum Directorate (2011, 2013); Ogawa et al. (2011); Szulczewski et al. (2012); US-DOE-NETL (2007, 2008, 2010); Zhou et al. (2008).

4.3.4 Storage Efficiency Coefficients within a Geologic Structure. When estimating storable quantities in an aquifer in a structural trap, Blondes et al. (2013) recommends the following range of storage efficiency coefficients to be applied to the effective pore volume of the trap:

- Minimum: 20%
- Median: 30%
- Maximum: 40%

The EU Geocapacity project (2009) developed a method in which storage efficiency depends on the entire pore volume (V_{bulk}) hydraulically connected to the pore volume within the structural trap (V_{trap}) and the depth of the structural trap, to avoid excessive pressurization, should no brine extraction be implemented. (All V_{bulk}/V_{trap} assume a closed boundary.) The resulting storage efficiency coefficients range from 0.1% to 36% **(Table 4.2);** the largest structures' storage efficiency coefficients (V_{bulk}/V_{trap} = 100) are closest in value to those recommended by Blondes et al. (2013).

	V_{bulk}/V_{trap}				
Depth (m)	1	5	10	50	100
1000	0.10	0.50	1	5	10
1500	0.15	0.80	1.50	8	15
2000	0.20	1	2	10	20
2500	0.25	1.30	2.50	13	25
3000	0.30	1.50	3	15	30
3500	0.36	1.80	3.60	18	36

Table 4.2—EU Geocapacity storage efficiency coefficients in a structural trap (in percent).

4.3.5 Calculation of the CO_2 Density and Column Heights in Structural Traps. The average pore pressure of the Stored CO_2 affects CO_2 density. For geologic traps open to large aquifers, the estimation should consider that the aquifer pressure returns to hydrostatic conditions and a static CO_2 column develops in each geologic trap. The maximum height of the CO_2 column within each trap should be estimated based on the sealing (i.e., capillary) properties of the caprock overlying the trap. In some geologic traps, filling the CO_2 to the spill point could lead to excessive CO_2 pressure within the trap and may exceed the sealing capabilities of the caprocks.

In the case of a fully confined trap (e.g., a stratigraphic trap), the storable quantities assessment may assume the trap is filled with CO_2 (to irreducible water saturation) up to maximum pressure, while also ensuring containment.

4.4 Traditional and Enhanced Material Balance Methods for CO_2 Storage in Depleted Oil and Gas Reservoirs

Traditional material balance is a volumetric, pressure-dependent reservoir balance of in-situ, produced, and injected fluids. Cumulative injection and production as a function of the average reservoir pressure and pressure/volume/temperature (PVT) data are required. In oil and gas applications, this method is used primarily to estimate the original oil and/or gas in place. After adequate production data are acquired, the predictions of production as a function of pressure can be made. A variety of enhancements (e.g., time dependency) are available.

Enhanced material balance methods are numerical approaches used for oil and gas production forecasts. The principle consists in coupling traditional reservoir analytical material balance principles with well representation through productivity indices, vertical lift curves, and export networks. When this method is calibrated to field performance (production and/or injection data), it is possible to forecast CO_2 injection, and as a result, storable quantities within the depleted hydrocarbon reservoir.

The storable quantities estimate will be based on injection quantities by wells under specific operational constraints (as maximum bottomhole pressure or tubinghead pressure). For an active storage project, the material balance model can be updated to match new pressure observations and well performance to validate or update the previous estimate of storable quantities.

Elements to review when using these material balance methods include:

1. If the fluids occupying the reservoir volume can be displaced with CO_2 at magnitudes similar to those of produced hydrocarbons and water volumes, the degree at which these fluids can be displaced is an uncertainty. A range of property values should be used to model the efflux of the aquifer water from the hydrocarbon reservoir.
2. CO_2 storage can reverse the process of hydrocarbon accumulation and production such that heterogeneities in the reservoir will store CO_2 within the hydrocarbon reservoir without spilling out of the structure before it is fully filled with CO_2.
3. No geomechanical damage was done during depletion that would lead to loss of pore volume (as pore collapse) or limitation of injection pressure before the caprock is compromised.

A key limitation of the material balance method is its inherent inability to model geologic heterogeneities that would lead to CO_2 flows toward unwanted areas (i.e., the risk of CO_2 injection into high-permeability layers that would lead to CO_2 leakage before the structure is filled, or risk that the CO_2 reaches a well with integrity concerns).

4.5 Reservoir Simulation Methods

Storable quantities for active and planned projects can be estimated by reservoir simulation methods. A set of possible realizations of the geologic formation(s) (including boundary conditions) will be used and simulated according to the project specifications (e.g., well locations and well constraints). Certainty in the storable quantities estimate is expected to increase when the reservoir simulation models are calibrated to performance history. Depending on input parameters, reservoir simulation enables estimation of the storable quantities buoyantly trapped within a structure, residually trapped, and dissolved in brine.

Multiple or single geologic models can be used:

- Multiple, unique geologic models can be used in reservoir simulation to provide ranges of storable quantities (e.g., low, best, and high estimates). This methodology is preferred, but not common practice given the time and cost of developing several geologic models.
- A single geologic model can be used to directly estimate a single most likely (or best) estimate of storable quantities.

4.5.1 Reservoir Simulations Applied to Aquifer Storage. Compared to oil and gas reservoirs, aquifers usually have less information available. Therefore, it is important to quantify the range of uncertainty by capturing geologic scenarios in terms of distribution of petrophysical properties when estimating storable quantities with reservoir simulation methods. Several reservoir models should be simulated to estimate the range of storable quantities. If there is uncertainty in the specifications of the development project, different development projects should be simulated to acquire a range of storable quantities.

In cases where pressure buildup of a development project reaches a maximum pressure, the effect on storable quantities should be included. Geomechanical models may be used to supplement reservoir flow simulation.

At the basin scale, reservoir simulation can be used to estimate storable quantities, CO_2 injection rates, and the number of wells required for a notional project. If a single development project's CO_2 injection (and brine extraction, if included) schedule is considered a likely basin-scale project, the simulated cumulative injection may establish the most likely (i.e., best) estimate of storable quantities for the basin.

Using reservoir simulation at the basin scale may have challenges due to uncertainties in petrophysical properties; boundary conditions (including outcrops on shore or at seabed and/or contact with other geologic formations); continuity and integrity of the caprock; acceptable pressure build up to avoid damage to the caprocks (note that damage could happen in shallow areas in the aquifer where the rock stresses are lower at large distances away from the storage resource); and to minimize induced seismicity within the geologic formation.

Reservoir simulation can demonstrate compliance with the specific objectives of CO_2 storage projects, such as

- Showing that injected CO_2 will not spill out of the structural closure
- Showing that injection rates are achievable without exceeding pressures that would risk containment or induced seismicity (e.g., fault activation)
- Optimizing the injector location and perforations
- Defining brine extractors, if needed, to mitigate pressure increase

Examples 2 and 3 (Section 4.8 Appendix) describe applications of reservoir simulation to estimate storable quantities. These examples illustrate two crucial findings: (1) Although volumetric methods may indicate large storable quantities, those estimated from reservoir simulation may be significantly smaller due to limitations placed on well injection rates and related notional project specifications; and (2) storable quantities estimated from reservoir simulation match more closely to the volumetric method applied to a "closed" aquifer (Eq. 4.2). Therefore, it is highly recommended that reservoir simulations be used to supplement the volumetric method. This is particularly important as the project matures and more site-specific data become available to generate effective numerical flow models.

4.5.2 Specificities When Applied to Depleted Oil and Gas Reservoirs. In the case of storage in depleted oil and gas reservoirs, the production and injection history of the reservoir provides the opportunity for calibration of the reservoir model. Well and development data (e.g., seismic data) may provide greater confidence in the reservoir model to estimate storable quantities from reservoir simulation. The capability of a reservoir model to replicate the production history of the reservoir is dependent on the quality and quantity of historical production and injection data.

4.6 Injection Performance Trend Analysis

For active projects, CO_2 injection performance trend analysis of the historical injection rate and pressure data can be used to estimate storable quantities. In addition to the injection well(s), trend analyses of monitoring-well measured parameters (e.g., forecast of pressure to a prescribed limit and the Stored CO_2 in proximity to geologic structure's spill point) can be completed. Forecasts of monitoring-well parameters can affect storable quantity estimates similar to that of the injection well.

4.7 Estimating the Total Storage Resources (TSR)

TSR may be estimated independent of a project. Specifically, for regional TSR estimates, it may be difficult to identify a project. However, in the context of storage classification and categorization, a specific or notional project is required. To determine the storable quantities classified as TSR, with or without a specified project, it is required that the geologic formation(s) and storage site area are identified.

TSR may be used in the calculation of storage efficiency for an active or development project; however, the TSR used would be specific to the project and not a regional estimate. The sections below provide guidance for estimating storable quantities classified as TSR using the volumetric approach, but similar considerations can be made for the other approaches.

4.7.1 Application to Aquifers. The TSR of free-phase CO_2 in geologic traps may be calculated with Eq. 4.1 using $E = 1 - S_{wirr}$. The TSR of free-phase CO_2 by residual trapping (outside geologic traps) may be calculated with Eq. 4.1 using $E = S_{gr}$, the residual CO_2 saturation.

4.7.2 Application to Depleted Hydrocarbon Reservoirs. In comparison to a brine aquifer, the presence of hydrocarbons will decrease the TSR of free-phase CO_2. Eq. 4.1 can be used with $E = 1 - S_{wirr} - S_{HC}$, where S_{HC} is the average hydrocarbon saturation within the pore volume. Note that this is a simplified formula because CO_2-hydrocarbon mixing (solubility) may affect the volumes of fluids at the pressure and temperature of the Stored CO_2.

The material balance approach to estimate the TSR in a depleted hydrocarbon reservoir can be expressed with Eq. 4.1. The product of A, h, ϕ, and E are equal to the cumulative withdrawal of all fluids *less* the cumulative injected fluids and water influx from hydraulically connected aquifers.

4.7.3 Implications for Basin-Scale Resource Assessments. Depending on the scope of basin-scale assessments, the TSR may include the combined storable quantities in aquifers and depleted oil and gas reservoirs. Moreover, each geologic formation's connection to the ground surface or fresh water must be considered as part of the assessment. Geologic formations isolated from the ground surface and fresh water may be considered as a single, geologic trap that can be filled with CO_2 near to the uppermost caprock. The limiting factor to the height of the Stored CO_2 column is the pressure exerted by the CO_2 against the caprock because the geologic formation at the top of the trap may experience excessive pressure.

For geologic formations in hydraulic connection with a seabed, ground surface, or fresh water, it would not be possible to fill the formation with CO_2 to irreducible water saturation because CO_2 would flow upward. In this case, structural and stratigraphic trapping can only be achieved in local structures where the rest of the geologic formation on regional dip is available for residual and dissolution trapping.

4.8 Appendix

Example 1: US DOE Volumetric Method for Resource Assessment

The US DOE's volumetric method is the basis for CO_2 resource calculations in the US DOE Storage Atlas (2008, 2010, 2012). This method relies only on geologic parameters and does not take pressure or containment under migration explicitly into account. However, the displacement efficiency terms can be used implicitly to represent pressure and containment. In contrast, reservoir simulation can account for pressure and migration containment directly (Example 2). The US DOE method is a simple method to use when limited data are available.

The US DOE methodology (US-DOE-NETL 2010) derives storage efficiency (E) from Eq. 4.3:

$$E = E_{A_n/A_t} \times E_{h_n/h_g} \times E_{\phi_e/\phi_{\text{tot}}} \times E_v \times E_d. \quad (4.3)$$

The US DOE's E represents the fraction of the accessible pore volume that is most likely to be contacted by Stored CO_2. Due to reservoir complexity, there is usually a high degree of uncertainty associated with E. In open systems, the accessible pore volume depends on geologic characteristics, volumetric displacement efficiency (E_v), and microscopic displacement efficiency (E_d) (Lake 1989).

The geologic parameters include net-to-total area (E_{A_n/A_t}), net-to-gross thickness (E_{h_n/h_g}), and effective-to-total porosity $\left(E_{\phi_e/\phi_{\mathrm{tot}}}\right)$. The volumetric displacement efficiency (E_v) is calculated by combining the areal and vertical connectivity components, and microscopic displacement efficiency (E_d) is derived from the capillary properties (e.g., wettability) of the reservoir rock. The geologic parameters reflect the percentage of volume that is amenable to CO_2 storage, and displacement efficiency components reflect different physical barriers that inhibit CO_2 from contacting the pore volume of a given basin or region (Goodman et al. 2011). The ranges of geologic and displacement parameters for aquifers in different lithologies are listed in **Table 4.3.** They are meant to serve as examples only and should be modified based on site- and project-specific requirements, when necessary.

		Low (P10)/High (P90) Values by Lithology		
Term	Symbol	Clastic	Dolomite	Limestone
Net-to-total area	E_{A_n/A_t}	0.2/0.8	0.2/0.8	0.2/0.8
Net-to-gross thickness	E_{h_n/h_g}	0.21/0.76	0.17/0.68	0.13/0.62
Effective-to-total porosity	$E_{\phi_e/\phi_{\mathrm{tot}}}$	0.64/0.77	0.53/0.71	0.64/0.75
Volumetric displacement efficiency	E_v	0.16/0.39	0.26/0.43	0.33/0.57
Microscopic displacement efficiency	E_d	0.35/0.76	0.57/0.64	0.27/0.42

Table 4.3—Storage efficiency coefficients for aquifers (US-DOE-NETL 2010).

Example 2: Evaluation of Large-Scale Storage in the Basal Saline System in the Williston and Alberta Basins (after Liu et al. 2014)

A joint reservoir simulation study was conducted by the Energy and Environmental Research Center and Alberta Innovates – Technology Futures for the Cambro-Ordovician saline system (COSS) to assess and define a notional project that can store approximately 94 Mtonne/year of CO_2 from the region. The specific objectives were to address questions including duration of a notional project to store CO_2 at the current emissions rate from the region (approximately 94 Mtonne/year of CO_2), number of wells needed, and impact of injecting this amount of CO_2. A 3D geocellular model was built from stratigraphic correlations, petrophysical analysis, structural models, facies models, and reservoir properties. The storable quantities from the volumetric method were calculated based on the US DOE Storage Atlas (2010, 2012) approach after applying various cutoffs. The P10, P50, and P90 storable quantities of 198, 373, and 640 Gtonne were calculated based on storage efficiency of 4.8%, 9.1%, and 15.6%, respectively.

The geocellular model and reservoir simulation were used as the framework for an assessment of the storable quantities of the formation by addressing the effect of multiple large-scale CO_2 injections and considering factors such as injection rate, injection pattern, timing of injection, and pressure interference between injection wells. Two scenarios were evaluated, each injecting 94 Mtonne/year:

- Scenario 1: injection clusters placed at the locations of the 16 aggregated sources
- Scenario 2: injection sources partitioned into 25 feeds that were pipelined to regions with better reservoir characteristics to optimize injection

The simulation results of Scenario 1, with a total of eight cases, are presented in **Fig. 4.3.** Seven cases were built from a base case to investigate the effect of various parameters, such as adding more injection wells, adding brine extraction, modifying the k_v/k_h, modifying the relative permeability curves, and implementing stepwise or ramped-up injection rates. Simulation of cases 1 through 5 had an injection period from 2014 to 2050 and a post-injection period from 2050 to 2100. The two largest impacts among the five cases were the addition of injection wells from 16 to 210 (Case 1) and the addition of brine extraction wells to a specific area (Case 2). Cases 3 and 4 showed that changes to the relative permeability and k_v/k_h had a small effect on overall injection. Case 6 gives the largest storable quantities by injecting CO_2 in a stepwise manner and brine extraction over a 50-year period, which is 28% of the total emissions from the region. The results of Scenario 1 indicate that the per-well annual injection rate of 90.7 to 136 ktonne/year was achieved with 210 wells; however, that was significantly below the target of 453.6 ktonne/year, which was needed to reach the notional project's annual storage rate. At these injection rates, approximately 700–1,050 injection wells would have been required to meet the storage target.

