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Expert Elicitation of the Timing and Uncertainty to Establish a Geologic Sequestration Well for CO_2 in the United States

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Table 1

Abstract
Many studies anticipate that carbon capture and sequestration (CCS) will be essential to decarbonizing the U.S. economy. However, prior work has not estimated the time required to develop, approve, and implement a geologic sequestration site in the U.S. We generate such an estimate by identifying six clearance points that must be passed before a sequestration site can become operational. For each clearance point (CP) we elicit expert judgments of the time required in the form of probability distributions and then use stochastic simulation to combine and sum the results. We find that, on average, there is a 90% chance that the time required lies between 5.5 and 9.6 years, with an upper bound of 12 years. Even using the most optimistic expert judgements, the lower bound on time is 2.7 years, and the upper bound is 8.3 years. Using the most pessimistic judgements, the lower bound is 3.5 years and the upper bound is 19.2

years. These estimates suggest that strategies must be found to accelerate the process. We conclude the paper by discussing seven potential strategies.

Significance Statement

Many energy experts have been assuming that if carbon dioxide can be captured from power plants or other industrial facilities, disposing of it deep underground will be relatively straightforward. This paper asks the question, "how long will it take to develop and get approvals to create and begin operating a carbon dioxide disposal well?" Using an average of the judgments provided by experts, there is a 90% chance that the answer lies between 5.5 and 9.6 years, with an upper bound of 12 years. If its antecedents are not addressed, this long and uncertain timeframe is likely to seriously slow the implementation of deep decarbonization in the U.S.

Main Text

Introduction

Most assessments of how to achieve deep decarbonization of the U.S. economy rely extensively on carbon capture and deep geological sequestration (CCS) (1–4). Carbon dioxide may be captured from a wide range of activities, including the generation of electric power and process heat from fossil fuels or biomass, the production of hydrogen from natural gas feedstock, and a wide range of industrial processes including iron and steel, cement, and chemical production (5–15). It may also be directly captured from the air (5, 16). While some of the captured CO_2 might be converted to saleable products, there is a limit to how much carbon can be abated in this way. Most utilization applications only partially reduce CO_2 released into the atmosphere and are expected to remain limited in the short term (17). To support sequestration, wide access to reservoirs for deep geologic sequestration will lie on the critical path to large scale decarbonization.

Deep geologic sequestration of carbon dioxide requires an appropriate geologic formation into which carbon dioxide can be injected, as well as an approved injection facility. Prior literature has focused on individual aspects of CCS project development including cost analysis, geologic characterization, and non-technical barriers that have inhibited large-scale deployment (18–29). What has been less understood until recently are the regulatory and other bottlenecks that may be encountered when securing approval to create and operate a sequestration facility in the U.S. Sequestration site operators require a permit from the U.S. Environmental Protection Agency, based on evidence that a potential site ensures safe and permanent sequestration of CO_2 (6). The timelines associated with this permitting activity have become a point of potential concern for developers and investors (16). States may also apply for primary enforcement authority, or primacy, which would allow state offices to manage the permitting process (30). Currently only two states have been granted Class VI primacy by the EPA (30).

Clearance Points for Project Implementation

Building on Pressman and Wildavsky's classic discussion of project implementation (31), in Figure 1 we identify the set of "clearance points" (CP) that a project developer must pass in order to develop and implement a sequestration well on private land in the U.S. The early stages of this process will be slightly different for projects developed on state or federal lands, but the steps remain similar.

A CCS project developer must first identify one or more sites with appropriate geology and surface location (CP1). Then, a detailed geologic characterization must be completed (CP2a), and arrangments must be made to acquire legal rights from property owners for use of pore space (CP2b). We assume that these two activities occur in parallel, so the time to pass CP2 is whichever takes longer. Having secured and characterized a site, the project developer must then submit a permit application to the EPA for the approval of a Class VI well. We assume that the developer prepares the application while working to pass CP1 and CP2.

Once the Agency reviews and issues a permit to construct a well (CP3), there is an opportunity for legal intervention by parties that wish to contest the Agency's decision (CP4). After resolving any legal challenges, the project developer can proceed to construct the injection well, gather data and geologic samples, and conduct necessary testing. We assume that injection well construction (CP5a) and any necessary CO_2 pipeline construction (CP5b) are done in parallel, so the time to pass CP5 is whichever of the two takes longer. Before CO_2 injection operations can commence, the developer must submit data to the EPA on the completed well so the Agency can compare these results with the expectations that were outlined in the initial application. Assuming that the Agency finds these are satisfactory, a final authorization to begin injection is provided (CP6).

