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Dependence of CO₂ Capture, Transport, and Storage on Reservoir Leakage Risk

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Abstract

In the carbon dioxide capture and storage (CCS) process, pipeline infrastructure may be used to redirect carbon dioxide (CO₂) flows from leaking geologic CO₂ storage reservoirs to those with storage integrity. We developed and implemented an approach that combined results from the Leakage Risk Monetization Model (*LRiMM*) that monetizes leakage risk from individual reservoirs with the Scalable infrastructure Model for CO₂ capture and storage (*SimCCS*) to determine the optimal deployment of integrated capture-transport-storage systems that are robust to leakage. We demonstrate this approach using a case study of 27 known coal-fired power plants in the U.S. state of Michigan and 42 potential CO₂ storage locations in the Michigan Sedimentary Basin. We compare three cases of leakage risk: (1) as a base case, reservoir leakage risk was not considered, (2) first-of-a-kind leakage risk, which does not consider the reduction in risk from re-directing CO₂ from leaking reservoirs, and (3) nth-of-a-kind risk that considers this reduction in risk. The results highlight the selection of reservoirs that quantitatively considers leakage risk, geospatial differences in infrastructure deployment that considers leakage risk, and the nominal increase in costs and total pipeline lengths for these systems.

Keywords: Leakage Risk; CCS Infrastructure; CO₂ Capture and Storage; Risk Assessment

1. Introduction

Carbon dioxide (CO₂) capture and storage (CCS) has the potential to mitigate substantial amounts of CO₂ emissions and thus decrease the rate at which CO₂ accumulates in the atmosphere, enhances the greenhouse effect, and exacerbates climate change. The CCS process involves separating CO₂ from impure exhaust streams (e.g. fossil fueled power plants, cement manufacturers), dehydrating if necessary, compressing the CO₂ and injecting it through wells into geologic CO₂ storage reservoirs. If a CO₂ source is not located above an available geologic CO₂ storage reservoir, that CO₂ must be transported by pipeline to a location where it can be injected into the subsurface for isolation and storage away from the atmosphere. The emplaced CO₂ will be buoyant at reservoir conditions and this CO₂ or the brine it displaces may leak through wells, faults, fractures, and other leakage pathways into overlying aquifers [1]. This leakage may incur financial costs [2]. Some of these costs depend on the opportunity to redirect CO₂ away from the leaking reservoir through an integrated pipeline network for injection into a reservoir in another location. For example, a contract between the CO₂ producer that the geologic storage operator may be severed, or an emissions

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credit or tax may need to be reconciled if the CO₂ must be vented to the atmosphere. Since some of these costs depend on the existence of other active geologic CO₂ storage reservoirs and their connection to a CO₂ source through a pipeline network, reservoir leakage risk may affect the choice of reservoirs and pipeline routes to deploy. The redundancy may be important for the successful operation of a CCS system to mitigate CO₂ emissions.

In this work, we investigated the optimal deployment of CCS infrastructure that is robust to reservoir leakage risk. We investigated the characteristics of CCS infrastructure and its relationship with reservoir leakage risk on a case study in the Michigan Sedimentary Basin. To do so, we integrated estimates from two major models: (1) the Leakage Risk Monetization Model (*LRiMM*) [3] estimates monetized leakage risk (MLR) for potential geologic CO₂ storage reservoirs, and (2) the Scalable infrastructure model for CO₂ Capture and Storage (*SimCCS*) [4,5]. The resulting cost-minimized geospatial deployment of CCS systems highlights important characteristics of deployment that should be manageable if CCS is to be deployed at a scale meaningful enough to contribute to climate change mitigation.

Nomenclature

FOAK First-of-a-Kind

LRiMM Leakage Risk Monetization Model

MLR Monetized Leakage Risk

NOAK Nth-of-a-Kind

SimCCS Scalable infrastructure model for Carbon Capture and Storage

2. Methods and Data

2.1. Case Study: Michigan Sedimentary Basin

The Michigan Sedimentary basin has 57 named sedimentary formations that have been classified into sixteen hydrostratigraphic units [1]. Within the basin, the Mt. Simon sandstone is one of two target aquifers for geologic CO₂ storage and has an estimated storage capacity up to 29 GtCO₂ [6]. We used a 3D geospatial model of the basin that was previously constructed to investigate the MLR of geologic CO₂ storage, which locates 45,000 existing wells as potential leakage pathways amid the depths, thicknesses, permeabilities, and porosities of each of the hydrostratigraphic units in the basin as these properties vary through the basin [1]. To assess the basin-scale potential for MLR and CCS infrastructure, we used a prior grid of 42 potential CO₂ injection locations into the Mt. Simon Sandstone that are uniformly spaced 50 km apart throughout the U.S. state of Michigan [7].