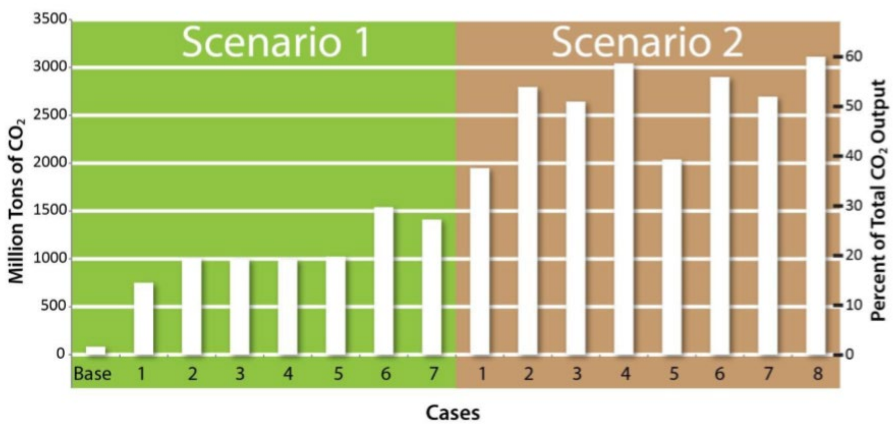


Fig. 4.3—Results comparison of Scenarios 1 and 2 (Liu et al. 2014).

Scenario 2 included the movement of injection clusters to areas where high permeability values were connected in the geocellular model and the distribution of injection clusters to 25 injection locations. Based on the results of Scenario 2 (Fig. 4.3), the selection of areas with better permeability and connected volume had a large effect on increasing the total amount of CO_2 stored and the per-well injection rate. The variables that had the largest effect in increasing CO_2 injection in Scenario 2 were rock compressibility, adding brine extraction at each site, and moving the injection locations to "better" locations. Each of these parameters were combined in Case 8, which injected 59.8% of the overall emissions from the large CO_2 sources in the region. This case exhibited the largest storable quantities over a 50-year injection period. However, even when injection locations were moved to a "better" area, the COSS was not able to support an average annual injection rate of 450 ktonne/year from 210 wells. In Scenario 2, the average per-well injection rate was between 168 and 249.5 ktonne/year. At these average injection rates, a total of 378 to 563 wells was required to meet the notional project's annual storage rate.

The volumetric method's storable quantities of 198, 373, and 640 Gtonne at P10, P50, and P90, respectively, suggest that at the current rate of 94 Mtonne/year of point-source CO_2 emissions from the overlying sources, the notional project's injection period should be between 2,100 and 6,780 years. Based on this volumetric calculation, the COSS should store 94 Mtonne/year for 36 to 50 years, resulting in a total storage of only 3.4 to 4.7 Gtonne. However, when different cases were designed to simulate the injection and storage of the notional project into the COSS, the investigators found that the notional project's annual storage rate was not met in any of the cases. Injectivity was a limiting factor, and in all cases, more wells would have been required to meet the storage target.

The post-simulation analysis revealed that to inject and store 94 Mtonne/year of CO_2 for 50 years (4.7 Gtonne) in the COSS, many more wells (>210) and areas (>25) would have been required Therefore, compared to the volumetric method, reservoir simulation predicted only a small fraction was used. The authors note that the reservoir simulations were only run for 50 years and, for a majority of the cases, the slope of the injection rate (vs. time) was constant across that time period. The constant injection rate indicates that the COSS was still accepting CO_2 and the storable quantities estimated from simulation could not be used to assess the TSR. The authors also note that the aquifer pressure increase was small in all cases in Scenario 2, which would help reduce the risk of leakage from the reservoir and maintain the integrity of the caprock.

The SRMS requires that a feasible, albeit notional, development project is applied to any estimate of storable quantities, even to regional estimates of prospective storage resource. The above comparison between storable quantities estimated from the volumetric method and reservoir simulation implies that a modification to the volumetric method's estimates would need to be applied to define a development project (i.e., to mature the notional project).

Example 3: Compatibility between Volumetric Methods and Reservoir Simulation Methods to Assess Basin-Scale Resources (after Thibeau et al. 2014)

The storable quantities from reservoir simulation were compared with the pore volumes of four aquifers of varying sizes: Mount Simon Sandstone (US), Basal Cambrian Sandstone (US and Canada), Bunter Sandstone (North Sea), and Rotliegend Sandstone (the Netherlands). A key finding in the Thibeau study was that the peak overpressure in the core injection area at the end of injection was only marginally affected by the chosen boundary condition for the aquifer (no-flow vs. infinite-acting). A range of the maximum average pressure buildup (up to the formation parting pressure) was used in the simulations to calculate the storable quantities of the aquifer. The Mount Simon Sandstone's storable quantities could support a notional project of 20 individual CO_2 storage projects in a core injection area suitable for long-term storage, each injecting 5 Mtonne/year for 50 years (a total of 5 Gtonne of CO_2). The peak pressure increase in this case was 3.6 MPa, which is an 18% increase over the initial pressure. To estimate the TSR of the Mount

Simon Sandstone, injection could have been modelled up to a 13.1 MPa pressure increase, corresponding to a regulated fractional pressure increase of 65%. Considering a quasilinear relationship between injection rate and pressure buildup, the storable quantities would have increased from 5 to 18.1 Gtonne of CO_2.

The storable quantities from simulation were compared to the volumetric method using closed and open outer boundaries. Using the volumetric method from the US DOE Storage Atlas (2012) for the Mount Simon Sandstone, the closed aquifer assumption yields storable quantities of 13.3 Gtonne and the open aquifer assumption gives 11 to 150 Gtonne. The USGS method (Brennan et al. 2010; Blondes et al. 2013) yields a larger (62 to 130 Gtonne) range (see discussion in previous section on the differences between volumetric methods). The authors note that the reservoir simulation results are closer to the volumetric storable quantities obtained using a closed aquifer assumption (Eq. 4.2).

Example 4: Goldeneye Depleted Hydrocarbon Reservoir Storage Resources Assessment (after Shell U.K. Limited 2014)

The Captain Sandstone at Goldeneye is a depleted hydrocarbon gas reservoir. Storable quantities may be estimated based on replacing the hydrocarbon gas produced with CO_2 by calculating the subsurface volume of hydrocarbon gas produced and setting this volume equal to the pure CO_2 subsurface volume (using average reservoir temperature and the storage pressure). This gives storable quantities of 47 Mtonne.

This estimate is simplistic because it ignores several trapping mechanisms and geologic features that affect the storable quantities. For the Captain Sandstone at Goldeneye, these features include:

- Reservoir heterogeneities resulting in uneven use of pore space
- Volumetric sweep reduction resulting from gravity segregation of CO_2 and brine
- Brine saturation resulting from increased immobile brine saturation, given aquifer water encroachment
- Mixing with residual gas where the compressibility of a methane-CO_2 mixture is less than that of pure CO_2
- CO_2 dissolution into the contacted reservoir brine
- Secondary filling of the low-permeability Captain E Unit
- Additional water-leg capacity within the structure below the original oil-water contact

The storable quantities based on these features were estimated and used to modify the 47 Mtonne.

Some of these features will have greater impact over longer timescales (e.g., dissolution, Captain E buoyancy filling); however, it is the impact over the timescale of the injection period that determined the storable quantities. Mineralization and pore space reduction resulting from irreversible compaction were considered negligible.

The storable quantities do not include volumetric sweep because of the displacement instability during injection (formation of a CO_2 gravity tongue; Dietz 1953; Dake 1978). The CO_2 tongue will form during injection because of the increased viscous forces, causing CO_2 to override formation brine within the trap rather than vertically displace it under gravity-stable conditions. It will determine the time when the edge of the CO_2 plume reaches the original oil-water contact and even the spill point **(Fig. 4.4)**. The injection pattern and the rate of injection determine the degree to which a CO_2 gravity tongue may affect storable quantities; however, for this calculation we assume that the injection pattern has been optimized so that CO_2 does not spill via the spill point. Once injection stops, CO_2 will come to a gravity-stable equilibrium inside the CO_2 storage site. Any CO_2 extending below the original oil-water contact of Goldeneye that is not at the spill point will be contained within the structural trap. Consequently, in this case, the post-injection distribution of Stored CO_2 is not constrained by the formation of a CO_2 gravity tongue, and the volumetric sweep efficiency does not include the gravity tongue. Nevertheless, the effect of a gravity tongue on storable quantities could be significant, depending on the reservoir structure.

(a)
(b)
(c)
(d)

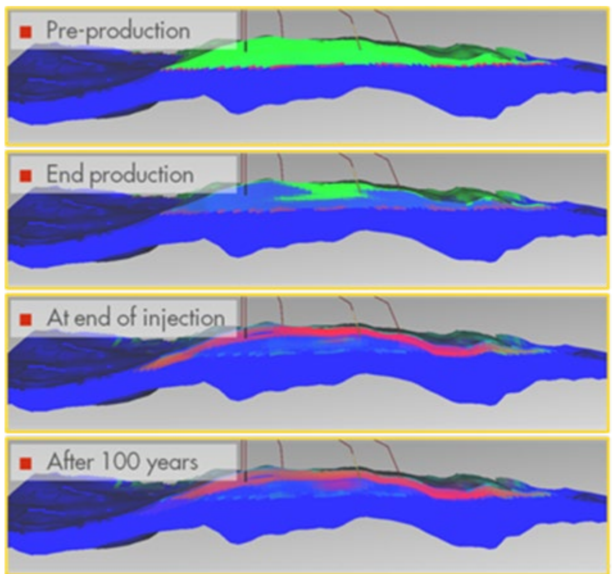


Fig. 4.4—Cross sections from the numerical simulation model illustrating the fluid at key development stages (after Spence et al. 2014). (a) The original hydrocarbon gas fill (green). (b) Post-hydrocarbon production (note the invasion of water above the original oil-water contact). (c) At the end of the CO_2 injection phase, note the CO_2 gravity tongue extending parallel to the top-surface below the original oil-water contact (left side of model). Predominantly CO_2 indicated by red color. (d) One hundred years post-injection—note that the gravity tongue has moved back up into the crestal CO_2/gas accumulation.

The impact of each of these features on the Goldeneye storable quantities is illustrated in a waterfall chart **(Fig. 4.5),** and the estimation of each is discussed briefly. Combining all components in the chart shows that Goldeneye's storable quantities are 34 Mtonne, which was more than adequate to store the 20 Mtonne specified by the notional project. [See the Peterhead CCS Dynamic Modelling Report (Shell U.K. Limited 2014) for more information.]

- ***Heterogeneities:*** The Captain Sandstone is divided into four sand subunits (Captain A, C, D, and E). Captain D has the best properties **(Fig. 4.6).** Reservoir simulation showed that Captain D was filled by CO_2 at the injection timescale because Captain D represents 78% of original gas initially in place (GIIP; of all four subunits); hence, storable quantities reduced by 10 Mtonne if only Captain D was filled.

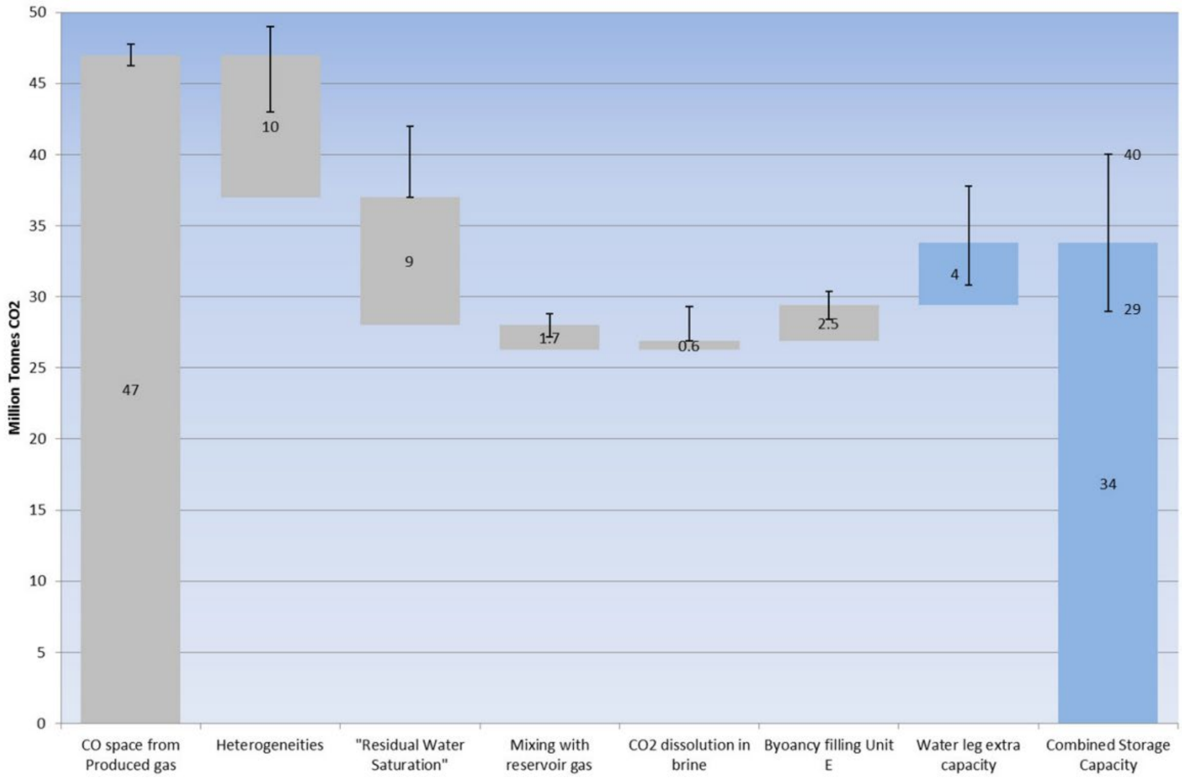


Fig. 4.5—Waterfall chart illustrating the adjustments (both increasing and reducing factors) made to storable quantities estimated from replacing hydrocarbon gas with CO_2 (left) to generate storable quantities for the Goldeneye Captain reservoir (right) that included specific trapping mechanisms and geologic heterogeneity (Shell U.K. Limited 2014).

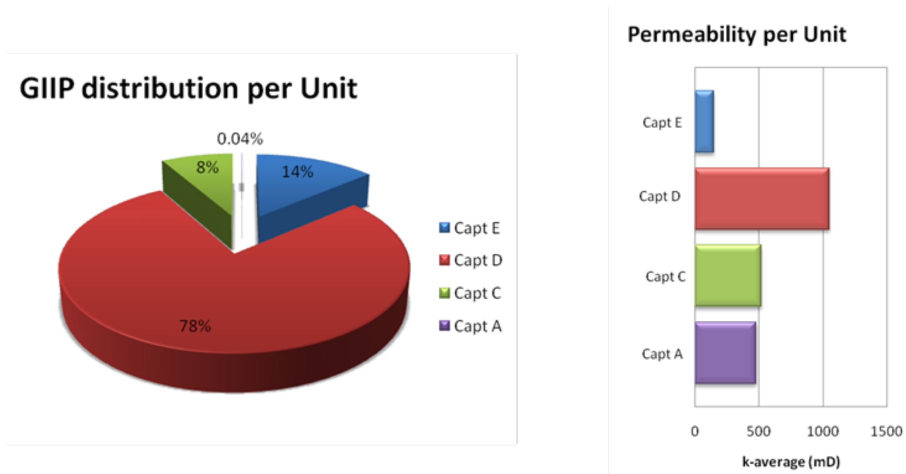


Fig. 4.6—Goldeneye GIIP distribution and average permeability per geologic unit (Shell U.K. Limited 2014).

- ***Residual water saturation:*** Following production of the hydrocarbon gas, part of the originally gas-bearing pore space was replaced with brine as the aquifer encroached into the original gas-bearing pore space. As CO_2 is injected, it will displace some of the brine back to the aquifer; however, part of the brine will be trapped at residual saturation due to secondary drainage and relative permeability effects. Fractional flow and Buckley-Leverett calculations estimated an additional 15% to 25% water saturation within the CO_2 plume. An additional 20% water saturation reduced the storable quantities by 9 Mtonne.