Our clearance point characterization was informed by EPA's own published descriptions of the regulatory requirements, further informal conversations we held with EPA staff, and prior engineering studies (25–28, 32–37) that describe the processes involved, as discussed in further detail below. There are other potential activities that could be necessary for project development that we have not included, so the estimates from our analysis should be considered as a lower bound.

Clearance Point 1: Site Identification

Because the geology can vary significantly throughout the country, for the elicitations regarding site identification the experts we interviewed were asked to consider only a select number of counties in the Pennsylvania, Ohio, West Virginia tri-state area (map shown in Figure S1). This region is as well or better characterized than most of the rest of the country due to shale gas development, so the results of these elicitations may represent a lower bound for time required. Initial injection site identification is typically done using publicly available geologic data as well as data that may be available for purchase from oil, gas, or other companies.

Clearance Point 2a: Site Characterization

There are basic subsurface requirements for proper geologic sequestration (GS) of carbon dioxide, including rock formation, reservoir depth, geological sealing units (cap rock), and potential reservoir volume and pressure capacity (33, 34). Several types of trapping mechanisms, both physical and geochemical, hold the CO_2 in place after injection (24, 34).The two most well-studied rock formations for GS are saline aquifer formations and depleted oil and gas reservoirs. Geologic properties for such formations have been well studied and found to be suited for CO_2 sequestration. Inactive oil and gas reservoirs have the benefits of being well characterized with useful data readily available, and some may have necessary infrastructure already in place, and have confirmed the presence of appropriate low-permeability cap rock. The minimum depth for GS of CO_2 is generally one kilometer below the surface (33, 34, 38). Class VI permit application requirements and guidance documents provide a roadmap of necessary characterization activities for this clearance point (32, 33, 39). In cases where a stratigraphic test well, or characterization well, is necessary to gather sufficient geological data for the Class VI permit application, an operator will need to get a permit from the state and/or federal agencies that have jurisdiction (37, 40). Because this can vary in different regions across the country, we do not include a time estimate for this activity. Thus, for cases where a characterization well is required, our estimates for the time to clear CP2a should be viewed as a lower bound.

Clearance Point 2b: Pore Space Rights

While in many parts of the world the deep subsurface is national or Crown property, that is not true in the United States. In anticipation that this could give rise to serious problems in developing CCS in the U.S., a comprehensive adaptive approach to address these issues, which included possible draft legislation, was developed and widely disseminated in 2008 (28). However, national legislation addressing this issue has never been adopted in the U.S. Instead, operating under the authorization provided by the Safe Drinking Water Act, the U.S. EPA added the Class VI well category in their Underground Injection Control (UIC) program (see Table S1). The federal UIC regulations only address groundwater protection; consideration of liability and long-term stewardship, if any, is left to the states. Each state must develop regulations to both differentiate pore space ownership from surface and/or mineral ownership, as well as set a consent threshold for landowner forced pooling or amalgamation (16, 41–43).

There is so little experience across the country in securing access to pore space for CO_2 sequestration that none of the land use or other experts we talked with felt comfortable providing estimates of the time required to obtain approval from landowners. Accordingly, we treated that quantity parametrically, using two values: 6 and 18 months. If the value is six months, the time to complete geologic characterization is likely to dominate. If the value exceeds 18 months, we assume that the developer would switch to some other site. The shorter time may be more characteristic of western regions that have relatively large land holdings whereas the longer time may be more likely in the Midwest and East where land holdings are smaller in size.

Clearance Point 3: EPA Class VI Permit Review

Requirements for a Class VI permit are more stringent than any other UIC well class, making the application process more complex and time consuming. Each EPA regional office is responsible for reviewing and approving all permit applications within their region (unless a state has obtained primacy). Based on what we have learned through interviews with EPA personnel, other experts, and several publications (36, 37, 44), Figure 2 outlines the steps in EPA's review of a Class VI well application. The first official review activity by the EPA is the administratively complete determination, at which point the Agency will list the project on the EPA website as a pending permit (45). The current timeline to approval stated in EPA materials is 18-24 months (32, 45, 46). The EPA recently released a list with timelines of current Class VI projects under review, which illustrates the high uncertainty in the Class VI permit review process (47). Additionally, the Class VI permit application requires CO_2 stream composition data, which means projects that have not yet fully identified or characterized their CO_2 source face potential delays in the permit approval process (6).