2.2. Major models

2.3. The Leakage Risk Monetization Model (*LRiMM*)

In order to estimate the MLR of a potential CO₂ injection location, the *LRiMM* integrates probabilistic injection and leakage simulations of emplaced CO₂ and displaced brine in three-dimensional data for hydrostratigraphic sequences and the locations of wells as leakage pathways [1] with the economic costs of leakage [8]. The estimated MLR depends in part on the geospatial characteristics of injection sites, their proximity to wells as leakage pathways, the other subsurface activities, the extent of the leakage, the outcomes of that leakage, and the financial consequences of those outcomes. Some of those financial consequences depend on the ability to redirect CO₂ away from a leaking reservoir to another injection location, or if that CO₂ must be vented to the atmosphere. The *LRiMM* also allows stakeholders to understand how siting assessments can reduce MLR, as well as how detecting and remediating leakage can reduce the MLR of a CO₂ injection location [3].

In the application for the present work, we used data for the Mount Simon and a probabilistic approach that was established in prior work [1]: (a) Monte-Carlo simulations that draw values from distributions for unit porosity and correlated unit permeability, and (b) a bounding analysis of the well leakage pathway permeability of 10⁻¹⁰ m², 10⁻¹² m², 10⁻¹⁴ m², and 10⁻¹⁶ m². We used four different leakage permeabilities: well leakage permeabilities are assigned to

all of the wells in the basin above the distributions. These leakage estimates are worst-case situations because: (i) the well leakage permeabilities are above empirically-established leakage permeabilities, and (2) we assigned them to every well in the basin. We conducted 500 simulations with each of the leakage permeabilities and thus each of the 2,000 simulations for the 42 sites held a unique combination of aquifer permeability and leakage permeability.

2.4. The Scalable infrastructure Model for CCS (*SimCCS*)

The *SimCCS* is an engineering-economic geospatial-optimization model that optimally determines infrastructure deployment for CO₂ capture, CO₂ transport, and geologic CO₂ storage. The *SimCCS* requires estimated costs and capacities for each potential source from which CO₂ could be captured and for each reservoir into which CO₂ could be geologically stored. The *SimCCS* also applies a pre-optimization algorithm to a geospatial cost surface to determine candidate pipeline routes between all combinations of sources and reservoirs [9,10]. From these candidate source, sink, and routes, the *SimCCS* determines how much CO₂ should be captured from each source, how much CO₂ should be stored in each reservoir, and the optimal pipeline routes and capacities to connect sources with reservoirs with a CO₂ pipeline network [4]. The following subsections provide more detail on how the costs and capacities were determined for each individual CO₂ source and each individual CO₂ storage reservoir.

2.4.1. CO₂ sources and capture costs

We used the emissions & GeneRation Integrated Database (*eGRID*) [11] to identify and locate 29 coal-fired power plants and their CO₂ emissions, in the U.S. State of Michigan. The total amount of CO₂ that could be emitted by these 29 CO₂ sources is 120 MtCO₂/yr. The costs to capture CO₂ for each individual source, were estimated with the Integrated Environmental Control Model (*IECM*) [12]. The *IECM* considers fuel properties, plant design, and cost factors to produce a systematic cost and performance analyses of emission control equipment at coal-fired power plants. For each coal-fired power plant, the *IECM* estimated the fixed costs, variable operations & maintenance (O&M) costs and fixed O&M costs. The estimated costs and CO₂ emissions of each individual CO₂ source are provided in Table A1, and were integrated into the *SimCCS*.

2.4.2. CO₂ storage locations, costs, and capacities

As in prior work [13], we estimated the costs and capacities to store CO₂ in each reservoir from a spreadsheet version of the *CO₂-PENS* model [14]. The *CO₂-PENS* platform is a comprehensive system-level computational model used to assess the overall performance of the CCS system, the results of which have been analyzed with reduced-order models to produce a tractable and computationally efficient tool for quickly estimating geologic CO₂ storage costs and capacities for individual locations [15–17]. In the present work, the reduced-form approach was applied to each of the 42 potential CO₂ storage locations. Table A2 shows the estimated CO₂ storage costs and MLR for each potential CO₂ storage reservoir, which include fixed costs and variable O&M costs.

