Geological Carbon Sequestration: A Performance and Economic Risk Analysis
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ABSTRACT

There is growing interest surrounding the economic and performance risks associated with carbon sequestration technologies. Wide-scale carbon sequestration is one of several options that may reduce the amount of carbon dioxide (CO_2) emitted each year. Sequestration allows for the burning of fossil fuels to continue along a 'business as usual' path, and provides a low cost method to help curb CO_2 emissions. However, like most technologies looking toward large-scale deployment, many issues regarding economic and performance risk remain to be characterized. The Carbon Sequestration and Risk (CSR) model has been developed to provide a high-level, user-friendly approach to quantifying both the performance and economic effectiveness of carbon sequestration and geologic storage.

The CSR model approaches performance risk in two ways. Sequestration risk determines whether carbon sequestration in leaky reservoirs will prove to be an effective strategy toward restricting atmospheric CO_2 to desired levels. The risk lies in whether or not enough CO_2 can be sequestered each year to offset both the emissions from fossil fuel consumption and the potential emissions from CO_2 leaking from sinks that store previously sequestered CO_2. Another facet of sequestration risk, relative capacity risk, calculates whether there is the necessary capacity in geologic reservoirs to store the sequestered CO_2. The second approach the CSR model takes to address performance risk is through economic risk. Economic risk would determine whether select carbon sequestration technologies can be deployed at an economically viable level and still meet the environmental goals of sequestration. Economic risk is a net present value (NPV) comparison of storage in permanent reservoirs and storage in leaky reservoirs. By analyzing different scenarios in the CSR model, a policy maker or researcher is able to assess conditions under which carbon sequestration would be an economically effective strategy of addressing global CO_2 emissions.

Introduction

The CSR model is a user-friendly, high-level dynamic simulation computer model, written in Powersim Studio (a dynamic simulation modeling language) that calculates risk and effectiveness of carbon sequestration schemes. The model allows the user to easily conduct sensitivity analysis for a number of key variables, including: CO_2 permit price, discount rate, reservoir leak rate, reservoir leak rate distribution and sequestration cost. For any combination of assumptions, the effective lifetime of a sequestration scenario is calculated. The goal of the CSR model is to improve the understanding of carbon sequestration from a performance risk standpoint.

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Model Structure

The CSR model includes sequestration options for both global policy discussions and region-specific investment decisions. The model calculates performance and economic effectiveness over a 300 year timeframe using leak rate as the model step. Each step equals a 0.01% increase in leak rate. By running the model on leak rate rather than time the model can determine how many years a sequestration scenario is effective, addressing the performance risk aspects of the scenario. The net present value of the scenario is also calculated and compared to permanent sequestration for additional context. The CSR model uses the three effectiveness calculations (sequestration, capacity, economic) as a way of rating sequestration scenarios. Figure 1 outlines the CSR model's structure.