- ***Mixing of CO_2 with reservoir gas:*** An additional reduction of storable quantities is expected to occur once CO_2 becomes mixed with the trapped hydrocarbon gas. An initial estimate of the impact is made based on the real gas equation ($pV = znRT$). The impact on z is assessed, given perfect mixing of the hydrocarbon gas (mainly methane) and CO_2 vs. no mixing. Reservoir simulation indicates that perfect mixing of the CO_2 and hydrocarbon gas is unlikely, and instead, a hydrocarbon gas bank is formed at the tip of the CO_2 plume. A small mixed region of CO_2 methane reduced the storable quantities by < 2 Mtonne.
- ***Dissolution of CO_2 in brine:*** The estimate of CO_2 dissolved in brine was based on CO_2 solubility of 4.6% [weight; from a correlation by Chang et al. (1998) using reservoir temperature, pressure, and salinity], given that the Stored CO_2 will contact approximately 25% of the brine (the water saturation left behind the CO_2 injection front). This corresponds to a resource increase of <1 Mtonne.

    Over longer timescales, the dissolution of CO_2 in brine is considerably more complicated than the instantaneous dissolution described here. Additional dissolution will occur as a result of diffusion and density-driven brine mixing.
- ***Captain E (buoyancy fill):*** Buoyancy forces will push CO_2 into the overlying, poorer-quality Captain E sand. After injection, buoyancy forces dominate, and the CO_2 contracts back into the original gas cap. The Captain E unit represents 13.7% of the original GIIP; however, the CO_2 will primarily invade the lower portion of the Captain structure. The storable quantities increase of 1.3 Mtonne estimated here represents a storage efficiency for the Captain E unit of 33%, which was confirmed by numerical simulation (20 years post-injection).
- ***Water-leg resource:*** Within the Goldeneye structure, there is a brine aquifer below the original oil-water contact that could also be used for CO_2 storage. The brine aquifer volume (vertically below and downdip of the trap) is determined from the range of models representing the geologic uncertainties. These are dominated by the top surface of the field's west flank and variations in the modelled pinch-out of sand units. The volumetric method predicts storable quantities of 3 to 7 Mtonne that would be stored by means of residual trapping and brine dissolution. (The reference case model could hold 6 Mtonne in the original brine-filled pore volume within the structure.)

Example 5: Snøhvit Injection Performance in Tubåen Formation (after Hansen et al. 2013)

Injection performance (rate and pressure) of geologic formation can be difficult to predict and can result in a wide variation of storable quantities or cessation of a project prior to the completion of the planned injection volume. **Fig. 4.7** illustrates the injection pressure history (performance trend) for the case of Snøhvit CO_2 injection (Offshore Norway, Barents Sea) into the Tubåen Formation. As injection pressure increased and approached the estimated fracture pressure, it was anticipated that the Tubåen Formation would be abandoned, and injection into another formation (Stø Formation) started, hence defining the storable quantities into Tubåen from this specific injector.

Note that injection performance trend analysis is less mature in the CO_2 storage industry than in the oil and gas industry. Formalized approaches similar to decline curve analysis remain to be developed until sufficient CO_2 storage projects have reached a stage at which performance trends are established.

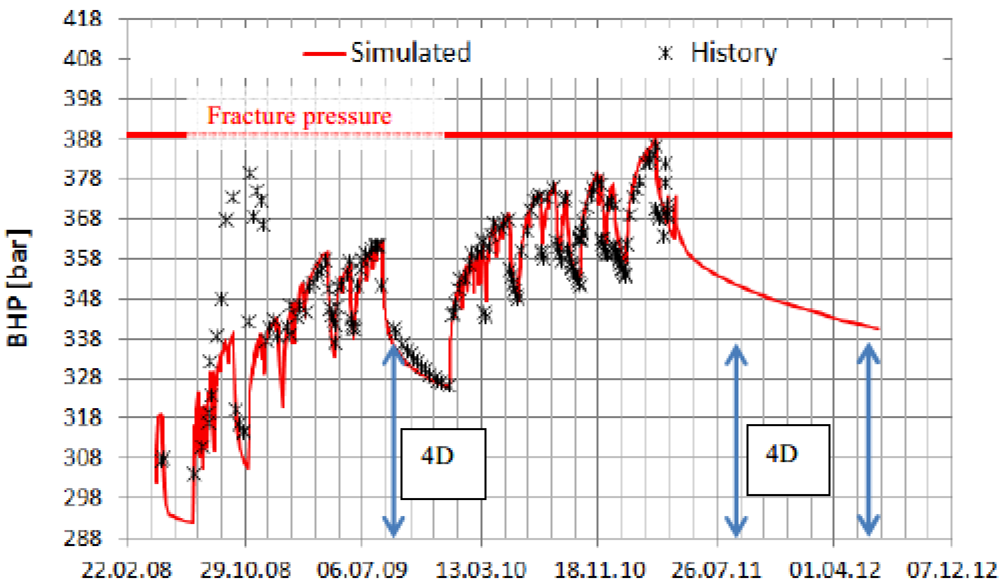


Fig. 4.7—Analysis of the pressure increase over time at Snøhvit CO_2 injector into Tubåen Formation (Hansen et al. 2013). (4D in the original figure, while irrelevant to this publication, signified the date time-lapse seismic surveys occurred.) BHP = bottomhole pressure.

Example 6: Reservoir Modeling Applied to Quest Project and Resulting Total Storable Quantities

Duer (2017) conducted a reservoir simulation study on CO_2 plume growth to assess the risk of CO_2 and brine leakage resulting from the Shell Quest project in the Basal Cambrian Sandstone (BCS) aquifer in Alberta. Full field, 3D reservoir simulation models and single well radial models were used in the study. The results from the 3D simulations **(Fig. 4.8)** show that the CO_2 plumes are contained within 5 km of the injection well for the project's specified duration (25 years).

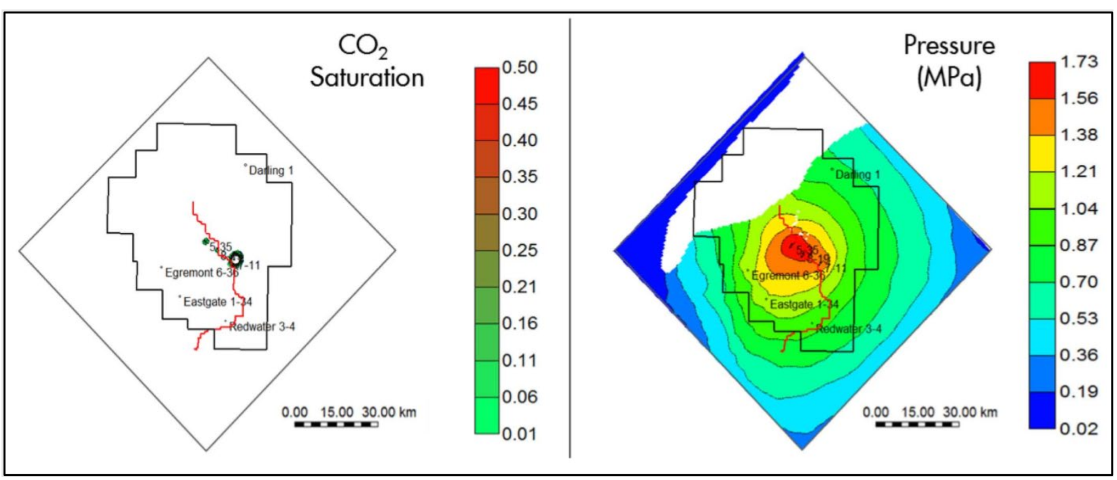


Fig. 4.8—Maps showing modelled CO_2 plume (saturation) and pressure footprint at Quest after 25 years of injection (Duer 2017).

A resource assessment was performed before drilling wells and is described in the Environmental Assessment (Shell Canada 2010). The low storage efficiencies shown in **Table 4.4** (compared to the basin-scale volumetric approach) result from selecting a large notional project area (i.e., the denominator of storage efficiency calculation). The area was selected based on the following principles:

- Design the project for the low case, subsurface scenario model (i.e., low storable quantities and injectivity) such that the project's storable quantities and injection rate of CO_2 may be accommodated within the specified area.
- Select the area to include the region of elevated pressure and prevent pressure interference between future CCS projects within the BCS, which may affect injection rates and volumes.
- Safeguard wellbore containment over the entire life of the project by having adequate offset distances between the project's injection wells and other wells that penetrate the BCS.

Note that a smaller area could have been used by extracting brine from the storage site to mitigate the pressure increase.

Item	Unit	Low	Best	High
Area (40 townships)	km^2		3730	
Net pore thickness	M	8.17	6.62	2.46
Pore volume	km^3	30.5	24.7	9.2
Mass of CO_2 to be stored	Mtonne		27	
CO_2 density	kg/m^3	761	731	711
CO_2 volume	km^3	0.035	0.037	0.038
Storage efficiency	%	0.12	0.15	0.41

Table 4.4—Storage Efficiency of the Quest Project, status before the drilling campaign

Example 7: Volumetric Estimation of the Pore Volume for a Storage Prospect in an Aquifer on Regional Dip (i.e., Outside a Structural Closure)

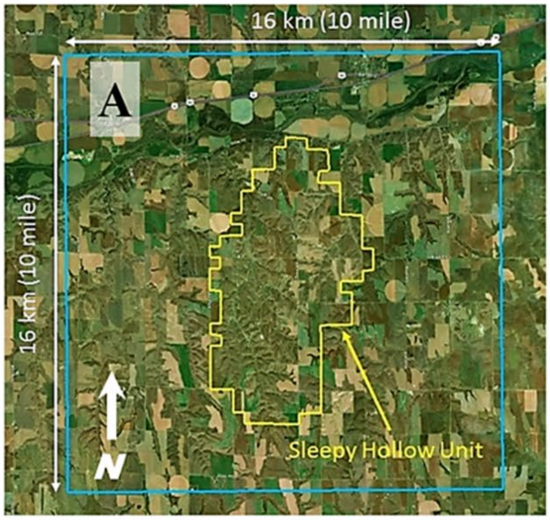
Eqs. 4.1 and 4.2 can be used to estimate storage efficiency and storable quantities on regional dip outside a structural closure for basin-scale resource assessments. Relative to the formation or basin scale, the geologic efficiency parameters (E_{A_n/A_t}, E_{h_n/h_g}, $E_{\phi_e/\phi_{\mathrm{tot}}}$) should be well-constrained at the project and site scales, and only the displacement efficiency parameters (E_v and E_d) may be needed to calculate E for site-specific storage resource assessments (e.g., Frailey 2013). E_v and E_d account for the fraction of the reservoir pore volume immediately surrounding an injection well that can be contacted by CO_2, essentially representing the volume of the CO_2 plume (Goodman et al. 2016). This volume may also be chosen to ensure that no excessive pressure increase occurs outside the boundaries of the area assessed. However, volumetric methods have not yet been established for calculating E_v to account for CO_2 migration and pressure plume propagation on regional dip. E_v may rely on the use of analogs and/or numerical simulations to derive high and low ranges of volumetric displacement efficiency. Microscopic efficiency (E_d) values can be determined from coreflood experiments, fluid saturation measurements, or estimated indirectly from resistivity log calculations.

In addition to the net pore volume, represented by geologic parameters (i.e., net area A_n, net thickness h_n, and effective porosity ϕ_e), it is important that project-specific criteria and input used in volumetric methods to constrain displacement efficiencies be clearly defined for aquifers outside of structural closures. This will help ensure that accurate estimates of storable quantities can be (re)produced and storage resources are classified appropriately.

Examples of project-specific criteria and input that can be used in the volumetric method to define the geologic parameters for Eq. 4.3 for regional dip assessments are provided in **Table 4.5. Fig. 4.9** shows how project-specific requirements can be applied to define (a) areal boundaries and (b) net reservoir storage volumes for an aquifer occurring outside of a structural closure in southwest Nebraska. The example data input and calculations in Table 4.5 and Fig. 4.9 are tailored to a specific site and project and may not be suitable for application in other CO_2 storage projects/resource assessments.

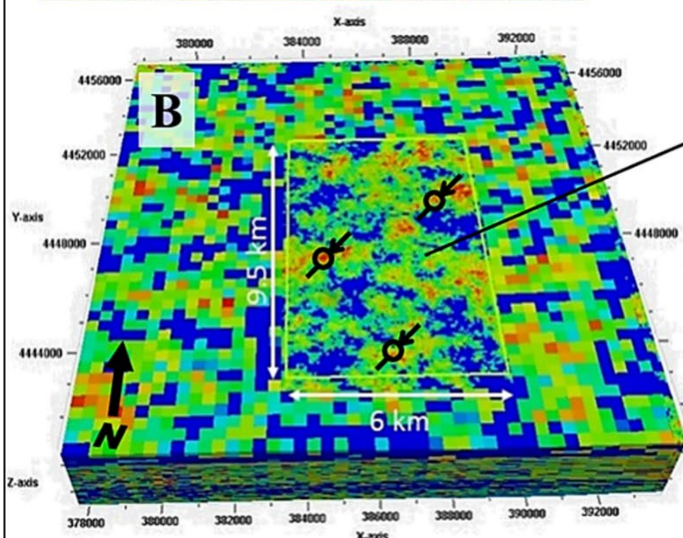
Symbol	Definition	Example Data Input/Calculation
M_{CO_2}	Storable quantities of CO_2	Parameters below.
A_t	Total area of the geologic formation	Determined by areal extent of geologic formation on 2D geologic maps (e.g., structure, isopach) and/or shapefile area.
h_g	Gross thickness of the geologic formation	Determined by zone top and base depths and/or associated isopach maps of the geologic formation within the total area.
f_t	Total porosity (isolated + clay bound + interconnected) of the geologic formation	Determined by core and log porosity of the bulk volume of the geologic formation (total area × gross thickness) within the total area.
ρ_{CO_2}	Density of CO_2 at geologic formation temperatures and pressures	Determined by geothermal and pressure gradients calculated from well log, bottomhole, and injection test data and the associated depth of the geologic formation within the total area.
E_{A_n/A_t}	Net-to-total area of the geologic formation	Determined by the fraction of the total area that is predominately clean sandstone or carbonate with interconnected pore volume; based on a maximum gamma ray log cutoff of 75 gAPI and a minimum permeability cutoff of 10 md.
E_{h_n/h_g}	Net-to-gross thickness of the geologic formation	Determined by the fraction of the gross thickness that is predominately clean sandstone or carbonate with interconnected pore volume; based on a maximum gamma ray log cutoff of 75 gAPI and a minimum permeability cutoff of 10 md.
ϕ_e	Effective, interconnected porosity of the net volume of the geologic formation	Determined by the integrated core and effective (shale-corrected) log porosity portion of the geologic formation that is predominately clean sandstone or carbonate with interconnected pore volume; based on a maximum gamma ray log cutoff of 75 gAPI and a minimum permeability cutoff of 10 md.
E_v	Fraction of the CO_2 plume immediately surrounding an injection well	Determined by numerical injection simulations in sector models (IEA-GHG 2009).
E_d	Fraction of the pore volume occupied by mobile pore fluids that can be displaced by CO_2 after residual water saturation (irreducible water saturation); 1-S_{wirr} from log and/or core data.	Determined from core flood experiments, fluid saturation measurements, resistivity log calculations.

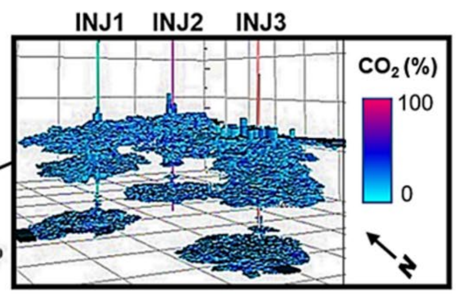
Table 4.5—Example data sources for parameters in Eq. 4.3 and examples of site-specific criteria/quantification methods used to define each parameter for a defined project.