For the MLR, we used data from the *LRiMM* for each of 42 potential CO₂ storage reservoirs that was previously used to investigate the role that the physical and economic consequences of leakage from CO₂ storage reservoirs has on the optimal deployment of energy systems worldwide in order to achieve climate goals [7]. In the present work, we used two estimated MLRs for each of the 42 potential CO₂ storage reservoirs. When the leakage risk was considered in the estimated costs of CO₂ storage, we added the MLR for each CO₂ storage reservoir to the variable O&M costs for that reservoir in two ways:

- (1) *First-of-a-Kind* (FOAK) costs, which do not consider the reduction in MLR from re-directing CO₂ away from leaking reservoirs; and
- (2) *Nth-of-a-Kind* (NOAK) costs, which do consider the reduction in MLR from re-directing CO₂ away from leaking reservoirs.

The prior work used only FOAK MLR estimated from *LRiMM* [7]. Here, we incorporated the FOAK MLR and the NOAK MLR into the analysis according to three scenarios for leakage and the state of deployment of CCS infrastructure.

2.5. Scenarios for leakage and the state of CCS infrastructure deployment

We investigated three scenarios that represent different states of CCS infrastructure deployment and consideration of leakage risk:

- (1) A **base case** scenario where MLR is not considered for any of the potential CO₂ storage reservoirs.
- (2) A **Naïve FOAK** scenario, where each reservoir is assigned its unique FOAK MLR.
- (3) A **Robust-to-Leakage** scenario where each reservoir is assigned its unique NOAK MLR if CO₂ can be directed to more than one reservoir, in the event of leakage (Figure 1).

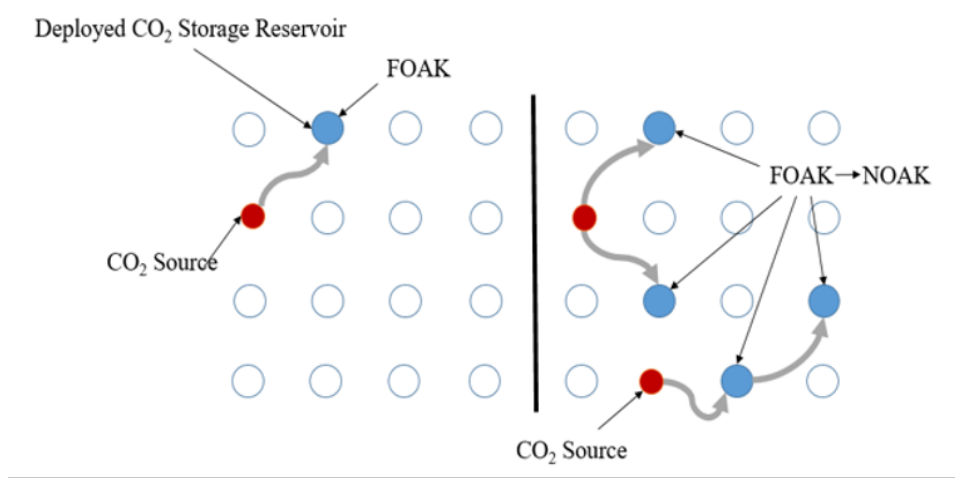


Fig. 1. Method for evaluating reduction in MLR when CCS deployment redundancy exists in the Robust-to-Leakage scenario. Blue = Deployed CO₂ storage reservoir; Red = Deployed CO₂ source; Gray = Deployed CO₂ pipeline.

2.6. Implementation

The CCS infrastructure deployments for the **Base Case** and the **Naïve FOAK** scenarios were determined by running the *SimCCS* to optimize the system for every CO₂ capture target from 1 MtCO₂/yr to 120 MtCO₂/yr, at 1 MtCO₂/yr increments. For the **Robust-to-Leakage** scenarios, the same CO₂ capture targets were implemented in the *SimCCS*, but if a redundant reservoir deployment occurred, the FOAK MLR costs were replaced with the NOAK MLR costs for that reservoir, for every remaining (higher) CO₂ capture target. As a result, at higher CO₂ capture targets, with more extensive CCS infrastructure deployment, the likelihood that the FOAK MLR is replaced with the NOAK MLR increases. Figure 2 shows this iterative method.