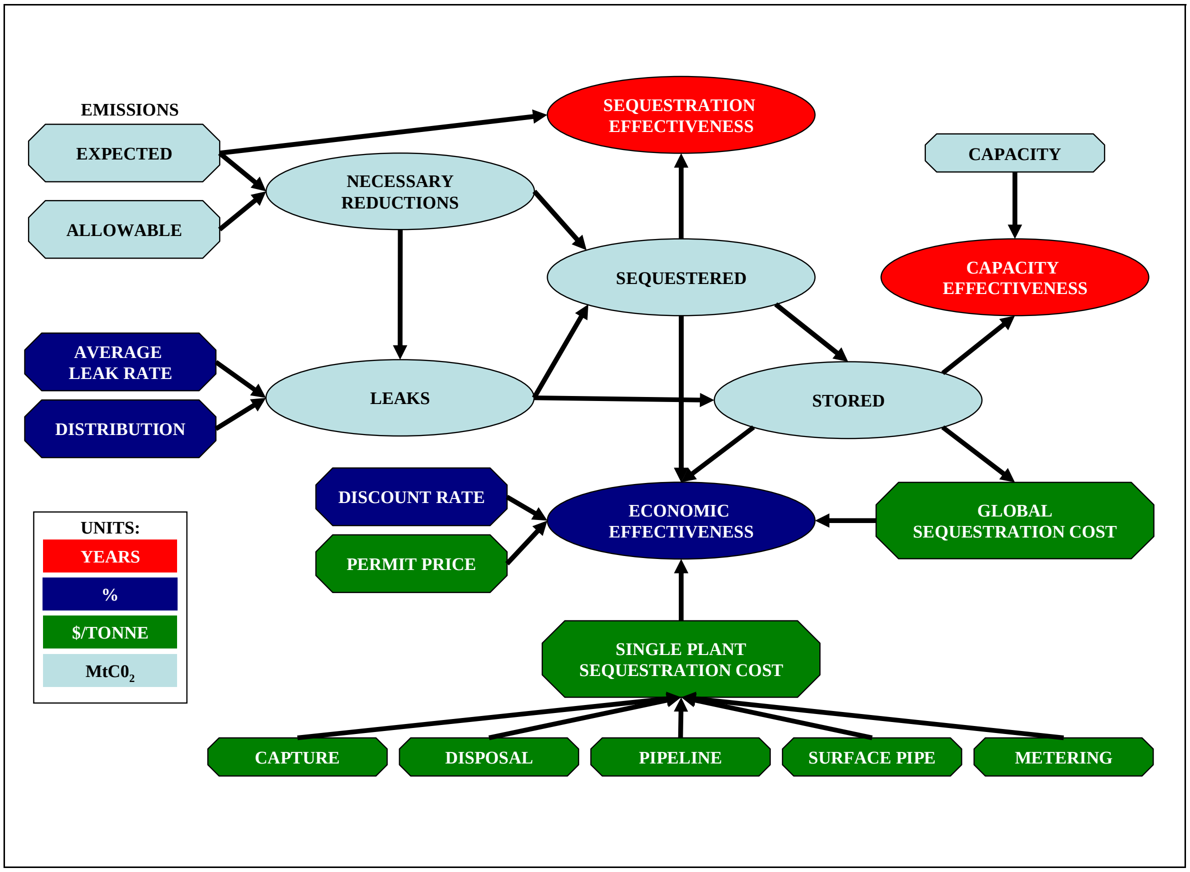
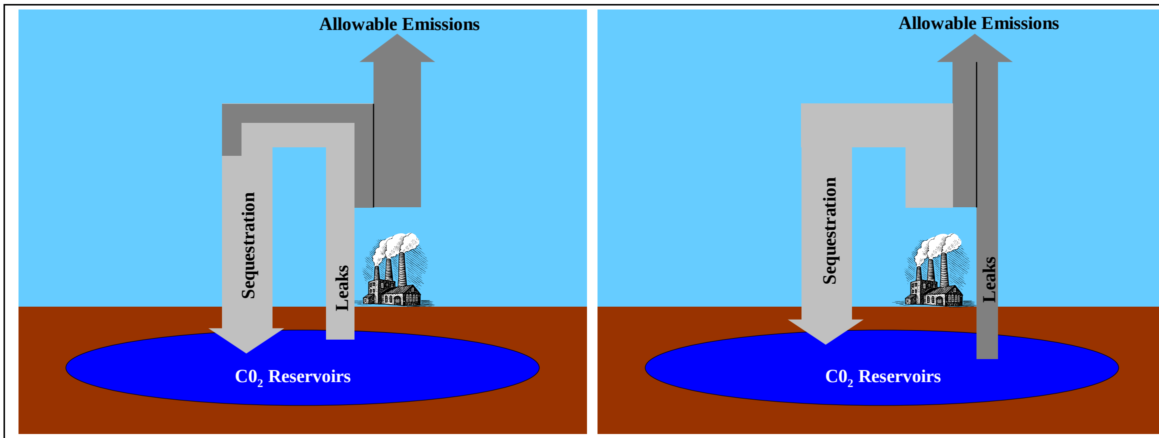


Figure 1. The Carbon Sequestration and Risk Model Structure

Performance effectiveness

Performance effectiveness metrics quantify how many years a sequestration scenario will effectively keep emissions at a desired level. Two methods are used to calculate performance effectiveness. Sequestration effectiveness calculates the number of years that CO_2 can be sequestered to achieve an atmospheric level consistent with policy goals and was adapted from Pacala (2001). Capacity effectiveness calculates the corresponding number of years that reservoirs can store enough CO_2 to keep emissions at similar levels.

Sequestration effectiveness is based on four variables: expected CO_2 emissions, allowable CO_2 emissions, the average leak rate of the storage system, and the statistical distribution of those leak rates across the storage system. The model assumes that all CO_2 emissions beyond allowable levels are sequestered. Additionally, any leaks from previously sequestered CO_2 must be accounted for in the overall emissions budget. Leaks from underground reservoirs are difficult to capture, but can be monitored. Monitoring the leaks, and sequestering an equivalent amount of fossil emissions, provides the same results as the capturing and sequestering all leaks (figure 2).



Source: adapted from Pacala 2001

Figure 2. Equivalent Sequestration Systems

The leak rate of the storage reservoirs is the key variable in this analysis. The higher the leak rate, the less likely it will be that sequestration can effectively hold emissions at the allowable level. If the storage sinks' leak rates are heterogeneous, a natural process of concentrating CO_2 into safer sinks takes place. As a result, the more heterogeneous a storage system is, the more likely it will be that sequestration can hold emissions at allowable levels. The heterogeneity of the systems leak rate is described in the leak rate section of this paper.