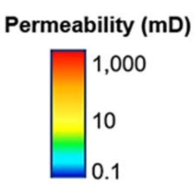
Storage Zone	$A_t \times h_g \times \phi_{tot}$ (million m^3)	ρCO_2 (kg/m^3)
1 (mixed clastic)	312	715
2 (limestone)	657	717
3 (sandstone)	112	721

Storage Zone	$E_{An} \times E_{hn} \times E_{\phi e}$		
	Low	Best	High
1	0.63	0.77	0.90
2	0.29	0.53	0.74
3	0.64	0.82	0.97





Storage Zone	$E_V \times E_d$		
	Low	Best	High
1	0.07	0.14	0.24
2	0.09	0.15	0.19
3	0.11	0.19	0.27



Storage Zone	MCO_2 (million tonnes)		
	Low	Best	High
1	14	28	49
2	31	56	92
3	5	11	19

Fig. 4.9—(a) Map view showing reservoir area (yellow) and project boundaries (blue) for an aquifer within a stratigraphic closure in southwest Nebraska and (b) the associated 3D geologic model showing the permeability distribution and simulated CO_2 plumes around three injection wells used to derive net-to-gross thickness and area and displacement efficiencies (E_V and E_d).

5.0 Analogy and Differences of SRMS to PRMS

Traci Rodosta and Steven G. Whittaker

5.1 Overview

The SRMS establishes a system for classifying and categorizing storage resources used for the geologic storage of CO_2 that is parallel to the PRMS used for petroleum reserves and resources by means of a project maturation process. The complementarity of the two systems is intentional to allow those familiar with the application of the PRMS—including the industrial community, national reporting and regulatory agencies, and financiers—to more readily apply the SRMS to the management of storage resources. Thus, most processes and workflows involved in applying the SRMS are very similar (and, in some cases, identical) to those of the PRMS, except for their respective terminology.

The intent of this chapter is to highlight and describe the significant differences, where they exist, between the SRMS (2017) and the PRMS (2007) documents. When applying experience with the PRMS to storage categorization, classification, and quantification, there are several notable differences, namely:

- The SRMS names the total resources as TSR, where the PRMS uses Total Petroleum Initially in Place (PIIP).
- The SRMS needs to demonstrate containment as a criterion for discovery status.
- The SRMS lacks project analogs available for estimating storable quantities.

5.2 Basic Principles

5.2.1 Resources. In the PRMS, the term "resources" refers to all quantities of petroleum (recoverable and unrecoverable) naturally occurring within the Earth's crust, discovered or undiscovered, including quantities already produced. In the SRMS, the term "resources" refers to storable quantities (accessible and inaccessible) within discovered or undiscovered geologic formations, including those quantities already stored.

"Total resources" are conceptualized and defined differently by the PRMS and SRMS:

- In the PRMS, they correspond to the Total PIIP.
- In the SRMS, they correspond to the TSR.

TSR in the SRMS are analogous to PIIP in the PRMS, as they both represent the total resources that can be produced or stored depending on economics and technology available.

5.3 Classification and Categorization

5.3.1 Discovery Criteria. The need to demonstrate that a geologic formation is suited for containment of injected CO_2 in the long term is a fundamental distinction between the discovery criteria for CO_2 storage resources and those applied to petroleum resources. In the PRMS, petroleum accumulations constitute a discovery when the existence of a significant quantity of potentially moveable hydrocarbons has been established. (It is implicit that a petroleum accumulation has containment for the accumulation to exist.) To classify Total PIIP as Discovered PIIP, the quantity of petroleum must be within known accumulations.

5.3.2 Unconventional Storage. Presently, there is no universal analogy of conventional or unconventional storage; hence, the SRMS does not use these terms.

5.4 Evaluation and Reporting

5.4.1 Financial Evidence and Economic Criteria. PRMS guidelines require financial appropriations evidence (they do not necessarily require that project financing be confirmed prior to classifying a project's PIIP as Reserves). SRMS does not require project financing be confirmed before classifying as Capacity (SRMS 2017, Section 3.1.2 Economic Criteria). Both the PRMS and SRMS specify that, for projects lacking a reasonable expectation that financing will be confirmed such that development can commence within a reasonable time frame, such projects should be classified as Contingent. Costs associated with future abandonment, decommissioning, restoration, and verification of long-term containment (e.g., monitoring) as may be required are included in the SRMS economic analysis when reclassifying volumes from Contingent to Capacity.

5.4.2 Economic Limit. The PRMS defines the economic limit as the production rate when the maximum cumulative NCF occurs from a project. In the SRMS, the economic limit is defined as the injection rate below which a project's NCF is negative. While these are different definitions, they are similar calculations.

When calculating the economic limit, both the SRMS and PRMS require that operating costs be included in the economic evaluation, excluding ADR costs. ADR costs may still need to be reported for other economic evaluations as appropriate (e.g., property sale/acquisition evaluations and accounting reports of future project costs).

5.4.3 Reference Point. In the PRMS, the Reference Point is typically the point of sale to third parties or the point at which custody is transferred. In the SRMS, the Reference Point location may vary by project type. See Section 3.2.3 Reference Point for further discussion. The Reference Point of a storage project could be located at the point of transfer from a CO_2 source or pipeline operator to the storage project, analogous to the typical PRMS Reference Point. For SRMS, this is highly dependent on using a standalone or integrated project definition. The stored and storable quantities should be quoted in terms of actual wellhead injection quantities.

5.4.4 Sharing Contracts. Due to the relative immaturity of the CO_2 storage industry, there are few examples of storage contracts and leases, and little publicly available contract information regarding active projects. There are no known examples of injection-sharing contracts for existing storage projects. The SRMS presents a discussion of this contract type based on Production Sharing Agreements, an analogous contract type in the oil and gas industry. At this time, it is not possible to predict what types of contracts may be used for storage projects, and the SRMS does not make any suggestions or recommendations as to the types of contracts expected or appropriate.

5.5 Estimating Storable Quantities

The PRMS and SRMS are similar in that methods for estimating recoverable quantities and storable quantities fall into one of three categories: analogs, volumetric methods, and performance-based methods (production performance analysis in the PRMS, and injection performance analysis in the SRMS). However, the SRMS has few available analogs for assessing storage resources or storage efficiency, whereas analogs are widely available for estimating hydrocarbon resources and recovery efficiency.

Volumetric estimation methods outlined in the SRMS account for uncertainties that may affect storable quantities, including factors that affect the mobility and distribution of Stored CO_2, as well as the extent and competence of the containment system. While these factors may be considered for making estimates of hydrocarbons using PRMS, they take on considerably greater importance for estimating storable quantities using SRMS.

6.0 Data Used to Characterize a Geologic Formation for a Storage Project

Jacqi Roueché, Paul Johnson, and Isis Fukai

6.1 Overview

This chapter includes a list of data that may be needed to characterize the suitability of a geologic formation for storage, a brief description of laws and regulations governing CCS data acquisition, and a bibliography of references containing well-established guidelines and best practices for acquiring and analyzing this data. The list of data is not intended to imply that it is a requirement or mandate to use every data type listed in the estimation, classification, or categorization of storable quantities. Furthermore, there is no attempt to define the data types associated with a specific storage resources classification (i.e., Prospective, Contingent, and Capacity).

6.2 Geologic and Technical Data Types

A comprehensive suite of data is needed to *fully* characterize a geologic formation (including the caprock) in terms of geochemistry, geology and hydrogeology, geomechanics, geophysics, fluid properties, fracture characteristics, well characterization, and geothermal properties. **Table 6.1** lists data, sources, and example applications in four key components that are typically addressed during geologic storage characterization: storable quantities, compartmentalization (geologic), injection rate (or injectivity), and containment (caprock and wellbore). These components correspond to the fundamental data types that apply to any assessment. Data sources are through the public domain, vendors or operators, purchase, or may involve acquiring new data. The data sources in Table 6.1 can be used in correlations for estimating properties; however, example correlations are not included. If using correlations, the degree of uncertainty should be considered in estimating storable quantities for a project. Table 6.1 does not include data types for surface site assessment, range of uncertainty, chance of commerciality, or data types established by specific regulatory regimes or legislation.

In the context of the SRMS, these four key components define important aspects of the estimation of storable quantities, and the classification and categorization of the storage resources of a defined project. In all instances, the pore volume defined by a project is directly related to the estimation of storable quantities. Neither injectivity, compartmentalization, nor the caprock are directly related to the estimation of storable quantities; however, they are related to the classification of storable quantities. The injection rate (or injectivity) of a geologic formation is not directly related to the estimation of storable quantities, but is important to the classification of storable quantities, as injection rate directly impacts the economics of a specific project and the ability of the geologic formation to meet the project's target injection rate. Geologic compartmentalization determines the portion of storable quantities that can be assigned to a specific project, specifically in terms of the geologic formations (or portions) that are accessible to the project and those that are inaccessible to the project. The assessment and analysis of containment for the longevity of the storage of CO_2 is a requirement of any subsurface estimate to be considered storable quantities.

In addition to direct and indirect applications to estimates of storable quantities, categorizations, and classifications, these data types are important to permit applications (e.g., area of review) and establishing baselines for CO_2 storage surveillance and monitoring during active injection.

Key Components	Data	Data Sources	Example Applications/Usage
Storable quantity (pore volume)	Geologic formation area (including structure)	Areal maps (structure, isopach), 2D and 3D seismic, vertical seismic profile (VSP), well cores and well logs	Constrain formation geometry, inform geologic models, evaluate storage efficiency, and estimate storable quantities.
	Geologic formation depth	Top depths, well reports, conventional logs (e.g., gamma ray, mud log), VSP, 2D and 3D seismic, well cores	
	Gross/net thickness	Formation top and base depth, conventional well logs (e.g., gamma ray), VSP, 2D, 3D seismic; well core data	
	Porosity	Well logs and cores, outcrop data	
	Pore size distribution	Mercury intrusion capillary pressure (MICP), computed tomography	
	Fluid saturations	Routine core analysis (Dean-Stark), resistivity log, electrical tomography	
	CO_2 solubility	Reservoir pressure and temperature, salinity	
Injection rate (injectivity)	Permeability	Routine core analysis, injection/pump test, nuclear magnetic resonance log, flowmeter log, permeability transforms to porosity	Determine injection rate, inform geologic models and risk analyses, optimize well design/operation, determine storage efficiency, and estimate storable quantities; risk assessment.
	Effective permeability	Specialized core analysis, pressure transient test	
	Fracture pressure gradient	Formation test, (extended) leakoff test, step rate test, sonic log	
	Pressure	Drill stem test (DST), pressure buildup and falloff tests, injection test, modular dynamic tester	
	Temperature	Bottomhole data, temperature log, geothermal gradient, pressure transient analysis	
	CO_2 brine, CO_2 oil relative permeability	Coreflood tests	
	CO_2 density	Equation of state (EOS) from reservoir temperature and pressure data, correlations, tabulated data	
	Well conformance	PNC logs, fiber optics, tracers, production logs	
	Fluid viscosity (CO_2, brine, oil)	PVT fluid analysis, EOS	

Compartmentalization	Subsurface structure/faults	2D and 3D seismic, VSPs, aeromagnetic survey, paleotopography, depositional models	Determine reservoir connectivity, and boundary conditions, inform geologic and risk models, determine operational conditions and well design, determine storage efficiency, and estimate storable quantities.
	Stratigraphic facies	2D and 3D seismic, lithostratigraphy, sequence/chronostratigraphy, depositional models, biomarker analysis, well-log correlation	
	Compartment boundaries	DST, DST to assess lateral connectivity, long term pump/injection test, with pressure transient analysis, geochemical tracer survey; injection-pressure history	
	Porosity and permeability distributions (macro/mesoscale)	Core and log data, static earth models	
	Lithostratigraphic heterogeneity	X-Ray diffraction, thin-sections, petrographic reports, gamma ray and elemental capture spectroscopy logs	
Containment (caprock)	Area	Areal maps (structure, isopach), 2D and 3D seismic, VSP	Assess containment requirement of storable quantities. Evaluate leakage pathways; risk assessment; estimate CO_2-rock/CO_2-fluid interaction; long-term fluid behavior and containment; evaluate and monitor for induced seismicity.
	Depth	Top depths, well reports, conventional logs (e.g., gamma ray, mud log), VSP, 2D and 3D seismic	
	Gross thickness	Formation top and base depth, conventional well logs (e.g., gamma ray), VSP, 2D, 3D seismic	
	Mineralogy/lithology	X-Ray diffraction, thin-sections, petrographic reports, gamma ray and elemental capture spectroscopy logs	
	Porosity	Tight rock analysis, MICP, well logs	
	Permeability	Tight rock analysis	
	Capillary pressure, threshold entry pressure	Specialized core analysis, MICP	
	Caprock Integrity	Lithostratigraphic continuity, subsurface structure, faults, hydrodynamic regime, existing wells/leakage pathways	
	CO_2 pressure front	DST, pressure gauges, dynamic injection simulations	
	Reservoir/caprock in-situ fluid geochemistry	Mass spectrometry	
	Mechanical properties, matrix and fractures	Acoustic borehole image logs, triaxial tests of core, acoustic and dipole sonic logs	
	Fracture gradient	Formation integrity test; step rate test; (extended) leakoff tests	

Containment (wellbore)	Plug positions: lengths and depths	Well records	Assess wellbore containment risk in the project area.
	Plug types: cement or mechanical	Well records	
	Cement tops behind casing	Drilling records	
	Cement placement: centralizers, rotation of string, plug bump	Drilling records	
	Plugging and cementing requirements and practices	Regulatory history, drilling company, operator	
	Age of cement, pipe, and plugs	Well and drilling records	
	Well locations: coordinates and depth	Drilling permits	

Table 6.1—Data to estimate, categorize, and classify CO_2 storable quantities.

6.3 Storage-Related Regulatory and Legislative Policy

Many countries, regions therein, and international coalitions have adopted storage-related regulations and enacted legislation and policy initiatives that directly impact the types of characterization data required for a storage project, and may include, for example, existing resource development, population centers, and environmentally sensitive areas.

Example references describing storage regulations and policies adopted by various organizations are listed below:

- **US Internal Revenue Service (2018),** Bipartisan Budget Act of 2018
- **Gibbs (2016),** *Effective Enforcement of Underground Storage of Carbon Dioxide.*
- **Rydberg and Langlet (2015),** CCS in the Baltic Sea Region—Bastor 2. Work Package 4: Legal and Fiscal Aspects, Elforsk.
- **AECOM (2013),** *Carbon Capture and Storage Regulatory Test Toolkit for Victoria, Australia: Outcomes and Recommendations*
- **US Environmental Protection Agency (2010)**, Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO_2) Geologic Sequestration (GS) Wells; Final Rule
- **Wilson et al. (2008),** Policy Brief: Regulation of Carbon Capture and Storage, International Risk Governance Council
- **International Standards Organization (2017),** *ISO 27914-2017, Carbon Dioxide Capture, Transportation, and Geological Storage*
- **Spanish Geological Survey: CCS Directive, European Union,** Directive 2009/31/EC of the European Parliament and the Council of 23 April 2009, on the Geological Storage of Carbon Dioxide (2012) and Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide: Guidance Document 1, CO_2 Storage Life Cycle Risk Management Framework (2012)

The US-DOE-NETL has released a comprehensive suite of best practice manuals containing experiences, lessons learned, and knowledge gained from numerous research and development projects funded by the US DOE's Carbon Storage Program in the US (US-DOE-NETL 2011). These manuals provide guidelines on data types, tools, and techniques associated with monitoring, verification, and accounting, public and stakeholder outreach, site screening, selection, and characterization, risk management, and operations for storage projects.

7.0 Case Studies and Examples of Storage Resource Classification

Lesley Rantell Seldon, Owain Tucker, and Scott M. Frailey

7.1 Introduction

This chapter demonstrates and discusses the application of the SRMS to classify example storage resources based on project evaluations, most of which have been described in publicly available documents. The storage resource classification and categorization of these evaluations is based on the reported data. Note that the published documents did *not* attempt to use the SRMS, and in some cases the documentation is insufficient to confirm that the required data quality and technical evaluation would warrant the interpreted classification given here as examples. In those cases, the assumptions are named that were necessary to classify and categorize storable quantities from these published evaluations.