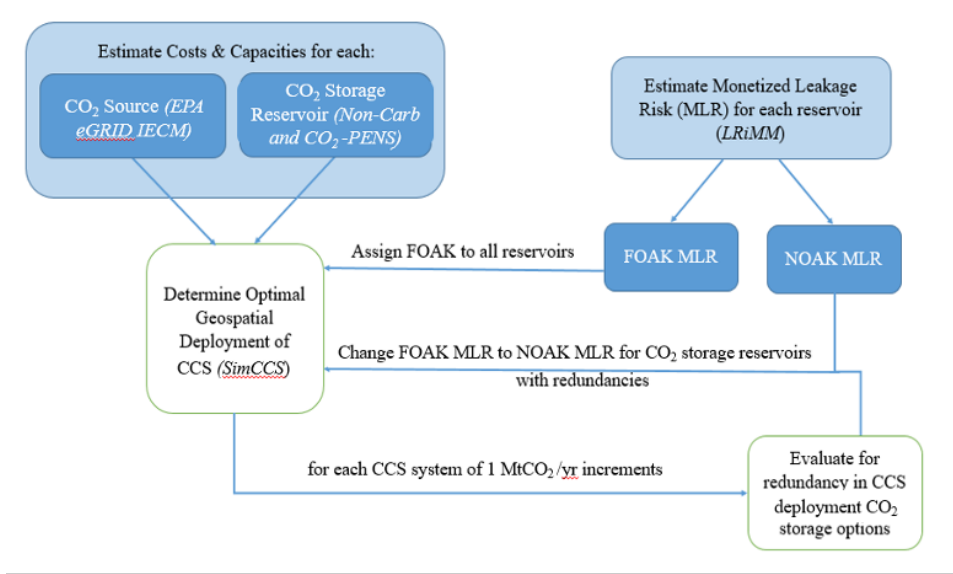


Fig. 2. The Iterative Process for Determining CCS infrastructure that is Robust to Leakage Risk.

3. Results

3.1. Monetized Leakage Risk (MLR)

Figure 3 shows the rank-ordering of each type of MLR (FOAK or NOAK) for each of the 42 potential CO₂ storage locations. Each marker represents a unique CO₂ storage reservoir. The majority of the injection locations have low MLRs; for example, there are fifteen reservoirs with an FOAK MLRs, and twenty with NOAK MLR, below \$2/tCO₂. In this region, only one reservoir switches in rank-order, which occurs between 10 and 11. Aside from that switch, the rank-ordering remains constant for the twenty reservoirs with the cheapest MLRs. Further, almost all of the reservoirs (38) have NOAK MLRs below \$5/tCO₂, and 27 of them have MLRs below \$5/tCO₂. The difference between FOAK MLR and NOAK MLR increases progressively down the rank-ordering, which suggests that a primary component of the MLR is due to the costs associated with not having an alternative reservoir available.