Since the Class VI Rule was promulgated in 2010, the U.S. EPA has approved only six permits, all of which were located in Illinois, EPA Region 5 (45, 48). Two were for projects by Archer Daniels Midland (ADM), and the other four were for a demonstration project by FutureGen Alliance, which was defunded before well construction began (49, 50). In addition, EPA Region 5 has recently approved two draft permits for the Wabash Carbon Services project in Indiana (45, 51).

The first ADM project, the Illinois Basin-Decatur Project (CCS#1), was constructed in 2009 under a Class I permit issued by the Illinois EPA, prior to the creation of the Class VI Rule (44, 52). It was later converted to a Class VI permit after injection ceased (53). The Class VI permit application was submitted in December 2011 (35) and issued in February 2015 (53). The other ADM project, the Illinois Industrial CCS Project (CCS#2), was permitted by EPA as Class VI (35). This Class VI permit application was submitted in July 2011 and the EPA issued the permit to construct in December 2014 (53). Both of these permits spent three years in the EPA application review phase. FutureGen Alliance submitted a package of four Class VI permit applications to the EPA in March 2013 and the EPA issued final permits in August 2014, which were appealed. The appeals were resolved by April 2015, but the project was canceled shortly after (49, 50).

The Class VI permit application review process includes the potential for much back-and-forth between the EPA reviewer(s) and the applicant, and timely communication is critical for minimizing the review process timeframe. This is why the EPA strongly recommends that applicants or interested parties reach out to their EPA regional office before starting a project and continue to do so frequently when preparing the application (32, 33). If drastic modifications to the permit are required, the applicant may have to update their models and application information with the new data and repeat the permit review process, including another public comment period and additional opportunity for appeals (each of which is likely to require many months) before they are able to obtain authorization to inject (54). Even if only minor modifications to the permit are required, the time to obtain authorization to inject is highly uncertain.

Clearance Point 4: Potential Legal Challenges

Once the Class VI permit has been issued, anyone who participated in the public comment period or public hearing has thirty days from issuance to file an appeal with the Environmental Appeals Board (EAB) regarding the issued permit decision (55). If a party is not satisfied with the ruling issued by the EAB, they can file an appeal with the U.S. Circuit Court of Appeals, at which point the Department of Justice becomes involved (56). The appeals process with the EAB can take several months to resolve (55, 56), and appeals to the Circuit Court of Appeals are likely to take longer (54).

Clearance Point 5a; 5b: Well Construction, Data Collection; Pipeline Siting, Permitting, and Construction

CP5 involves several activities. We obtained probabilistic judgments from experts on how long it is likely to take to complete well construction and data collection. However, we do not include estimates for the time to site and build a pipeline. In some cases, the construction of a CO_2 pipeline of substantial length from the capture site to the injection well may not be required. In the case that such a pipeline is needed, we show it as CP5b in Figure 1. However, because the length of such a line and the issues involved in securing rights of way will be site specific, we do not include a time estimate for this activity. Thus, for cases where a substantial pipeline is required, our estimates for the time to clear CP5 should be viewed as a lower bound.

We assume for CP5 that all materials and equipment have been preordered and are on-hand for the construction to begin once approval is received. This assumption is highly dependent on the willingness of a project developer to assume risk and their priorities related to front-end loading. Obtaining specialty materials, such as chrome alloy piping, can have long lead times and high costs. The situation is similar for lining up contractors and equipment, which, if not done ahead of time, can result in additional delays.

Clearance Point 6: Injection Authorization

As mentioned in CP3, a Class VI permit only provides the developer permission to construct the injection well and conduct pre-operational testing and data collection (36, 54). As shown in Figure 2, the EPA must review the new information and determine what, if any, modifications must be made to the permit before granting operational approval. If drastic modifications to the permit are needed, the application must be revised and resubmitted. Even if the permit does not need to be resubmitted, the authorization for injection review period has the potential to take substantial time.

The amount of time to go from initial project development to the start of routine injection is the sum of the times required to pass the six stages in the process outlined in Figure 1, each of which is uncertain. Accordingly, at each stage of the process we have used standard methods of expert elicitation (57–60) to construct subjective probability distributions for the time to pass each individual clearance point. Then, using stochastic simulation, the resulting distributions are summed to obtain a probability distribution of the total time to achieve project approval. While we do not link any of the experts to any specific probability distribution, consistent with standard practice, the experts we interviewed are identified in Table S4.