The first classification and categorization examples consider several independent CO_2 storage estimates published for the Captain Sandstone (Central North Sea, UK). These examples range in maturity and scale from relatively simple volumetric regional resource estimates for open aquifers to a very detailed evaluation of the depleted Goldeneye field. The next example discusses a set of storage evaluations from northern Australia. An early regional storage assessment (Storage Atlas) highlights storage resources in the Petrel Sub-basin near Darwin. Two evaluations further studied areas of this basin, applying a notional project, which further matured a part of the original storage resource described by the regional study. The final example use of the SRMS is a generalization of the maturation of storage resources in the Illinois Basin.

These storage resource classification and categorization examples demonstrate how the authors of this chapter applied the SRMS to these projects, and the factors that were considered to drive the assignment of an SRMS classification. Due to the subjectivity of storage resource classification, these examples are not unique, and other people may determine different classes and categories. The examples discussed here are not exhaustive. There may be additional and more recent evaluations of the storage resources associated with the basins and formations discussed here. Given that each evaluation is considered and notionally classified on the basis of the data available and assessment described, these additional studies would not change the author's classification of the storable quantities.

7.1.1 Discovery Status. Projects that rely on an extensive regional dipping caprock formation (i.e., outside of a geologic structure) to prevent lateral and vertical migration of CO_2 outside the project area must ensure containment by determining that the regional caprock formation extends over the area that injected CO_2 will migrate before it is immobilized (by dissolution, capillary trapping, and small buoyancy traps). This contrasts with a project targeting storage within a geologic structure, where injected CO_2 will remain in the area of injection (with limited or no lateral migration expected) and the CO_2 migration is limited to the structure.

The examples in this chapter apply the following approach to determine discovery status for the storable quantities associated with storage outside of a structure on regional dip. To discover a storage resource on regional dip (e.g., the Captain-X project), a relatively large area covering the projected area of Stored CO_2 must meet the discovery criteria. As with all storable quantities, evidence for geologic containment is provided by a combination of well data (log and core; direct evidence of presence and properties) and seismic data (continuity) as described in Chapter 4 Estimating Storable Quantities. Each well that meets the discovery criteria for storable quantities can effectively "discover" the geologic formation and caprock. To demonstrate that the caprock is "suited to containment" of the evaluated storable quantities, the primary focus is on the continuity and "discovered area" of the caprock.

The SRMS does not prescribe an appropriate well sampling density (or discovery area per well) to prove the presence of storable quantities. The well sampling density required (or discovery radius) will be unique to each project based on the geological interpretation of the caprock and data available. The assumptions for the discovery radius should be documented in sufficient detail to clearly understand the basis for use of the Discovered status. To build confidence in caprock continuity and define the discovered area, understanding of the broader stratigraphy (original areal extent and lateral variation of both thickness and caprock properties), and structural history of the region (which may also influence caprock continuity, e.g., by faulting, uplift, and erosion) must be understood. Useful input data might include well correlations (including wells beyond the project area), biostratigraphy, quality seismic, seismic stratigraphy, interpreted depositional environment and paleogeography, and analogs. Some factors, such as a thicker caprock formation, marine deposition, or excellent seismic data quality, could increase the discovered radius of each well. Note that the discovered area associated with each well might not be circular and might also vary areally within a large basin as the caprock properties and degree of structuration vary. The evaluator cannot assume that the stratigraphy (including caprock thickness and properties) observed on one side of a significant fault will also be found across the fault, which could have significantly different deposition originally or later erosion.

The area that meets the locally defined required sampling density could be classed as Discovered (provided all other criteria are met); the resource area that does not meet the required sampling density would remain Undiscovered, and any associated storable quantities classed as Prospective Storage Resources. Further to demonstrating suitable caprock properties and continuity across the injected CO_2, a Discovered Storage Resource would require a demonstration of the containment of all faults (under predicted pressure changes) that will be encountered by the injected CO_2.

7.2 Storage Resource Classification Example: Captain Sandstone, UK North Sea

7.2.1 Overview of Geology. The Captain Sandstone is in the Outer Moray Firth region of the UK Central North Sea. The region is dominated by the Halibut Horst, an area that remained emergent throughout most of the Jurassic and Lower Cretaceous periods. The shelf edge depositional setting of the Lower Cretaceous resulted in the ribbon-like deposition of the Captain Sandstone along the southern margins of the Halibut Horst and South Halibut Shelf, continuing east along the southern margins of the Renee Ridge and through the Glenn fault **(Fig. 7.1).** The formation covers a total area of approximately 6000 km^2.

Erosion of the Halibut Horst and associated turbidite deposition occurred throughout the Jurassic and Lower Cretaceous in the Outer Moray Firth **(Fig. 7.2),** leading to the periodic deposition of sand-rich turbidite facies with a background deposition of hemipelagic shales, marls, and occasional limestones. The proposed permeable geologic formation, the Captain Sandstone, formed predominately by high reservoir-quality turbidite facies with a sand-rich gross thickness of approximately 100 m or greater.

Primary geologic containment is the shales and marls of the overlying Herring Formation (specifically the Plenus Marl and the Hidra Formation). The Lista mudstone (secondary caprock) is a proven caprock to hydrocarbons elsewhere in the Outer Moray Firth Basin.

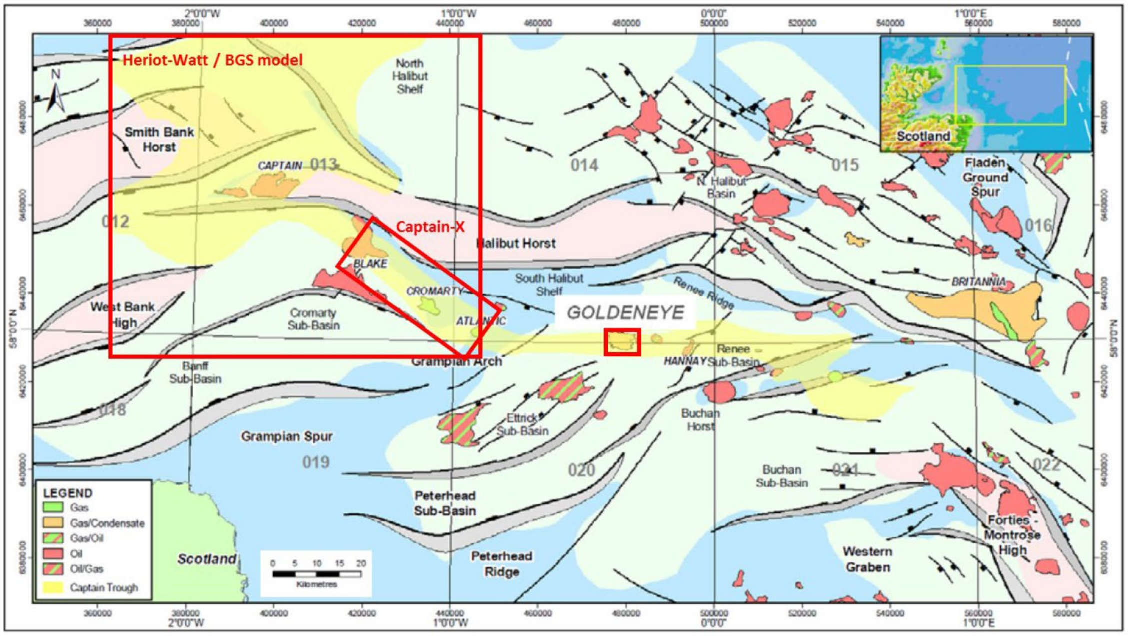


Fig. 7.1—Map reproduced from Shell U.K. Limited (2015). Captain Sandstone is indicated by the yellow shading. Approximate formation areas covered by storage resource estimates indicated by the red outline boxes.

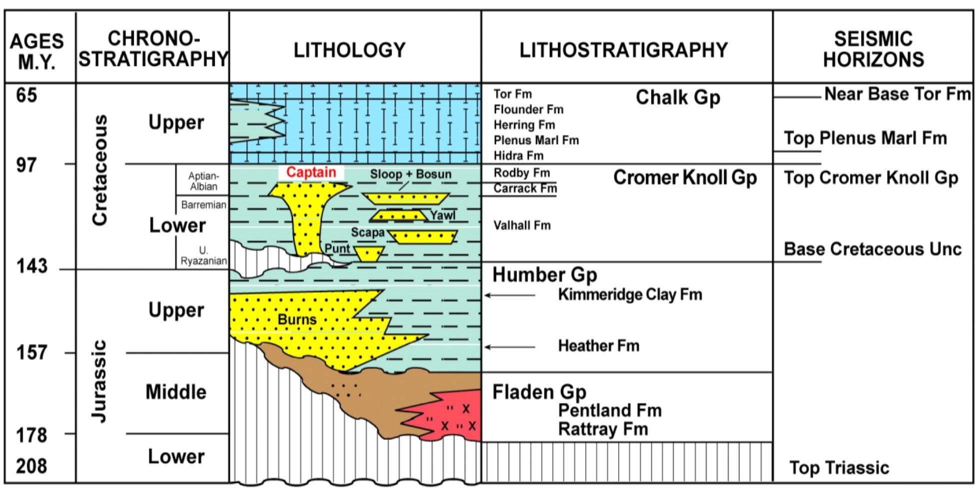


Fig. 7.2—Jurassic and Cretaceous stratigraphy of the Outer Moray Firth (Shell U.K. Limited 2015).

7.2.2 CO_2 Storage Resource Evaluations. The Captain Sandstone has been subject to several CO_2 storage resource assessments (Fig. 7.1 and **Table 7.1)** that fall into three broad categories:

- Post-hydrocarbon production storage assessment for hydrocarbon fields:
    1. "CO_2 Stored" database: Storable quantities estimated using a voidage replacement evaluation (Grammer et al. 2011)
    2. Peterhead CCS project: A full static and dynamic modelling evaluation of the Goldeneye field (Shell U.K. Limited 2014, 2015)
- Site-specific brine aquifer storage assessments:
    1. Dynamic modelling of a regional dip, brine aquifer storage project called Captain-X (Pale Blue Dot Energy and Axis Well Technology 2016b)

- Regional assessment (basin-scale) CO_2 storage assessments for the Captain Sandstone aquifer (regional dip):
  1. "CO_2 Stored" estimate for whole Captain Sandstone aquifer storage (static volumetric evaluation; Grammer et al. 2011)
  2. Heriot-Watt/British Geological Survey dynamic simulation study incorporating the bulk of the brine filled aquifer formation (Jin et al. 2012)

(Note: "CO_2 Stored" is a name of the UK CO_2 storage database and organisation responsible for the publications used for this SRMS example. This name is not associated with the SRMS classification Stored.)

The storable quantities associated with and identified by the published evaluations of the Captain Sandstone (Table 7.1) cannot be simply aggregated. Several evaluations represent the same pore volume. A unified view of TSR for the Captain Sandstone would require further assessment of the interaction (pressure and CO_2 plume) of storage activities at the various sites (Goldeneye field, Captain-X project area, and entire basin) to exclude double counting of storable quantities across the maturity classes.

Storage Assessment	Storage Type	Methodology	Storable Quantities (Mtonne)	SRMS Resource Class–Subclass
Peterhead CCS project (Goldeneye field)	Hydrocarbon reservoir	Static and dynamic modelling of detailed storage development project	29-34-38	Contingent Storage Resources–On Hold/Unclarified
CO_2 Stored (UK storage database)	Hydrocarbon reservoir	Volumetric voidage replacement estimate	34-37-40	TSR
Captain-X project	Brine aquifer	Static and dynamic modelling of detailed storage development project	60	Contingent Storage Resources–Unclarified
CO_2 Stored assessment (UK storage database)	Regional assessment	Volumetric estimate using a storage efficiency factor*	76-153-203	Prospective Storage Resources–Play
BGS/Heriot-Watt project	Regional assessment	Basin-wide dynamic modelling of open or closed boundary aquifer storage injection	358-2496	Prospective Storage Resources–Lead

*A storage efficiency was applied directly to the net pore volume to estimate storable quantities because the storage efficiency is physically attainable (considers both pressure and migration constraints and associated with a project, e.g., injection only or brine extraction).

Table 7.1—Summary of Captain Sandstone storage resource assessments. The range of storable quantities is quoted directly from the available documentation, which may not specifically identify these quantities as P90, P50, or P10.

7.2.3 Storage Resources Associated with Known Captain Sandstone Hydrocarbon Fields. There are several known hydrocarbon accumulations in the UK Central North Sea Captain Sandstone. These include the Goldeneye gas-condensate field [subject to an extensive CO_2 storage assessment for the Peterhead CCS project (Shell U.K. Limited 2014)] and the Atlantic and Cromarty gas fields within the Captain fairway, as well as the Blake and Captain oil fields (Fig. 7.1).

In principle, these hydrocarbon fields could have Discovered Storage Resources **(Table 7.2).** The geologic containment of buoyant hydrocarbons provides evidence to demonstrate the potential for geologic containment of Stored CO_2, although further assessment of containment risks associated with the project would be required to mature the Contingent Storage Resources to Capacity for development. Hence, storable quantities estimated by both the "CO_2 Stored" database and Peterhead CCS project assessed could be classified as a Contingent Storage Resources (i.e., Discovered, Subcommercial), rather than Prospective Storage Resources (i.e., Undiscovered).

<table>
<tr><th>Discovery Criteria</th><th>Supporting Data</th><th>CO_2 Stored Database*</th><th>Peterhead-Goldeneye</th></tr>
<tr><td>Direct and convincing evidence of permeable formation and geologic containment</td><td>Log, seismic and core data from the field</td><td colspan="2">Original field discovery, appraisal, and production data sufficient to demonstrate geologic formation and caprock suitability</td></tr>
<tr><td>Flow test to support expectation of commercial CO_2 injection rates</td><td>Field production data</td><td colspan="2">Field production data used to demonstrate and calibrate injectivity</td></tr>
<tr><td>Expectation that geologic containment will be maintained long term (CO_2 will not migrate laterally or vertically out of the geologic formation)</td><td>Vertical geologic containment: hydrocarbons held long term by the caprock
Lateral geologic containment: hydrocarbon field closure</td><td>Presence of hydrocarbons demonstrates the potential for CO_2 geologic containment. The storage resource should not exceed the field voidage without further assessing caprock competence and closure volume</td><td>Extensive dynamic assessment supports an expectation that injection of the storage resource defined by the project will not increase geologic formation pressure to the initial value, or result in migration beyond the mapped structure</td></tr>
<tr><td colspan="2">Outcome</td><td>Discovered</td><td>Discovered</td></tr>
<tr><td colspan="4">*"CO_2 Stored" is the name of the UK national storage database and should not be related to or confused with the SRMS classification Stored.</td></tr>
</table>

Table 7.2—Discovery criteria review for CO_2 storage in depleted Captain Sandstone hydrocarbon fields.

None of the historic oil and gas fields that produced from the Captain Sandstone have a CO_2 storage permit or management commitment to develop the project. Hence, the storable quantities for these fields cannot be classified as Capacity, and any associated storable quantities would be restricted to the Contingent Storage Resources classification.

An assignment to a Contingent Storage Resources subclass is determined by whether the project has been shown to be technically viable, economically viable and whether the project is under active maturation.

The CO_2 Stored database depleted field resource evaluations use a voidage replacement methodology: $M_{CO_2} = \rho_{CO_2}\left(HC_p + W_p - W_{inj}\right)$ (Section 4.2 Containment Assessment). The CO_2 Stored database documentation indicates that a 100% voidage replacement has been assumed. In this case, the reported storable quantities would represent TSR.