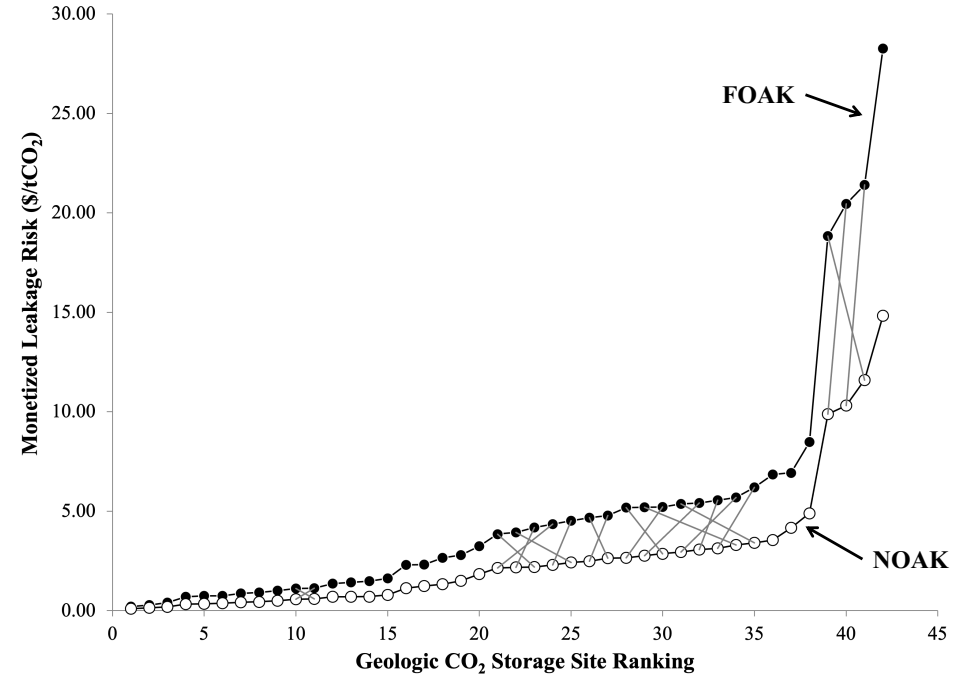


Fig. 3. MLR rank-ordering for 42 potential CO₂ storage reservoirs in the U.S. state of Michigan, including where there is a switch in the rank-order of the individual reservoirs

3.2. Geospatial deployment

Figure 4 shows the differences in the spatial distribution of the injection locations that are deployed according to the three scenarios, where almost all of the CO₂ emissions from coal-fired power plants in the U.S. state of Michigan is captured and stored.

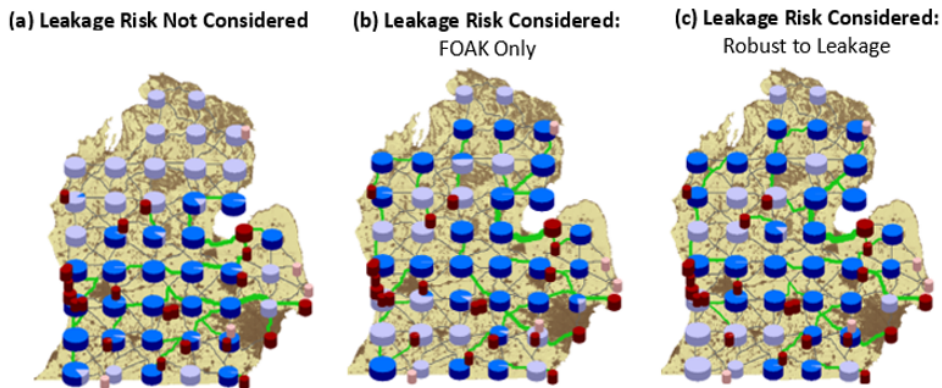


Fig. 4. Optimal deployment of CCS infrastructure for the scenarios that we Investigated: 120 MtCO₂/yr. Green=deployed route; Red = portion of CO₂ from source that is captured; Blue = portion of reservoir capacity that is occupied by stored CO₂.

There is a higher spatial variation in CCS infrastructure between scenarios where leakage risk is not considered (Figure 4a) and when it is considered (Figures 4b and 4c). First, there is more deployment of reservoirs in the northern portion of Michigan when leakage risk is considered. Second, almost all of the same reservoirs are deployed. Third,

these reservoirs are deployed with higher storage utilization when the system is robust to leakage risk. Fourth, as Figure 5 shows, there tends to be more reservoirs deployed when MLR is considered, especially at higher CO₂ storage rates. At a storage rate of 20 MtCO₂/yr, five CO₂ storage reservoirs are deployed in all of the scenarios. At the highest CO₂ storage rate of 120 MtCO₂/yr, there are 25 reservoirs deployed in the **Base Case**, 28 reservoirs deployed in the **Naïve FOAK** scenario, and 27 reservoirs deployed in the **Robust-To-Leakage** scenario.