Results

Total Time from Project Conception to Beginning Sequestration

Figure 3 displays boxplots that summarize the probability distributions elicited from experts. We obtained three for each of the six clearance points. Some experts provided distributions for more than one clearance point, depending on their expertise and availability. From the long right tail of several of these distributions, it is apparent that some experts believe that clearance points one, two, three, and four all have some probability of generating long delays that could impede the successful development and approval of a sequestration well.

In Figure 4 and Table 1, for each clearance point we report the results of the average time estimate of the relevant three experts by randomly sampling each distribution, summing them in a stochastic simulation and dividing by three. We do this for each stage in the process and then stochastically sum the resulting distributions (see Methods). As noted in the clearance point discussions above, in several cases the time estimates should be viewed as lower bounds; the same is true of the distributions reported in Figure 4 and Table 1.

For this averaged scenario, the mean time to project completion is 7.5 years with a 5th percentile minimum time of 5.5 years and a 95th percentile maximum time of 9.6 years. In other words, there is a 90% chance that the time required will lie between 5.5 and 9.6 years. In the SI (Table S2, Figures S2 and S3) we report additional results using the most optimistic and the most pessimistic of the elicited expert distributions at each clearance point. The most optimistic and pessimistic scenarios result in mean times to completion of 4.1 and 10.9 years, 5th percentile minimum times of 3.6 and 6.9 years, and 95th percentile maximum times to completion of 7.1 and 15 years, respectively. Estimates for the time to Class VI permit application approval are shown in Table S3 of the SI.

Discussion

Strategies To Speed the Process

The wide interval and considerable uncertainty reported in this analysis show that the development, approval, and implementation of a Class VI sequestration well can be impeded by several bottlenecks which, if not addressed, may seriously slow the adoption of CCS in the United States. Depending upon specific circumstances, geologic characterization, pore space acquisition, the Class VI permit application process, and potential litigation are the clearance points likely to cause the longest delays. We offer seven strategies that may be used to accelerate the contribution of CCS to meeting the nation's climate goals.

To reduce the time required to pass clearance points one and two, both state and federal government could conduct assessments of the most promising sequestration sites on land they control in order to create a set of "pre-vetted" sites. States might also create incentives for private property owners to host sequestration sites. Both state and federal governments could create grant or tax incentive programs to encourage private owners to pre-vet sites in anticipation of future income from sequestration.

Especially in the Eastern U.S., CCS infrastructure is likely to cross state boundaries. Moving today to reduce the potential barriers to multi-state coordination could reduce the risks of future delays. For example, Ohio, West Virginia, and Pennsylvania could create a joint commission to develop and propose common regulations, or address discrepancies among existing approaches, to facilitate the implementation of projects for which desired reservoirs cross state boundaries.

For private landowners, there remains great ambiguity about the appropriate level of compensation they will receive in exchange for the sale or lease of the pore space beneath their property. Some of these ambiguities and associated delays could be reduced if the DOE developed guidance on appropriate strategies for, and levels of, compensation.

Both our interviews and much of the prior literature suggest that a lack of public understanding or acceptance has the potential to derail project timelines (24–29). Early and transparent community engagement will be required to minimize potential objections and resulting project delays, but engagement does not automatically guarantee public support (61). Organizational models that feel more like public utilities and less like private industry may also strengthen public acceptance. Behavioral social science research may offer insight into how this could best be done. For example, conducting open-ended conversations (62) with community members early in the process to learn about their major sources of concern would show respect and allows developers to address concerns to the extent possible in project design and implementation.

We found in our interviews that the time required to complete EPA Class VI review and approval (CP3) depended heavily on the number of staff performing reviews in the UIC program. EPA, OMB and Congress could rectify this situation by substantially expanding the level of staffing, specifically in the regional offices that are responsible for conducting permit review. Expanding staffing levels would also allow states seeking primacy to obtain it more quickly. To avoid adverse outcomes in the longer term, the federal government could consider programs to assist states in developing staff numbers and competency in UIC permitting.

Our interviews suggested that granting states primacy may, but would not necessarily, speed up the permitting process. Obtaining primacy takes time. Currently only North Dakota and Wyoming have Class VI primacy. North Dakota applied for primacy in 2013, but it was not granted until 2018 (44, 63). Wyoming's official application was submitted in 2019, after working closely with EPA Region 8 for "some years," and primacy was granted in 2020 (35, 44). In early 2021, Louisiana submitted a Class VI primacy application, which is still under review (35, 63, 64). Texas, West Virginia, and Arizona are currently in a "pre-application" phase with the EPA, with many other states considering the primacy option (35, 63).