The Goldeneye field evaluation for the Peterhead CCS project is more mature (both technically and commercially) than the CO_2 Stored database assessments. However, the project was halted before the final investment commitment. The Peterhead-Goldeneye CCS project was technically and commercially viable. The storable quantities associated with the storage project (20 Mtonne) would have progressed to Capacity had project investment been approved. However, upon cessation of the project (with no expectation of continued progress toward development in the near term), the storable quantities would initially be classified as Contingent Storage Resources–On-Hold while the project description and evaluation are current (project could still go ahead as originally planned, evaluation of storable quantities is valid). Later changes to the storage site (e.g., decommissioning of wells or facilities flagged for reuse in the project) mean that the project could not go ahead as described. The project description and evaluation of storable quantities require an update. Because of the maturation status of the project, the resource classification is Contingent Storage Resources–Unclarified. The resource classification for any project resource "on hold" should be updated and reviewed regularly to confirm that the technical and commercial assessment underpinning the storable quantities and classification are valid at the time of assessment. If the project is unlikely to be developed in the near term, then the project should be Contingent Storage Resources–Unclarified.

The best estimate (e.g., 2C) of storable quantities reported for the Peterhead CCS project using the Goldeneye structure was 34 Mtonne, with low and high cases (1C and 3C) of 29 Mtonne and 38 Mtonne, respectively (Shell U.K. Limited 2014).

The TSR associated with the Peterhead-Goldeneye project is represented by the 100% voidage replacement quantity for the produced gas (47 Mtonne). For an estimate of the TSR, the residual CO_2 saturation in the aquifer below the spill point and dissolution potential in all the water volume within the storage project area should also be included.

7.2.4 Captain-X Project: A Development-Scale Site-Specific Open Brine Aquifer. The Pale Blue Dot Energy storage assessment (Pale Blue Dot Energy and Axis Well Technology 2016b) included a project injecting CO_2 for storage in a specified area of the Captain Sandstone brine aquifer northwest of the Atlantic field (Fig. 7.1). This assessment defined a notional storage project (well numbers, locations, and injection rates).

The CO_2 footprint resulting from the Captain-X project is predicted using a dynamic simulation of the defined project (well location, rate, and pressure) and static model of the geologic formation (Pale Blue Dot Energy and Axis Well Technology 2016b). The predicted CO_2 plume **(Fig. 7.3)** remains within the discovered area (with a 5-km radius). Given the availability of regional core and well log data, and evidence provided by the fault behavior observed in Captain Sandstone hydrocarbon accumulations, this example assumes that the caprock competence over the plume could be demonstrated. Hence, the storable quantities associated with the Captain-X project (60 Mtonne) would be classified as a Contingent Storage Resource because it met the criteria of discovery. The case of claiming "discovery" of the storable quantities associated with the Captain-X project is summarized in **Table 7.3.**

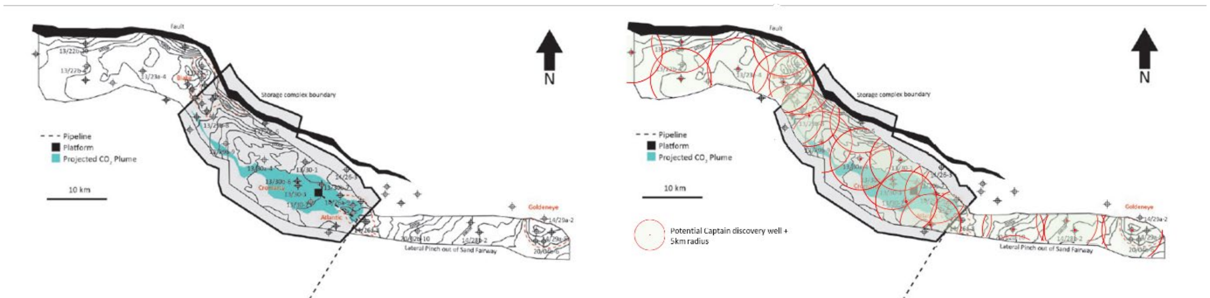


Fig. 7.3—(a) Map of base case dynamic model; Stored CO_2 footprint 100 years post injection, reproduced from the Pale Blue Dot Energy summary report. (b) Plume map annotated with 5-km discovery radius at each well penetration. (Courtesy of Pale Blue Dot Energy and Axis Well Technology 2016b and the UK Energy Technologies Institute).

The Captain-X project was a notional project, albeit with a detailed project description. Hence, the associated storable quantities could not qualify for the Contingent Storage Resources–Development Pending subclassification. It is proposed that the resource should be classified as Contingent Storage Resources–Development Unclarified. For this example, the Unclarified subclass indicates that the project must be (re)evaluated to assess technical and economic viability prior to maturation for development.

The Pale Blue Dot Energy notional project was projected to store 60 Mtonne. An expectation that this quantity might be contained in the "most likely" or base case has been demonstrated, hence the 2C category is 60 Mtonne. The documentation includes some discussion of a storable quantities range linked to the project, which might have provided the storable quantities for the categories 1C, 2C, and 3C. However, the static calculation applied cannot demonstrate containment for the range of storable quantities described because there is no evaluation of the resulting CO_2 migration area associated with this range.

Discovery Criteria	Supporting Data	Captain-X Project
Direct and convincing evidence of permeable formation and geologic containment	Log data; multiple wells 3D seismic data Core data from "analog" sites (Goldeneye and Atlantic fields)	Data from wells (and analog core) indicates suitable geologic formation and caprock properties across expected CO_2 plume. Seismic data supports caprock continuity across expected CO_2 footprint and fault juxtaposition data for leak assessment. Suitability of analogs and quality of well data requires confirmation.
Flow test to support expectation of commercial CO_2 injection rates	Analog flow test (field production data)	Suitability of analog requires confirmation.
Expectation that geologic containment will be maintained long term (CO_2 will not migrate laterally or vertically out of the geologic formation)	Vertical geologic containment: dynamic model, caprock fracture pressure data Lateral geologic containment: dynamic model, well and seismic data	Expected CO_2 plume provided by dynamic modelling (multiple realizations). Pressure impact of CO_2 injection assessed (dynamic model) over the CO_2 plume; caprock fracture pressure is not exceeded (vertical geologic containment). No faults identified with expectation of leakage. Sufficient well data to confirm geologic containment potential across entire area of expected footprint (lateral containment)*.
Outcome		Discovered

*Discovery radius applied was defined for this SRMS example. No geological understanding or assessment of caprock thickness and quality variation was applied for this example.

Table 7.3—Captain-X project CO_2 storage resource discovery criteria.

7.2.5 Captain Sandstone Basin-scale Regional Aquifer Assessments.

Both the CO_2 Stored (Grammer et al. 2011) and the Heriot-Watt (Jin et al. 2012) Captain Sandstone storage CO_2 assessments incorporate the bulk of the Captain Sandstone in its entirety (i.e., these are regional, basin-scale storage assessments). The notional projects associated with both evaluations target only the brine aquifer on regional dip of the Captain sandstone (oil and gas fields were excluded). For this SRMS example, demonstration of containment was assumed.

The CO_2 Stored database assessment's storage resource estimate (Bentham et al. 2014) was estimated from a simple volumetric calculation (Section 4.2 Containment Assessment). The assessment does not include defined injection locations, geologic traps, or a prediction of the expected CO_2 plume. The notional project defined for this example is represented by the value of storage efficiency, which assumes injection wells drilled on a pattern across the entire formation area with a maximum injection pressure restricted to below caprock fracture pressure.

The analog storage efficiency applied to the Captain Sandstone evaluation implies containment of lateral migration within the pattern area; however, the development patterns cover the whole geologic formation area, hence the injected and migrated CO_2 will be located across the whole formation area. The existing wells **(Fig. 7.4a)** do not have sufficient well density to provide direct evidence of the project's containment and storage to justify discovery of the *entire* regional caprock overlying the Captain Sandstone, so the CO_2 Stored database assessment's regional storable quantities are classified as Undiscovered Prospective Resources. The assessment of discovery criteria for the CO_2 Stored database Captain Sandstone evaluation is summarized in **Table 7.4.**

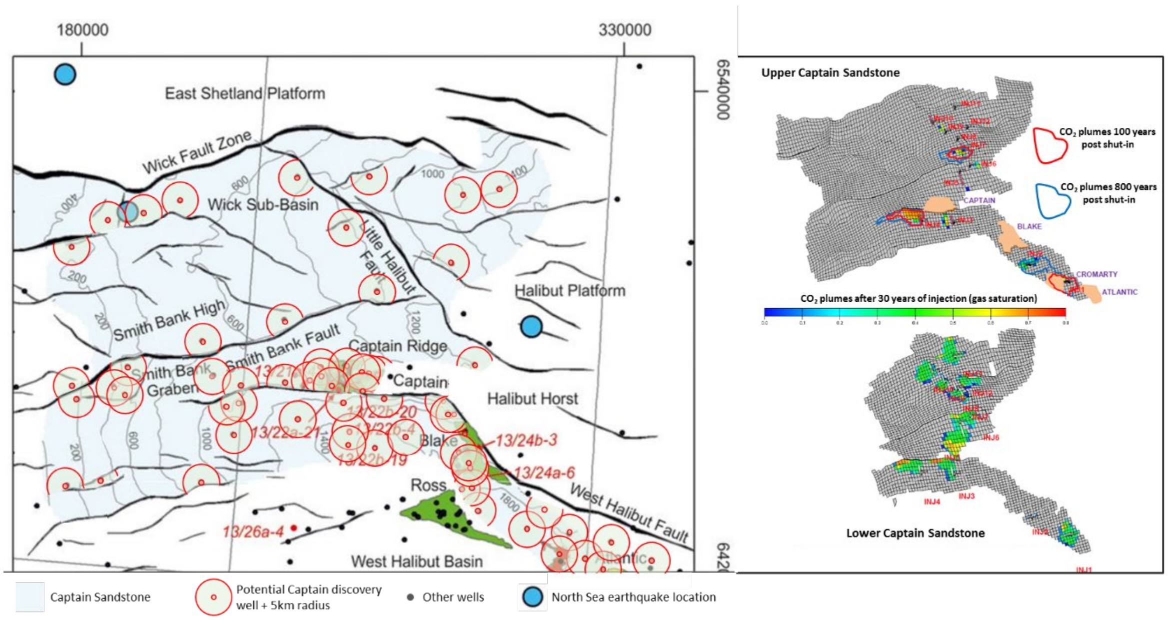


Fig. 7.4—(a) Map of the Captain Sandstone annotated with 5-km discovery radii (after Williams et al. 2016). (b) Simulated CO_2 footprint (blue outline) (Jin et al. 2012).

Discovery Criteria	Supporting Data	CO_2 Stored	BGS/Heriot-Watt
Direct and convincing evidence of permeable formation and geologic containment	Log data; multiple wells Seismic data; 60% coverage Core data from fields	Large areas of the regional Captain Sandstone unpenetrated. Quality of well data and suitability of core data analogs unconfirmed.	
Flow test to support expectation of commercial CO_2 injection rates	Captain reservoir fields oil and gas production data (analog)	Field production data (various Captain reservoir fields) used to demonstrate and calibrate injectivity potential as an analog. Suitability of analog to be confirmed.	
Expectation that geologic containment will be maintained long term (CO_2 will not migrate laterally or vertically out of the project area)	Vertical containment: fracture pressure data, core and log data. Hydrocarbons. Lateral containment: dynamic migration prediction	Pattern development consistent with notional project has CO_2 migration areas across the whole formation. Insufficient data to discover entire caprock area at defined radius.*	Expected plume migration area estimated by notional project modelled dynamically. Insufficient well data to discover caprock over footprint at defined radius.*
Outcome		Undiscovered	Undiscovered

*Discovery radius applied was defined for demonstration purposes. No geological understanding or assessment of caprock thickness and quality variation was applied for this example.

Table 7.4—CO_2 Stored and BGS/Heriot-Watt regional Captain Sandstone storage resource discovery criteria.

The CO_2 Stored database assessment's storable quantities are based on geologic formation averages (e.g., porosity, thickness) and provide a statistical assessment of the entire formation with no indication of potential injection sites within the basin. Hence, this resource would be subclassified as a Prospective Storage Resources–Play.

The CO_2 Stored assessment had a range of storable quantities for the Captain Sandstone by combining individual parameter uncertainties in the volumetric calculation (e.g., porosity and storage efficiency). These are reported directly as P90, P50, and P10 cases (76, 153, and 230 Mtonne respectively), which are Prospective Storage Resources categories 1U, 2U, and 3U.

The BGS/Heriot-Watt Captain Sandstone assessment's storage resource assessment uses dynamic simulation (Jin et al. 2012). The bulk of the Captain Sandstone formation is incorporated in the modelled area (Fig. 7.4b). The notional project represented has 12 injection wells located in the eastern part of the main formation area, injecting constrained by maximum injection pressure, and a project life of 100 years. A scenario with 10 brine extraction wells located in the western part of the formation to relieve formation pressure (managed voidage development concept) was also tested. This represents a different project to the injection only case, and the resulting storable quantities classification of the two should not be combined.

The modelling provides a prediction of the CO_2 plume; however, the well (and seismic) coverage is insufficient to provide direct evidence for the presence and suitable properties of the caprock over the CO_2 plume given a 5-km discovery radius (applied for illustrative purposes). Specifically, modelled injection sites with predicted CO_2 plume within the Wick Sub-basin, or close to the Little Halibut fault, have insufficient well data to provide direct evidence for geologic formation and caprock presence and local properties (Fig. 7.4). The storable quantities associated with some of the southern injection locations are predicted to remain within the local discovered area and would qualify as Contingent Storage Resources. The documentation does not provide storable quantities by injection location; therefore, it was not possible to split the resource into subprojects with different classifications. For this example, the entire evaluated storage resource associated with the modelled multisite project is categorized as Undiscovered Prospective Resources. The assessment of discovery criteria for the BGS/Heriot-Watt Captain Sandstone assessment evaluation is summarized in Table 7.4.

For the notional project that has specified potential injection locations and has assessed the time-dependent factors controlling containment risk (CO_2 migration and pressure response), it is appropriate to assign these storable quantities to Prospective Resources–Lead.

7.3 Maturing a Play to Justify Drilling an Appraisal Exploration Well: Petrel Sub-Basin, Australia

This example focuses on the Bonaparte Basin, which is predominately located offshore, west of Darwin (straddling the border between Australian states: Northern Territories and Western Australia). The Northern Territory of Australia has a concentration of CO_2 sources in Darwin, mainly from liquefied natural gas facilities that process the hydrocarbon gas from fields in the Darwin region. Consequently, the Government of Australia has funded storage resource exploration projects. This example illustrates the use of a notional project to mature a basin or regional assessment through the Prospective Resource maturation subclasses. The example shows the progression of two notional projects to store CO_2 from industrial sources at Darwin in the Cretaceous Sandpiper or Jurassic Plover formation. The classification of the associated storage resource with each maturation activity and notional project is discussed.

The various project stages discussed, and the classification and quantity of associated storable quantities assessed, are summarized in **Table 7.5.**

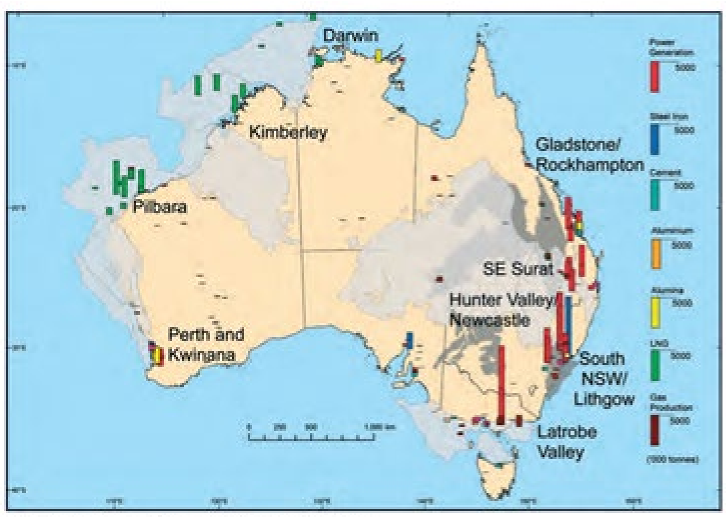
7.3.1 Initial Basin Identification. In 2009, the Australian Carbon Storage Taskforce identified clusters of CO_2 emission sites around the country (**Fig. 7.5;** Carbon Storage Taskforce 2009). This was a national storage resource assessment activity and not focused singularly on a Darwin project. Concentrations of industrial emission sources and sedimentary basin were highlighted in a number of locations including Darwin and the Petrel Sub-basin (Fig. 7.5).