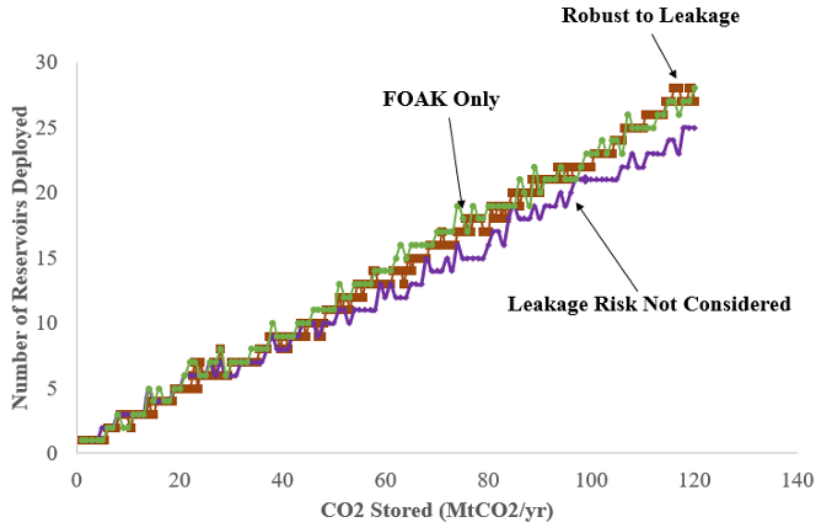


Fig. 5. MLR supply curve for 42 potential CO₂ storage reservoirs in Michigan CCS system

3.3. Average costs of the integrated CCS system

Across all the scenarios, the average cost of the integrated CCS system decreases until about 20 MtCO₂/yr are stored. At that size of the system, the average costs flatten and increase slightly until 11 MtCO₂/yr systems (Figure 6). Compared to the **Base Case** when leakage risk is not considered, the average costs of a **Robust-to-Leakage** system is ~\$7/t CO₂ more expensive, and the **Naïve FOAK** system is ~\$7.50/tCO₂ more expensive.

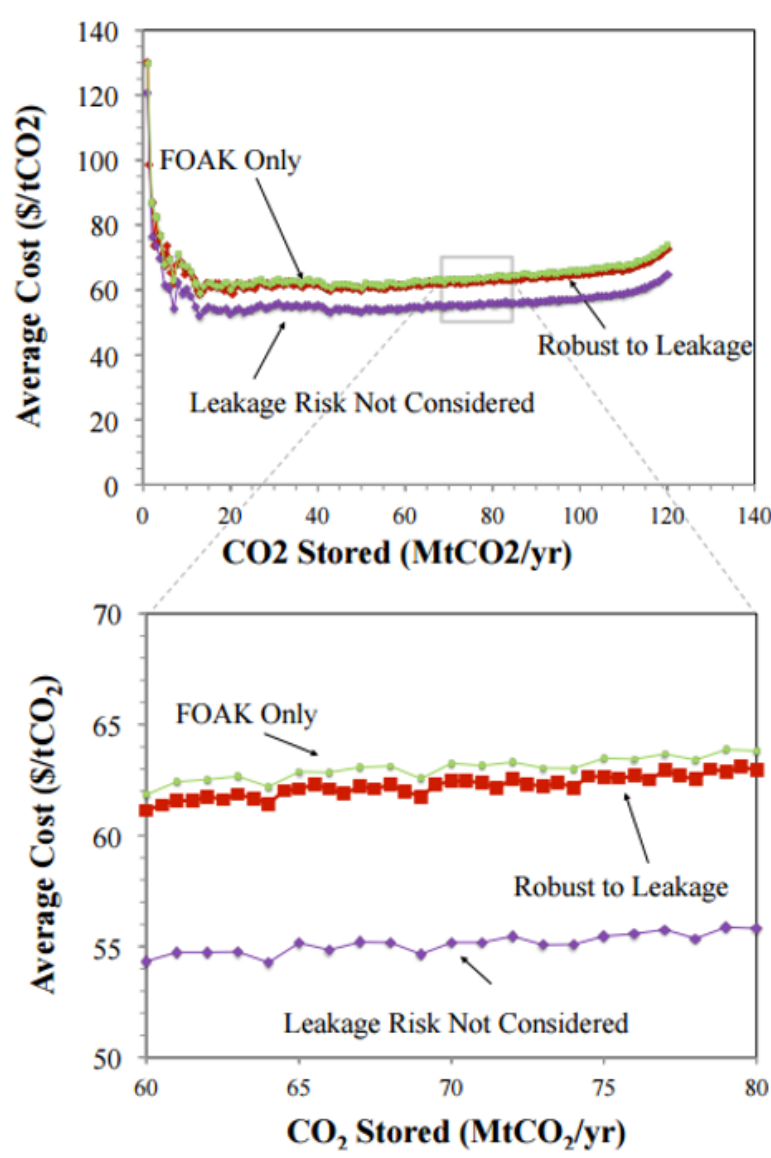


Fig. 6. Average Costs of the Integrated CCS System for the Three Scenarios that we Investigated