Past experience in the United States suggests that there are almost always parties prepared to oppose any new development through litigation. This makes shortening the time to pass any potential legal disputes (CP4) challenging. However, legal scholars could anticipate and preempt objections that could be easily overruled and advise on how to minimize potential legal difficulties. Class VI rules only address groundwater protection; however, litigation is also likely to address issues of long-term stewardship and liability. States could preempt at least some such suits by developing appropriate legal frameworks, with the help of academic institutions and policy think tanks. Community engagement early in the siting process could also help to mitigate such opposition.

If strategies are not found to shorten the timeline to develop sequestration sites, it is unlikely that CCS will meaningfully contribute to meeting the nation's mid-century climate goals. While the seven strategies outlined above hold the potential to contribute to safely speeding the Class VI approval process, it is likely that a variety of others can also be found. We urge EPA, DOE, states, project developers, NGOs, and academic parties to work on improving and implementing this set and developing and promulgating others.

Materials and Methods

Expert elicitation

We performed expert elicitations (57–60) to obtain estimates of how long it would take to pass each clearance point in the process summarized in Figure 4. Experts were identified through a literature review, lists of CCS conference attendees, the professional connections of faculty members, and recommendations from other participants. Candidate experts were contacted via email. We developed a recruiting text, consent form, and interview protocol, and obtained approval from the Institutional Review Board (IRB) at Carnegie Mellon University. The recruiting texts were informational documents tailored to the expertise of the subject matter expert and the clearance point we wished to discuss with them. Similarly, while they all employed the same structure, the interview protocols were tailored with background information, assumptions, and questions specific to the clearance point being discussed.

Construction of distributions

During an interview, for each clearance point, we established the lower and upper bounds on the timeframe estimate given by each participant. Following standard elicitation practice, we urged the respondent to consider, and possibly expand, their bounds. Again, following standard elicitation practice, we then asked about several intermediate points that were chosen to provide a spread of values between the bounds provided. These were used to build a cumulative distribution as the interview proceeded. The resulting distribution was shown to the expert at the end of the interview, and they were given an opportunity to make revisions as needed. The protocol used for the clearance points related to site geology is included in Exhibit S1 of the SI. The others followed a similar format with the specific questions modified appropriately.

Analytica® model

CP distributions were combined by stochastically summing the distributions to obtain a composite distribution representing the time required to pass all clearance points shown in Figure 5. Individual distributions of the total time for project completion were modeled and combined in Analytica®. The meaning of the colors and shapes in Figure 5 are shown in Table S5, along with the definitions used in Analytica® and shorthand descriptors for reference. Estimates for time to authorization to inject could not be elicited but there are two possible outcomes with very different timeframes. For this reason, it was modeled as two separate uniform distributions with the minimum and maximum bounds based on the only existing Class VI permit that completed the injection authorization stage. For T13, the time for injection authorization when major permit modifications are required, we assumed a uniform distribution from nine months to three years. This range was selected based on the amount of time it took for the ADM CCS#2 project to receive authorization to inject, which was approximately 30 months (53, 65, 66). For T14, the time for injection authorization when major permit modifications are not required, we assumed a uniform distribution from two to nine months.

We elicited judgments of the time to pass each clearance point from three separate relevant experts. In addition to the result shown in Figure 4, which used the average of the three distributions for the time to pass each clearance point, a variety of additional results which, make use of those judgments in different ways, can be found in the SI.