Initially, the Carbon Storage Taskforce project reviewed the sedimentary basins across the continent to determine the best regions for CO_2 storage. They used two processes: (1) to score the basins based on a range of qualitative macrocriteria related to location, geology, size, and available data and (2) to quantitatively determine the storable quantities within each basin (Carbon Storage

Taskforce 2009). The storable quantities were calculated using a volumetric method by combining distributions of the geologic formation's area, thickness, porosity, density of CO_2, and storage efficiency using Monte Carlo sampling to derive a probabilistic estimate of the range of each basin's storable quantities. Storage efficiency realizations of 1% and 4% were assumed using the US DOE Storage Atlas (Frailey 2008) evaluation as an analog.

Storage Assessment	Storage Type	Methodology	Storable Quantities	SRMS Resource Class/Subclass
Australian Carbon Storage Taskforce (2009)	Regional assessment	Volumetric estimate using a storage efficiency factor	32-55-88 Gtonne	Prospective Storge Resources - Play
Geoscience Australia (Consoli et al. 2013): Cretaceous units	Regional assessment	Volumetric estimate using S_{gr} and accessible vertical thickness	6-9-13 Gtonne	Prospective Storge Resources–Play
Geoscience Australia (Consoli et al. 2013): Jurassic units	Regional assessment	Volumetric estimate using S_{gr} and accessible vertical thickness	5-6-9 Gtonne	Prospective Storge Resources–Play
Geoscience Australia (Consoli et al. 2013): Jurassic units	Open aquifer	Static and dynamic modelling of notional storage development project	420 Mtonne	Prospective Storge Resources–Lead
2016-17 Shell study (Seldon et al. 2017): Jurassic units	Open aquifer	Static and dynamic modelling of notional storage development project	150 Mtonne	Prospective Storge Resources–Lead

Table 7.5—Summary of Petrel Sub-basin storage resource assessments. The range of storable quantities is quoted directly from the available documentation, which may not specifically identify these quantities as P90, P50, or P10.



(Note: grey shaded areas indicate limits of sedimentary basins)

Fig. 7.5—Geographical distribution of emissions by industry estimated for 2020 (Carbon Storage Taskforce 2009).

Use of an analog implies that an analogous target geologic formation and/or development project exists. However, the available documentation for the analog project (US DOE Storage Atlas) does not clearly define the development assumptions including the development concept (e.g., injection only or managed voidage). The definition of a more detailed notional project underpinning the assessment is inferred (although not explicitly described) in the economic analysis discussed in the regional assessment report (Carbon Storage Taskforce 2009). A storage cost per tonne of CO_2 avoided was calculated using the NPV of cash flows and avoided emissions over a 25-year project life. Three cost categories per basin were evaluated (shallow, mid, and deep reservoir target) with notional well numbers assessed from injectivity (permeability, initial reservoir and caprock fracture pressure) and well cost estimated from target depth and location (onshore/offshore) using oil and gas industry analogs.

The Bonaparte Basin has large storable quantities associated with basin-scale geologic formations, which do not have sufficient data density to classify as Discovered. In addition, the Jurassic formations within the Petrel Sub-basin (of the Bonaparte Basin) are not hydrocarbon bearing and have no flow test data to demonstrate injectivity, a discovery criterion, although a suitable analog might be sought within the basin or greater area. Hence, the storable quantities for this basin are considered undiscovered and classified a Prospective Storage Resources. Because the project is very immature and has no specific site defined, the subclassification is Play. For the Northern Territory Bonaparte Basin, the P90, P50, P10 values of 32.2, 55.3, and 88.0 Gtonne were categorized as 1U, 2U, and 3U (i.e., low, best, and high), respectively.

7.3.2 Identification of Potential Injection Site(s). Further study by Shell and Geoscience Australia (Consoli et al. 2013) independently identified that the Petrel Sub-basin was an attractive storage resource based on the criteria of geologic formation depth, presence of reservoir properties suited to injection and caprock properties suited to containment, and lack of competing subsurface interests. Geoscience Australia collected additional seismic and seabed data; however, no additional wells were drilled, or flow tests performed, to facilitate project maturation to Discovered Storage Resources. This study narrowed the search for Discovered Storage Resources, focusing on specific areas of the Petrel Sub-basin. A notional storage project targeting a specific site within the basin was modelled by dynamic simulation. The notional project included nine injection wells drilled in a regular pattern (3-km spacing; **Fig. 7.6**), collectively injecting 14 Mtonne/year over 30 years (420 Mtonne total) into the Plover Formation based on the predicted 2020 CO_2 emissions from the Darwin industrial sources. Injection is limited to a maximum bottomhole pressure of 90% of the estimated caprock fracture pressure. Managed voidage (brine production) was not applied. This is a clearer example of a notional project for the assessment of storable resources than the basin-wide estimate of storable quantities, where no such details regarding the assumed development project are documented.

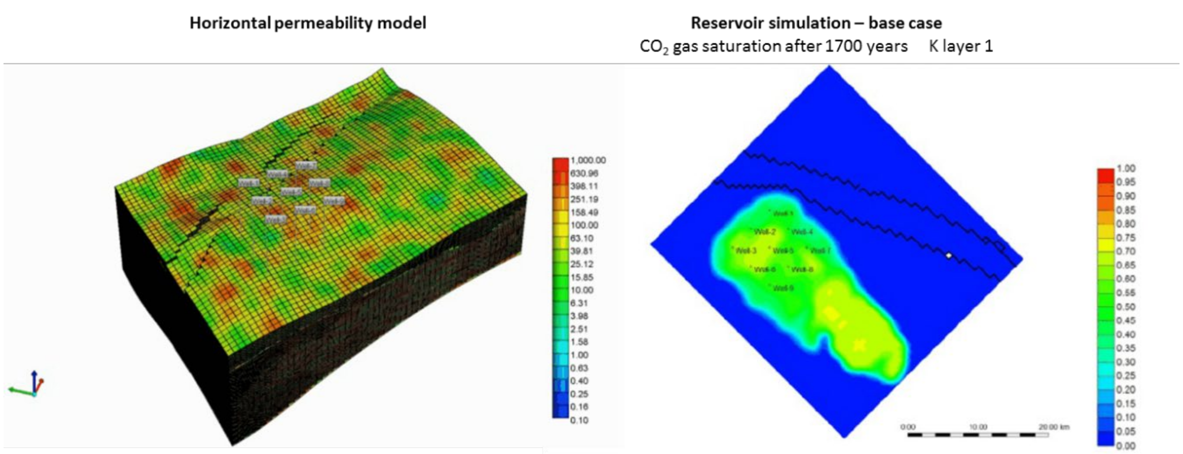


Fig. 7.6—Geoscience Australia's study of Jurassic units "lead" sector model. Left: static horizontal permeability model. Right: dynamic plume migration model at 1,700 years post-injection startup (Consoli et al. 2013).

The Geoscience Australia team (Consoli et al. 2013) made a refined basin-scale estimate of storable quantities using a volumetric calculation with Monte Carlo sampling analysis for each geologic formation grouping (e.g., Jurassic units; lower frigate upper shoreface, Elang-Plover upper shoreface, and Elang-Plover coastal facies) to determine the combined probabilistic storable quantities. This refinement combined the mapped seismic area (excluding areas where the base of the caprock formation was shallower than 800 m subsea), with the predicted plume thickness (indicated by dynamic modelling), average porosity distribution from well data, residual CO_2 saturation from a correlation (tied to porosity), and a CO_2 density range representing the deepest and shallowest reservoir within the assessment unit. A storage efficiency factor was not incorporated into the volumetric calculation directly. Applying the simulated plume thickness and trapped CO_2 saturation to the entire basin area assumes that the simulated development might be repeated as a pattern over the basin area. The fraction of the pore volume accessible for storage is represented by the combination of the residual CO_2 saturation and average plume thickness ranges. This basin-scale estimate of storable quantities would still be classified as Prospective Storage Resources–Play despite the additional technical work. The storable quantities for the Cretaceous and Jurassic units of the Northern Territory Petrel Sub-basin (Bonaparte Basin) were 12.3, 15.9, and 20.0 Gtonne for 1U, 2U, and 3U, respectively (Consoli et al. 2013).

Some areas of the basin were identified as more favorable for storage based on mapped reservoir and caprock property variation as indicated by available well data. The area of the geologic model represents a part of the basin that has satisfied the initial site selection criteria (expectation of suitable reservoir properties for sustained injection, caprock properties suited for containment) and could be viewed as a more advanced site-specific resource assessment associated with the notional project simulated (nine injection wells in a pattern). The notional project for this specific site, and associated storable quantities of 420 Mtonne, have demonstrated an expectation of long-term containment:

- The Stored CO_2 migration rate indicated that the CO_2 would not reach the lateral limit of the caprock formation within thousands of years.
- Formation pressures did not exceed 90% of estimated caprock fracture pressure.
- The prediction of induced pressure difference across the faults was insufficient to meet the estimated value required for fault reactivation (associated with potential loss of containment).

This could satisfy part of the discovery criteria (expectation of long-term containment), but the geologic formations' properties (and injectivity) as modelled require confirmation from a local well to qualify for discovery.

The Geoscience Australia (Consoli et al. 2013) documentation indicates that an economic evaluation was not performed as part of the study. Economic assessment is desirable to justify investment for project maturation and to exclude storable quantities that are considered prohibitively expensive to develop (now and in the foreseeable future) and hence have negligible chance of development. The chance of development/maturation (Section 2.1.4 Project Status and Maturation) cannot be evaluated without a view to the economic attractiveness of a project, which is recommended to estimate risked storable quantities. Geoscience Australia did not progress the project further to assess economic viability.

These storable quantities are associated with a specific area of the basin (some geographical narrowing of the original basin-wide estimate) and linked to notional injection well locations. Hence, the modelled storable quantities might be classified as Prospective Storage Resources–Lead.

The simulation study included the impact of some geologic and dynamic uncertainties on CO_2 migration and time to immobilize Stored CO_2 (through solubility or residual gas trapping), but these results were not reported as an uncertainty range that might be mapped to the storage resource categories 1U/2U/3U. Consequently, only a 2U (best case) estimate of 420 Mtonne can be assigned to the Lead subclass represented by the Jurassic-age geologic formation and caprock from this model. The dynamic modelling study was not designed to assess the total range of storable quantities associated with deploying the notional development described at the proposed site (under containment constraints resulting from migration and pressure increase).

7.3.3 Identification of Alternate Potential Injection Site(s). In 2016, Shell reassessed the Petrel Sub-basin's Jurassic formations for a notional development to store 3 Mtonne/year over 50 years (total 150 Mtonne) using two wells. The Prospective Storage Resources–Lead (notional project site) investigated by Geoscience Australia was not favored because of the proximity to mapped faults. However, the Geoscience Australia notional project evaluation provided an expectation that the more modest Shell project injection rates could be achieved at an analogous site with fewer faults. The Shell team reviewed available well and seismic data to redefine an area of interest **(Fig. 7.7)** based on the expected presence of suitable containment and sustained injectivity, reservoir depth to inject dense CO_2, and absence of potential leak features (e.g., faults or risky wellbores).

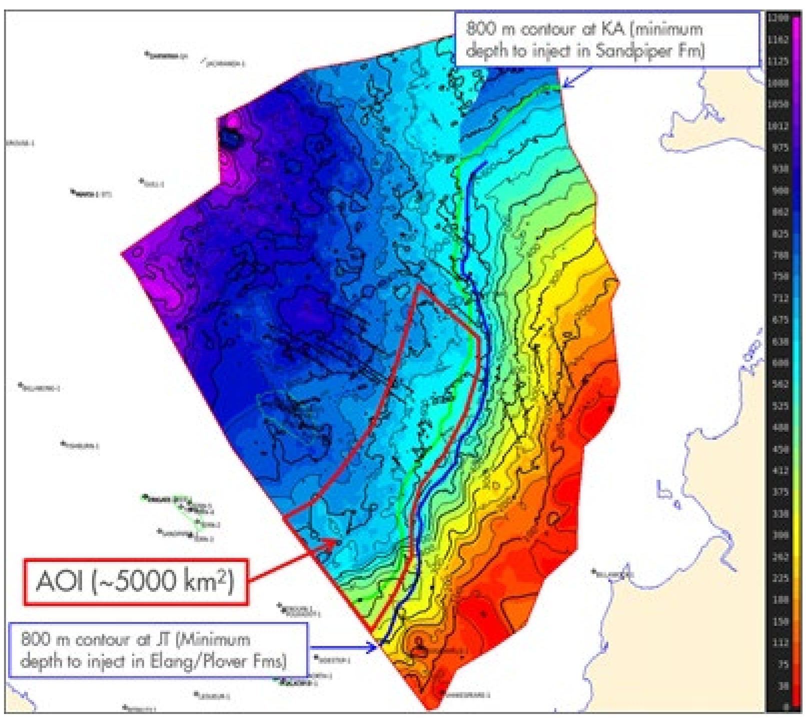


Fig. 7.7—Shell area of Interest. Isopach map of the Wangarlu Formation, contour interval 50 m (Frailey et al. 2018).

To select and mature a prospect for future exploration activities, five notional injection project sites were assessed using dynamic simulations. A notional project using two vertical injection wells (injecting at a maximum bottomhole pressure of 90% of the estimated caprock fracture pressure) was simulated at each site. The notional project was costed to demonstrate economic viability given the identified CO_2 source (notional integrated project with contaminated gas production).

At four of the five sites, the simulated CO_2 plume remained below the seismically mapped caprock formation and did not reach any identified potential leak feature (mapped fault or risky well). At the remaining site, the CO_2 plume migrated more rapidly toward the edge of the mapped caprock formation, reducing confidence in long-term containment, although an improved understanding of the local topography and reservoir properties (through exploration and appraisal activities) may show this site to be suitable in future.

A site was selected based on the simulation assessment. Acquisition of local 3D seismic data over this site was recommended to target an exploration well; therefore, the storable quantities were classified as Prospective Storage Resources–Lead until such time that the seismic data is acquired, and drill set is chosen to mature the project to Prospective Storage Resources–Play.

Although some testing of uncertainties was incorporated into the dynamic modelling, it was not sufficient to define a credible low/best/high case for storable quantities. Hence, only the best estimate (2U) of storable quantities is defined.

Future activities to mature the storable quantities to a discovered Contingent Storage Resource would require an exploration well and flow test, which would establish that the local geologic formation and caprock properties support injectivity and containment to meet the project requirements as modelled. A single well may be inadequate to ensure containment, depending on the size of the predicted CO_2 plume and paleogeology (variation and orientation of reservoir and caprock properties). Additional wells needed to discover additional storable quantities could be drilled after the discovery well to mature the project and identify additional Contingent Storage Resources.

7.4 Storage Resource Classification of a Maturing Project from Play to Injection: Mount Simon Sandstone, USA

This SRMS example is generalized from a comprehensive assessment and field demonstration projects of the Mount Simon Sandstone (MtS) in central Illinois, USA (Frailey et al. 2018). This work was completed as part of the MidCARB and Midwest Geological Sequestration Consortium, a US Department of Energy Regional Carbon Sequestration Partnership. Statements regarding years and costs are examples only and not intended to be specific to these projects.

The MtS is a pervasive and vast North American basal sandstone with a caprock (it crosses two countries and eight states); it is expected to be a good geologic formation for CO_2 storage. This expectation is based primarily on the MtS's successful and sustained use for natural gas storage. There are no known minerals of commercial interest in the MtS or deeper formations, and therefore, very few wellbore penetrations exist outside of natural gas storage fields. Rock samples from drilled wells and outcrops indicate the MtS are void of minerals reactive to CO_2-brine mixtures.