3.4. CO₂ pipeline length

In general, total pipeline length increased when leakage risk was considered (Figure 7). At a CO₂ storage rate of 20 MtCO₂/yr, the **Naïve FOAK** and **Robust-to-Leakage** systems required about 475 kilometers of CO₂ pipelines, whereas the **Base Case** systems that do not consider MLR only required about 300 km. From systems that store about 30 MtCO₂/yr to about 45 MtCO₂/yr, however, the **Robust-to-Leakage** and **Base Case** systems required about the same length of CO₂ pipelines. At higher CO₂ storage rates, up to about 75 MtCO₂/yr, **Naïve FOAK** systems required more pipeline length than **Robust-to-Leakage** systems, which in turn required more pipeline length than **Base Case** systems. For larger systems, the scenarios that considered leakage risk, **Naïve FOAK** and **Robust-to-Leakage**, required about the same length of CO₂ pipelines, and more than the **Base Case** systems.

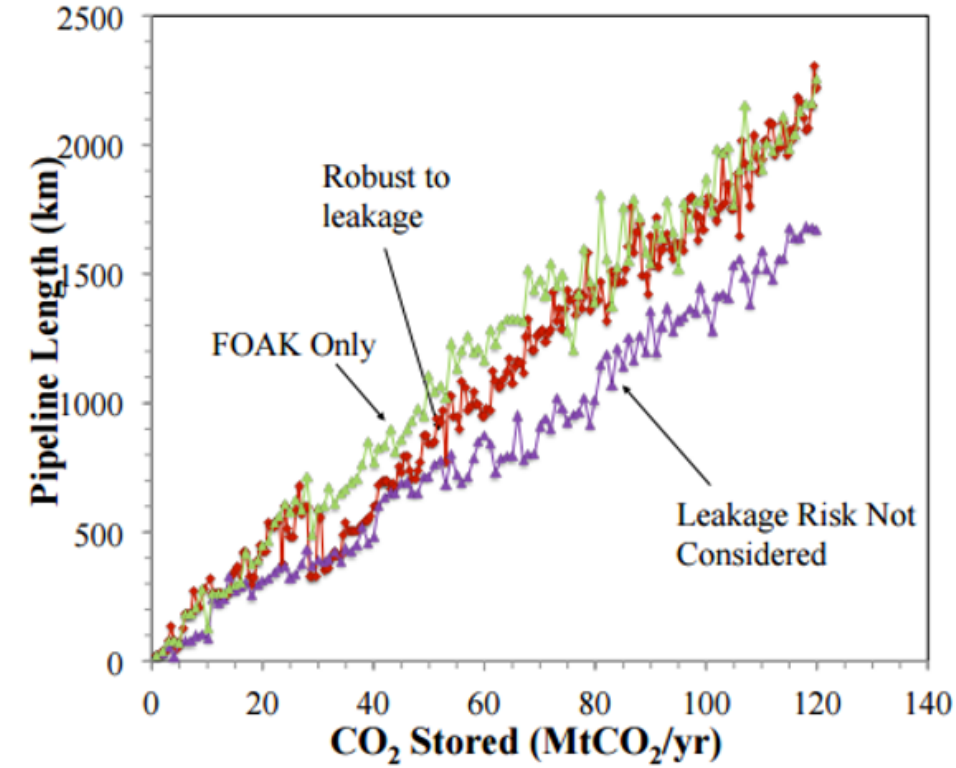


Fig. 7. Total length of CO₂ pipelines

4. Conclusions

To investigate integrated CO₂ capture, transport, and storage (CCS) systems that are robust to reservoir leakage risk, we developed and implemented an approach that integrates estimates of monetized leakage risk (MLR) for potential geologic CO₂ storage locations from the Leakage Risk Monetization Model (*LRiMM*) into the Scalable infrastructure model (*SimCCS*) to determine the optimal deployment of systems that are robust to reservoir leakage. In a case study of geologic CO₂ storage in the Mt. Simon sandstone in the Michigan Sedimentary Basin, we found that the ordering of locations where it is desirable to store CO₂ may change when reservoir leakage risk is considered, but assuring a redundancy in infrastructure to redirect CO₂ away from leaking reservoirs reduces the likelihood that the system might not be able to accommodate CO₂ and has negligible impact on system-wide costs. The results highlight the importance CO₂ infrastructure system that is robust to leakage, which may differ spatially and economically from a system that is susceptible to interruptions due to a leaking reservoir.