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Figures and Tables

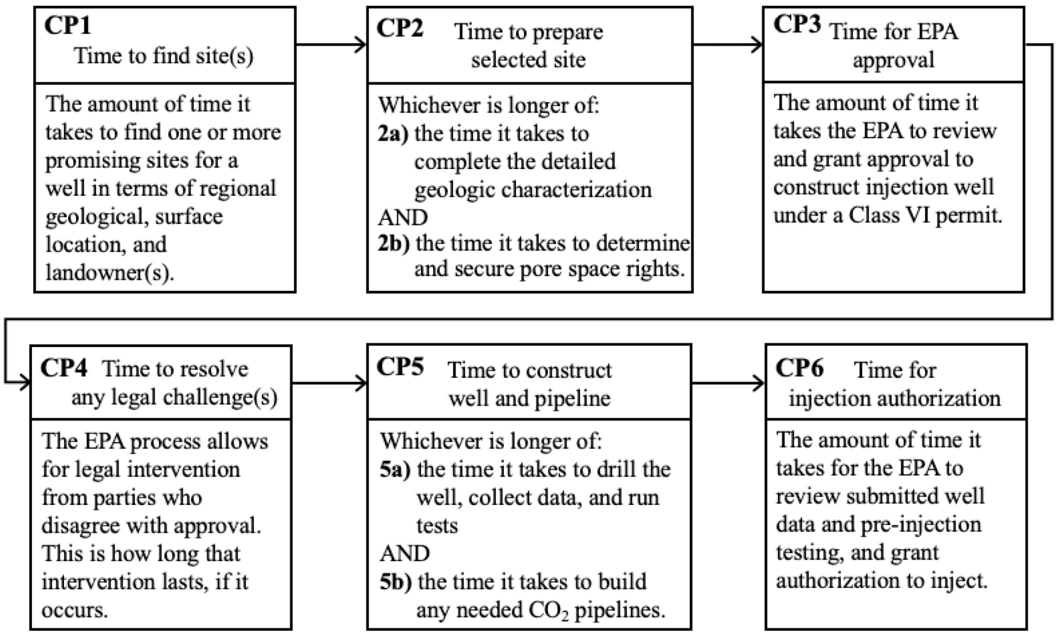

Fig 1. Diagam depicting the clearance points (CP) that must be successfully passed if a geologic sequestration project is to move from initial site identification and characterization to final operation for the case in which EPA performs the the Class VI permit review and approval.