The 1995 regional assessment scoping study resulted in a single-storable-quantity estimate of 800 Gtonne, with low certainty. A minimum depth cutoff was applied to support a pressure temperature of geologic formations to sustain liquid-like CO_2 density; a maximum depth cutoff was applied because a reduction in MtS porosity was known to occur at greater depths. Because very few wells were available directly and none were studied as a specific project, the classification of this estimate is Prospective Storage Resources–Play. The categorization of the estimate is 3U. **Table 7.6** summarizes this example.

This was followed in the year 2000 by a site screening study to assess storage resources. A volumetric approach was used but combined with GIS so local MtS differences (e.g., thickness and depth) were included in the assessment. The pore volume estimate was enhanced by using an actual natural gas storage field as an analog within a specific geologic structure. The pore volume of the structure was determined (using more than 100 well logs), and a natural gas storage efficiency was estimated. This screening study was limited to suspected geologic structures defined by overlying oil-bearing geologic formations defined by geologic structures. The same depth limitations (minimum and maximum depth cutoffs) were applied as per the 1995 study.

Storage Assessment	Methodology	Storable Quantities	SRMS Class/Subclass
1995 scoping study	Regional assessment; volumetric estimate using a storage efficiency factor	800 Gtonne (3U)	Prospective Storage Resources–Play
2000 site screening	Regional review of geologic structures; Graphical Information System (GIS) volumetric estimate using a storage efficiency factor; included only pore volumes within structures	6 Gtonne (2U)	Prospective Storage Resources–Lead/Prospect
2005 site screening	Regional assessment; volumetric estimate using range of geologic parameters and storage efficiency factors	25-50-100 Gtonne	Prospective Storage Resources–Lead/Prospect
2010 site appraisal	Project specific, regional dip, dynamic simulation	70 Mtonne (2C)	Contingent Storage Resources–Development Pending
2015 active project	CO_2 injection data from active project	1 Mtonne (P1)	Capacity–Proved, Developed, Injecting
	Potential project expansion; additional compression or extended injection period	69 Mtonne (2C)	Contingent Storage Resources–On Hold/Development Pending

Table 7.6—Summary of an example of the project maturity and storage resources assessment based on the Mount Simon Sandstone, Illinois, USA. The range of storable quantities is quoted directly from the available documentation, which may not specifically identify these quantities as P90, P50, or P10.

The 2000 study resulted in a single estimate of storable quantities (6 Gtonne) for the MtS underlying several different oil fields. Because no well was drilled, but specific geographical locations were identified for single well storage projects, the classification of this estimate is Prospective Storage Resources–Lead or Prospect. (The class or subclass that individual structures could satisfy might vary by geologic structure and project.) The Prospect subclass requires a viable drilling target, which was the center of each oil field assessed; hence, there is sufficient data to support the planning of a well and the investment decision to drill it. Geologic structures with insufficient data at the time of evaluation would be classified as Prospective Storage Resources–Lead. Because the estimate includes storage efficiency based on an analogous displacement process in the same formation, the categorization of the 6-Gtonne storable quantities is 2U (or best estimate). Because a unique value of storable quantities for each MtS structure was available, and confidence in the presence of an MtS structure was high, the storable quantities calculated for each oil field were classified as Prospective Storage Resources–Prospect. If the evaluation reported only a single value for storable quantities for all combined structures evaluated, then this total would be classified as Prospective Storage Resources–Play.

The purpose of the 2005 study was to enhance the 1995 scoping study of the entire MtS (including areas outside of oilfield structures) using a more rigorous calculation of storage efficiency by applying a range of geologic factors and displacement efficiency factors. A Monte Carlo simulation using distributions of three geologic and four displacement efficiency factors provided low, medium, and high storage efficiency values (1%, 2%, and 4%) to be used on the bulk volume of the basal sandstone. This study resulted in storable quantities ranging from 25 to 100 Gtonne of CO_2. Because no well was drilled, but additional drilling locations were located, this range of storable quantities was classified as Prospective Storage Resources–Prospect. Based on the probabilistic approach used, the categorization of the estimates are 1U = 25 Gtonne, 2U = 50 Gtonne, and 3U = 100 Gtonne.

The purpose of a subsequent study in 2010 was to drill an injection well for a specific source to evaluate CO_2 storage. A location to drill the well was found within 1 mile of the CO_2 source where the MtS was on regional dip (i.e., there was no known or expected geologic structure). (Primary challenges to project maturation were competitive needs for surface acreage and current industrial infrastructure, e.g., buildings, roads, and pipelines.) Pre-drill site screening information was taken from the 2000 and 2005 studies. An exploration/appraisal well was drilled, and, using geologic, geocellular, and flow modelling, estimates of injection rates were made in the context of the maximum CO_2 quantity available for capture at the CO_2 source and likely project plans for purchase of capture, compression, and transportation facilities and infrastructure.

This study determined that the maximum CO_2 quantity of 3000 tonne/day could be injected without restrictions for the 25-year anticipated life of a specific compression facility. A maximum daily rate of up to 8000 tonne/day could be injected into the MtS in this well if additional CO_2 sources were found and equipment purchased. Permitting was not projected to be a challenge.

Given that discovery criteria were met (the well tested favorably for CO_2 injection), the storable quantities were classified as Contingent Storage Resources–Development Pending. At this time in the study, the contingency preventing maturation to Capacity was the required management approval of capital for infrastructure and obtaining an injection permit. Based on the maximum CO_2 injection rate projected through modelling and field testing, demonstration of expected containment, and assumption of a 25-year facility life, a 70 Mtonne estimate was categorized as 2C because it was considered "most likely" and neither overly optimistic or pessimistic. The storable quantities were classified as Contingent Storage Resources–Development Pending given that the active maturation of the project was expected. (If the well results were not as prognosed, or additional uncertainty remained for which there were plans for future evaluation prior to commercial development, the subclass Unclarified may have been used.)

Following management and regulatory approval, a facility to capture 1000 tonne/day was completed for storage over three years (a total of 1 Mtonne). Injection started and 1000 tonne/ day was readily achievable with the specification of operation plan and permit.

The projected duration of injection operations and size of the facility for this project define clearly the storable quantities to be classified as Capacity–Developed Injecting. Because of the high degree of certainty of maintaining this rate for the entire three-year period, at the time of injection, the 1 Mtonne is categorized as Proved. There is no management commitment or permit to inject at a higher rate or for longer period of time to classify any additional storable quantities as Capacity; however, there is discussion for adding additional compressors and extending the duration of the project. Therefore, this extension project (accounting for the remaining 69 Mtonne of storable quantities) would remain classified as Contingent Storage Resources. While the extension project is very immature (such that economic viability cannot be assessed) or is not expected to be developed within a reasonable time frame, then the storage resource is classified as Contingent Storage Resources–Development Unclarified.

During the three years of injection, as CO_2 was injected and stored, the 1 Mtonne Capacity decreased as the Stored CO_2 increased. For example, at the end of year one, 1/3 Mtonne was injected. The Capacity would be 2/3 Mtonne and the Stored would be 1/3 Mtonne.

8.0 Glossary

These SRMS Guidelines use terms predominantly defined in the SRMS. Therefore, the SRMS Glossary should be referenced for terms not appearing in the SRMS Guidelines Glossary.

CO_2 footprint (or plume): The subsurface volume or corresponding area occupied by Stored CO_2. In these guidelines, this refers to CO_2 in the free phase, not to dissolved or mineralized CO_2.

CO_2 price: Revenue generated per unit of CO_2 injected and stored. This could be a tax credit, subsidy, direct payment for storage, or an assigned transfer price.

Fiscal metering: Metering of quantity of injectant to a specified standard, generally agreed by contractual of regulatory parties. This is normally a high standard of metering and often involves significant capital and operating cost. As such, it is generally done at a single point for any storage project.

Pressure footprint: The subsurface volume or corresponding area in which pressure is changed as a consequence of Stored CO_2.

Transfer price: Generally applied to cases in which CO_2 is transferred between units of an integrated capture, compression, transport, and storage project where the accounts for each part of the system are made up separately. This separation of accounting might reflect different legal entities, different shareholders, or different tax treatments for different units. In these cases, a price is assigned to the CO_2, termed the transfer price, so that costs and income can be apportioned between the accounting entities. Depending on the situation there may be external rules relating how this transfer price is established.

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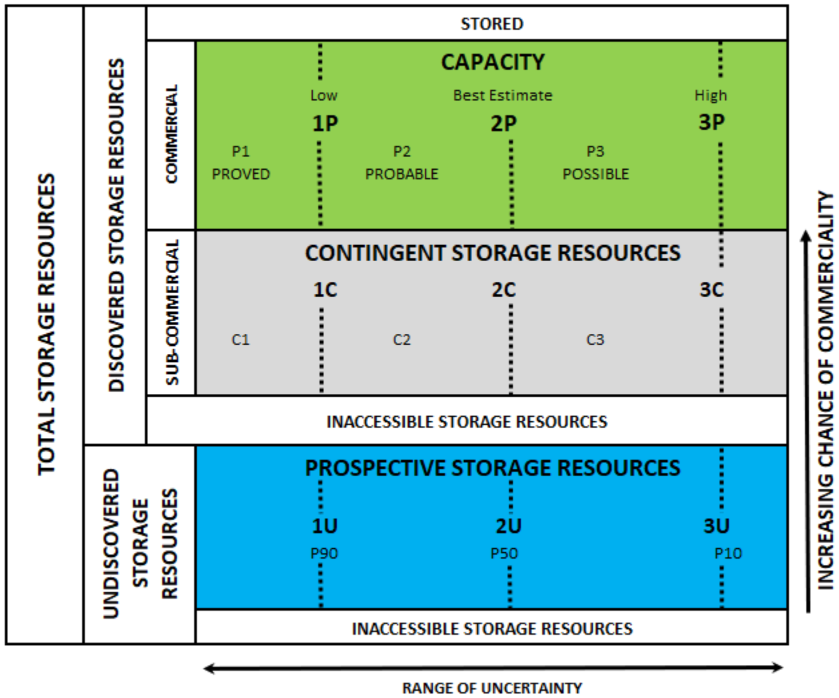
Errata to the 2017 CO_2 Storage Resources Management System (SRMS)

Sect	Pg.	Para	Action	Reason
1.1	3	3	The "Range of Uncertainty" on the horizontal axis reflects a range of storable quantities ~~**(e.g., pore volume potentially accessible within a geologic formation by a project)**~~, while the vertical axis represents the "Chance of Commerciality,"	Term is defined. Adding a slightly different definition is confusing and not needed.
1.1	4	Fig	Capacity, CSR, PSR should be the same. All have low, best, high and P90, P50, and P10. A revised **Fig. 1.1** is at the end of this document.	Consistency in graphic.
1.1	5	2	*Contingent Storage Resources*. Those quantities of Total Storage Resources estimated, as of a given date, to be ~~**potentially**~~ accessible in known geologic formations, but the applied project(s) are not yet considered mature enough for commercial development, as a result of one or more contingencies.	Use of potential is redundant in the context of something happening in the future.
1.1	5	4	*Prospective Storage Resources*. The quantity of Undiscovered Storage Resources estimated, as of a given date, to be ~~**potentially**~~ accessible within undiscovered geologic formations or uncharacterized parts of discovered geologic formations by application of future exploration/development projects.	Use of potential is redundant in the context of something happening in the future.
1.1	5	5	… storage resulting from physical/societal constraints of the storage location, both surface and subsurface**.**	Missing period at end of definition.
1.1	6	1	Conceptually, the sum of Storage Capacity, Contingent Storage Resources, ~~**and**~~ Prospective Storage Resources, **and inaccessible storage resources** may be referred to as "Remaining Storage Resources."	Missing from list "inaccessible storage resources."
1.2	8	2	The storable quantities being estimated are those volumes (or mass) that can be stored from a project, as measured according to ~~delivery~~ regulator specifications at the point of **injection.** ~~**of sale or**~~ **This may also coincide with the** custody transfer **point** (see Section 3.2.1 Reference Point)	Aim of SRMS to track Stored/injected quantities – not quantities received by project which may then be processed / changed – although these MAY be the same (no processing).
2.1	11	Fig	A revised **Fig. 2.1** is at the end of this document.	Consistency in graphics.
	18		3.2.1 Reference Point. Reference Point is a defined location(s) where the stored quantities are measured (metered) or assessed. The Reference Point ~~**is typically**~~ **may coincide with** the point of transfer from a CO_2 generator or pipeline operator to the storage project operated by a third party or the CO_2 generator's storage operations.	Aim of SRMS to track Stored/injected quantities – not quantities received by project which may then be processed / changed – although these MAY be the same (no processing).
Table 1	30	2	Under the Prospective Storage Resources definition: Those undiscovered storable quantities of pore volume in a geological formation that are estimated, as of a given date, to be ~~**potentially**~~ accessible.	Use of potential is redundant in the context of something happening in the future.

Gloss	38		~~*Inaccessible*: Portion of discovered resources that are inaccessible from development as a result of a lack of physical, societal, or regulatory access at the surface or subsurface.~~ ~~*Inaccessible Contingent Storage Resources*: Portion of Contingent Storage Resources' storable quantities that is identified but is not considered available for storage.~~ ~~*Inaccessible Resources*: That portion of Contingent (Discovered) or Prospective (Undiscovered) Storage Resource quantities, which are estimated as of a given date, not to be used for storage. A portion of these quantities may become storable in the future as commercial circumstances change, technological developments occur, or additional data are acquired.~~ ~~*Inaccessible Storage*: Storable quantities for which a feasible project cannot be defined by use of current, or reasonably forecast improvements in, technology~~	Delete all. Redundant to have many variations of parts of a definition intended to have the same meaning. New single term to replace all of these below.
Gloss	38		*Inaccessible Storage Resources*: Storable quantities classified as Discovered or Undiscovered Storage Resources, which are estimated as of a given date, not to be developed for storage. These quantities may be developed for storage in the future if circumstances change. For example, current regulatory restrictions may prohibit storage at the time of the assessment and foreseeable future.	New single term to replace all of these above. Also, what is used in the text.
Gloss	39		~~Potentially Accessible: Quantity of Undiscovered Storage Resources estimated, as of a given date, to be potentially accessible within undiscovered geologic formations or uncharacterized parts of discovered geologic formations by application of future exploration/development projects.~~	Delete. everything accessible has a name other than accessible. Not used and not needed.
Gloss	40		*Prospect*: A project associated with a **~~potential accumulation~~** **undiscovered storable quantities** that is sufficiently well defined to represent a viable drilling target. A project maturity subclass that reflects the actions required to move a project toward commercial production.	Consistency and clarity with text.
Gloss	41		*Remaining Storage Resources*: The sum of **Storage** Capacity, Contingent **Storage** Resources, **~~and~~** Prospective **Storage** Resources**, and inaccessible storage resources**, excluding stored (i.e., previously injected) quantities.	Consistency and clarity with text.
Gloss	42		*Stored Quantities: Part of the Capacity for a geologic formation that has injected **and retained** CO_2 occupying pore volume; it can be reported as mass or volume.* *Any back-produced CO_2 quantities or emissions to atmosphere or seabed are deducted.*	Clarity to exclude emitted / produced quantities.
Gloss	42		*Stored: A classification that includes the cumulative quantity of CO_2 that has been actually injected **and retained** over a defined time. **Any back-produced CO_2 quantities or emissions to atmosphere or seabed are deducted. Quantities of CO_2 that have migrated beyond the defined boundaries of the project but remain isolated from the atmosphere and hydrosphere may be considered retained.** While all storage-resources estimates and injection are reported in terms of the metered CO_2 specifications, raw-injection quantities (including non-CO_2 constituents) are also measured to support engineering analyses requiring voidage calculations.*	Clarify that injected volumes alone is not stored - any later back produced quantities should definitely be excluded.
Gloss	42		*Reference Point: A defined location within an injection and storage operation where quantities of injected CO_2 are measured under*	Aim is to track injected (and stored)

			defined conditions before ***injection*** ~~***custody transfer (or consumption)***~~***. This may also coincide with*** *the* ~~***called Point of Sale or***~~ *Custody-Transfer Point.*	quantities, not necessarily the quantity of waste gas handed over to the storage project.

REVISED FIGURE 1.1



REVISED FIGURE 2.1