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Appendix A: Estimated costs

Table A1. Estimated costs and CO₂ emissions of coal-fired power plants in the U.S. state of Michigan

Source ID	Fixed Costs (\$M)	Fixed O&M Costs (\$M/y)	Variable O&M Costs (\$/tCO ₂)	CO ₂ Capture Potential (MtCO ₂ /y)
1	356.30	11.34	118.18	0.92
2	1034.00	38.19	26.94	3.06
3	3237.00	85.33	25.54	12.30
4	45.20	15.70	465.43	0.02
5	83.49	16.73	150.41	0.06
6	1504.00	48.53	17.86	4.97
7	70.02	16.38	205.31	0.04
8	886.50	35.00	11.94	2.51
9	284.90	21.65	32.50	0.48
10	590.50	28.32	29.79	1.50
11	3563.00	91.89	24.94	13.88
12	1049.00	38.52	25.57	3.12
13	321.60	22.51	24.50	0.57
14	1279.00	28.72	18.88	3.68
15	294.40	21.88	19.90	0.50
16	28.39	15.21	1346.74	0.01
17	35.87	15.43	750.91	0.01
18	366.70	11.48	133.62	0.92
19	1834.00	40.43	29.03	6.15
20	7955.00	175.10	19.58	29.80
21	1634.00	35.54	25.64	4.83
22	1544.00	49.38	18.55	5.15
23	3473.00	90.29	16.49	13.48
24	301.70	22.04	37.39	0.52
25	2000.00	59.21	15.34	7.07
26	353.90	11.35	74.16	0.92
27	355.60	11.31	135.79	0.92
28	107.10	17.34	112.48	0.10
29	1008.00	23.52	63.87	2.76

Table A2. Estimated costs and monetized leakage risk for potential CO₂ storage locations in the Michigan Sedimentary Basin

Source ID	Fixed Costs (\$M)	Fixed O&M Costs (\$M/y)	Variable O&M Costs (\$/tCO ₂)	CO ₂ Capture Potential (MtCO ₂ /y)
1	18.18	3.00	8.20	10.86
2	18.18	3.02	9.22	12.35
3	18.18	2.97	24.37	34.69
4	18.18	3.02	7.53	9.84
5	18.18	2.99	31.25	46.07
6	18.18	2.98	4.46	5.16
7	18.18	3.04	3.78	4.13
8	18.18	3.90	8.24	10.39
9	18.18	3.01	9.85	13.39
10	18.18	2.99	8.40	11.17
11	18.18	2.96	7.15	9.32
12	18.18	2.96	11.44	16.34
13	18.18	3.00	8.54	11.62
14	18.18	3.01	3.87	4.28
15	18.18	3.04	7.72	10.35
16	18.18	3.01	21.85	33.45
17	18.18	3.04	5.34	6.48
18	18.18	2.97	4.39	5.09
19	18.18	2.94	4.57	5.36
20	18.18	2.79	9.72	13.88
21	18.18	2.99	6.93	9.35
22	18.18	3.04	3.96	4.40
23	18.18	3.22	4.24	4.74
24	18.18	2.87	8.06	10.92
25	18.18	3.04	7.82	10.30
26	18.18	2.98	5.63	6.96
27	18.18	2.96	4.09	4.67
28	18.18	2.94	5.73	7.24
29	18.18	2.91	6.75	8.95
30	18.18	2.95	8.31	11.72
31	18.18	2.81	3.50	3.83
32	18.18	3.23	3.98	4.35
33	18.18	3.14	23.59	33.47
34	18.18	3.01	8.70	11.64
35	18.18	2.98	5.30	6.53
36	18.18	3.01	4.37	5.06
37	18.18	2.88	6.12	7.96
38	18.18	2.93	3.34	3.54
39	18.18	3.04	3.25	3.35
40	18.18	3.23	8.43	11.74
41	18.18	3.19	4.31	4.90

42

18.18

2.96

3.23

3.38

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