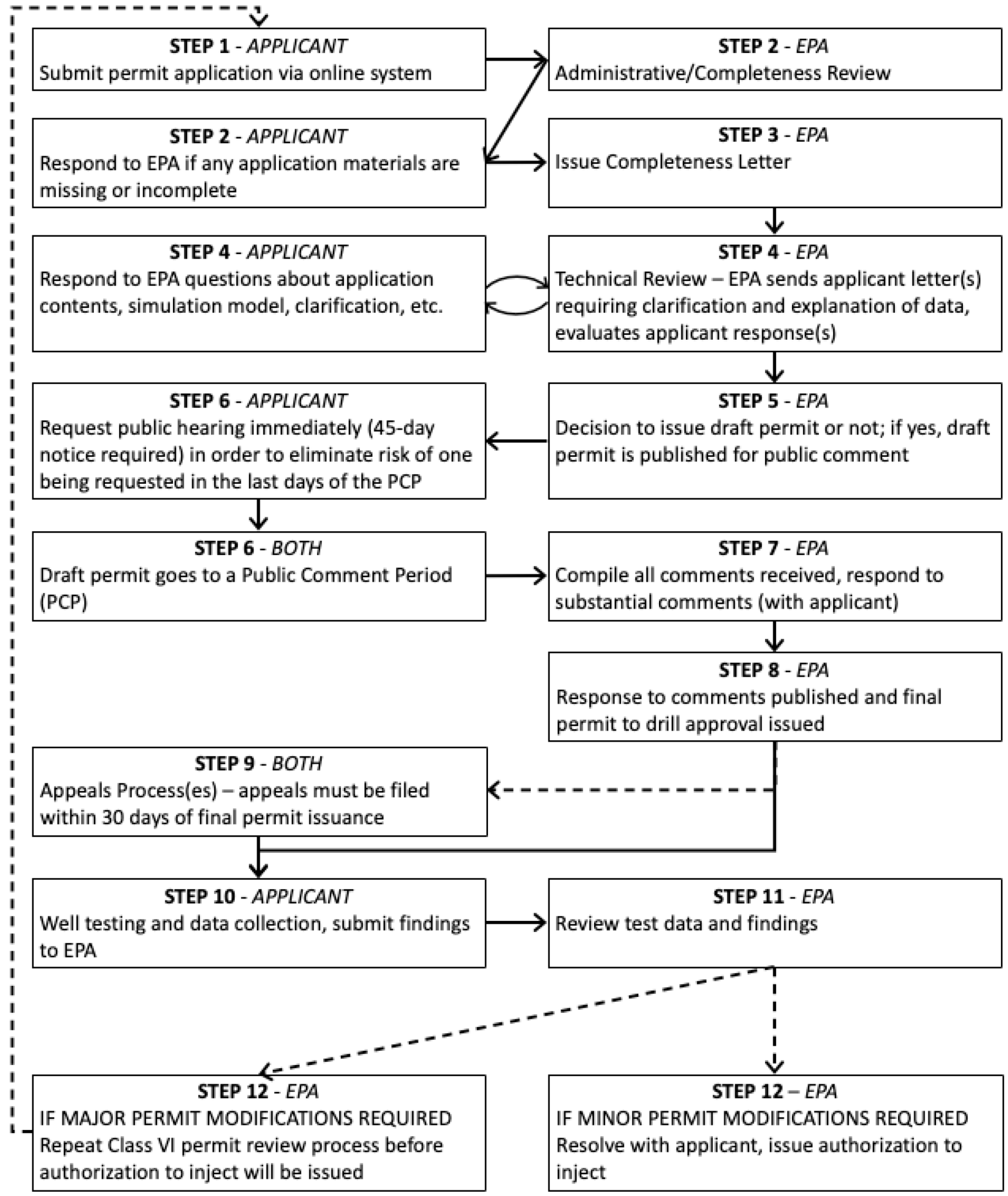

Fig 2. Flowchart of the Class VI permit application review process constructed on the basis of information obtained through expert elicitations conducted in this study and literature by Austin et al., 2021; Korose et al., 2022; Van Voorhees et al., 2021 (36, 37, 44, 54).

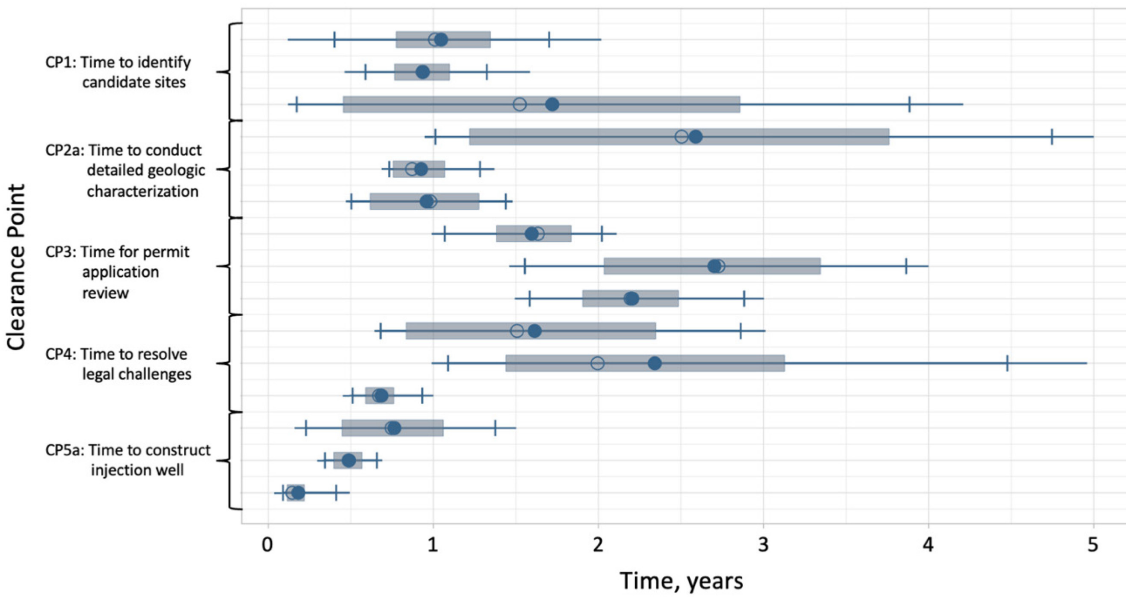

Fig 3. Boxplots displaying the time estimated by each expert to clear individual clearance points. Boxes display the interquartile range (IQR), open circles display median values and solid dots display means, vertical lines display fifth and ninety-fifth percentiles, and horizontal lines display the full range of each distribution. Given the long right tail of several of these distributions, it is apparent that some of the experts believe that clearance points 1, 2, 3 and 4 all have some probability of becoming bottlenecks to the successful development and approval of a sequestration well.

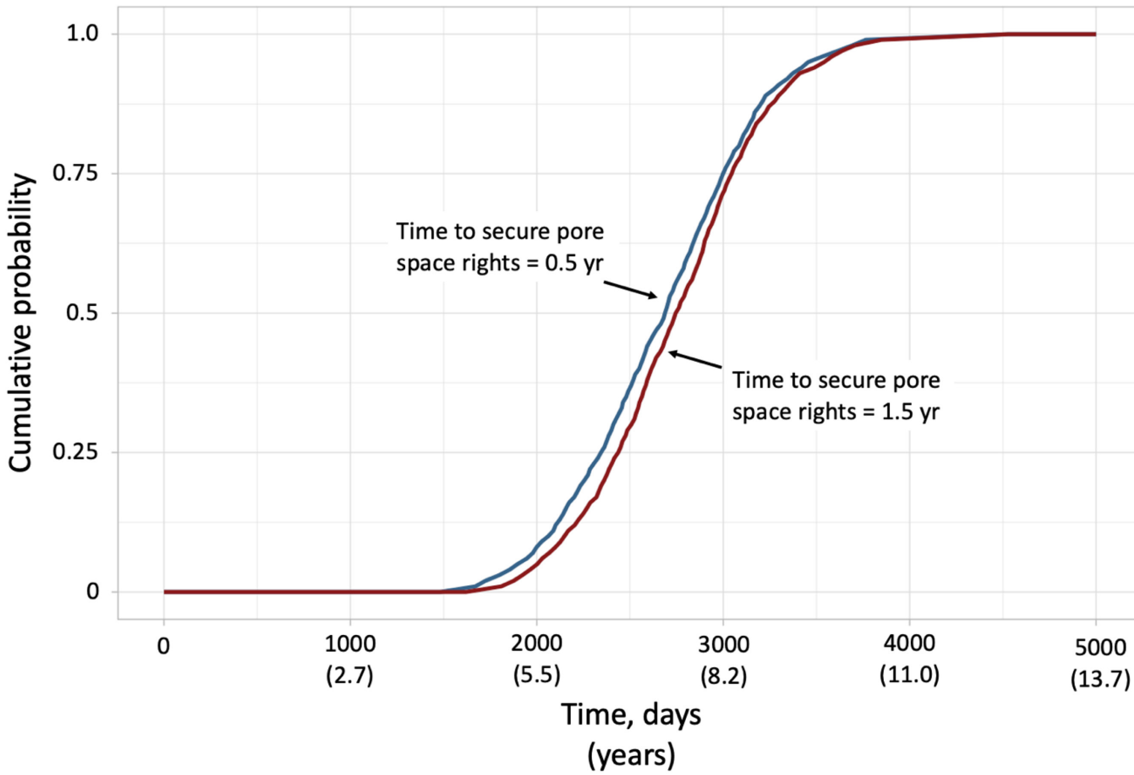

Fig 4. Cumulative probability distribution for the time to move from initial project conception to first injection. This result is obtained by using the stochastic average of the CDFs for the three experts at each clearance point and then stochastically summing those estimates to obtain a probabilistic estimate of the total time to begin operational injection. Given several limitations discussed in the text, in some circumstances this distribution may underestimate the actual time for project completion.

Table 1. Results of stochastically computing the average of the three experts at each stage in the process and then stochastically summing the distributions for total time to project completion, all given in years.

	CP2b = 0.5 years	CP2b = 1.5 years
Minimum	4.2	4.3
5th percentile	5.4	5.7
Mean	7.4	7.6
95th percentile	9.5	9.7
Maximum	12.0	12.0

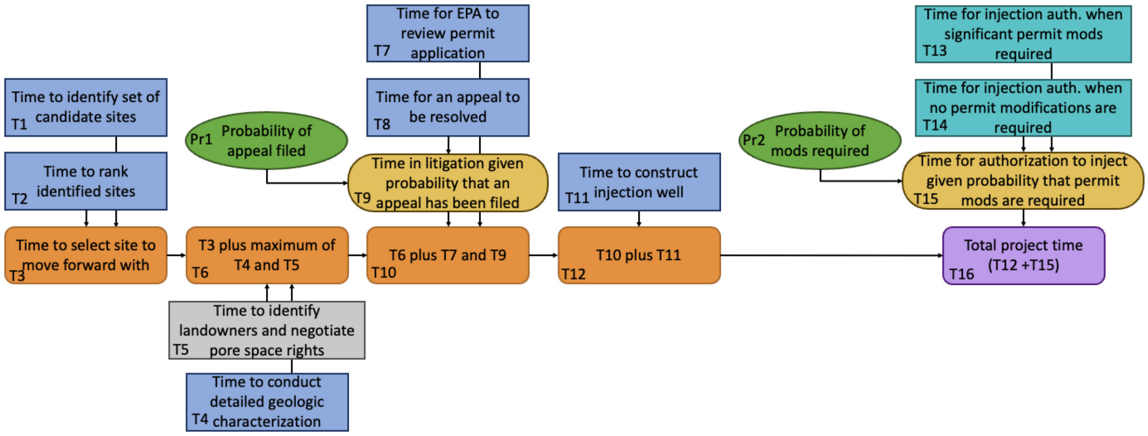

Fig 5. Structure of the stochastic simulation model in Analytica® used to estimate the total time for project completion. The colors here indicate variable type, which are described in Table S5.