Capacity effectiveness determines how many years sequestration will last given a limited amount of storage capacity. When the cumulative sum of the CO_2 stored is greater than the total capacity, the sequestration scenario would not be effective from a performance perspective. When a high leak rate causes sequestration to fail, less CO_2 is injected into the sinks than required. Less capacity is used, and therefore capacity effectiveness increases.

Economic Effectiveness

Economic effectiveness is the ratio of NPV costs, for an identical sequestration scenario, for leaky storage and permanent storage. This ratio provides a *percent effective statistic* that can be compared between scenarios. The basic methodology for the economic effectiveness calculation is based on the work of Herzog et al. (2003).

Permanent storage is represented two ways in the CSR model. Permanent sequestration assumes that storage is taking place in geologic reservoirs that do not leak, and is considered to be the best case scenario for geologic sequestration. Permanent sequestration costs differ from the leaky sequestration costs because permanent geologic sequestration does not have to deal with reservoir leaks. The total costs of permanent and leaky sequestration include credits for any CO_2 permits sold.

The model also compares the sequestration scenario to an identical scenario achieved through the buying of CO_2 permits in a global trading system. If permits are bought, and never sold, then the amount of CO_2 equal to the number of permits bought is sequestered permanently.

When economic effectiveness is calculated using permits as the comparison, the final sequestration costs for leaky storage are not offset by permits sold. The comparison using CO_2 permits offers a different method of permanent sequestration for the economic effectiveness calculation.

Emissions

Variables in the CSR model are input as 'paths' spanning 300 years. The main inputs are the allowable and expected emissions curves (million tons[1] CO_2). The expected emissions curve represents emissions per year assuming a 'business as usual' scenario for annual CO_2 emissions. The allowable emission curve represents emissions per year that would be acceptable. The difference between the two curves gives the amount of CO_2 that needs to be captured and sequestered. Assuming that sequestration is completely effective for 300 years, fossil fuels could be burned so that emissions would match the expected emissions curve, but after sequestration, actual CO_2 emissions would only equal the allowable emissions curve.

In the global scenario, the base case emissions curves are based on the International Panel for Climate Change (IPCC) atmospheric concentration stabilization goals. The curves were derived from Pacala (2001) and represent the amount of CO_2 emissions that would meet atmospheric CO_2 stabilization goals (table 1). The expected emissions curve is the S750 emission scenario, where the 750 refers to the eventual atmospheric concentration of CO_2. Allowable emissions match the S450 (default case) or the S550 scenarios. The user can define either emission curve by inputting expected values at 50 year increments, as the model projects growth rates to complete the curves. The user is also able to 'draw' the expected and allowable emissions curves to any shape.

Table 1. Global Scenario Base Case Emission Curves (Mt$C0_2$/Year)

	Expected (S750)	Allowable (S450)	Allowable (S550)
2000	8500	7900	8000
2050	13000	6200	8200
2100	13200	3800	8100
2150	9500	3000	4800
2200	7000	2000	3600
2250	4200	1900	2400
2300	4000	1800	2300

The single plant scenario of the CSR model allows the user to select different electricity production and capture technologies. The single plant scenario can employ coal or natural gas plants, existing or new, with capture technology (table 2). Expected emissions are calculated using the reference plant data, assuming no capture technology. The electricity plant characteristics are from the IPCC (2005). The model user can adjust the annual allowable CO_2 emissions for the 300 year model run. To account for different $C0_2$ capture efficiencies the model calculates the potential reductions of a single plant and uses this number to determine whether the sequestration goal will be met.

[1] Metric tonnes

Table 2. Plant and Capture Characteristics (IPCC 2005)

	Existing		New	
	Coal	**Gas**	**Coal**	**Gas**
Reference Plant Size (MW)	470	507	524	527
Net Plant Size (MW)	275	423	492	492
Reference Emission Rate (tons/MWh)	0.9	0.4	0.8	0.8
Capture Emission Rate (tons/MWh)	0.2	0.04	0.1	0.1
Ref Cost of Electricity ($/MWh)	18	43	46	61
Capture Cost of Electricity ($/MWh)	70	59	74	79
Potential Avoided Emissions ($MtC0_2$/Year)	2.8	1.2	2.8	2.9
Reference Cost of C02 Avoided ($/ton)	67	49	40	25
Plant Life (years)	20	20	25	25
Capacity Factor (%)	81	81	85	85

Leak Rate

The average leak rate of the sink system is assumed to be constant over time and the base case scenario assumes that the leak rate is heterogeneous. The model assigns a distribution around the mean leak rate to account for varying leak rates across the sinks[2]. The user sets the distribution around the mean using either a normal or uniform distribution. If the reservoir system is heterogeneous, as time passes more CO_2 will be stored in reservoirs with the lowest leak rates. As a result, the amount of carbon that actually leaks out of the sinks is less than the amount that would leak out if the leak rate was assumed to be homogenous (table 3).

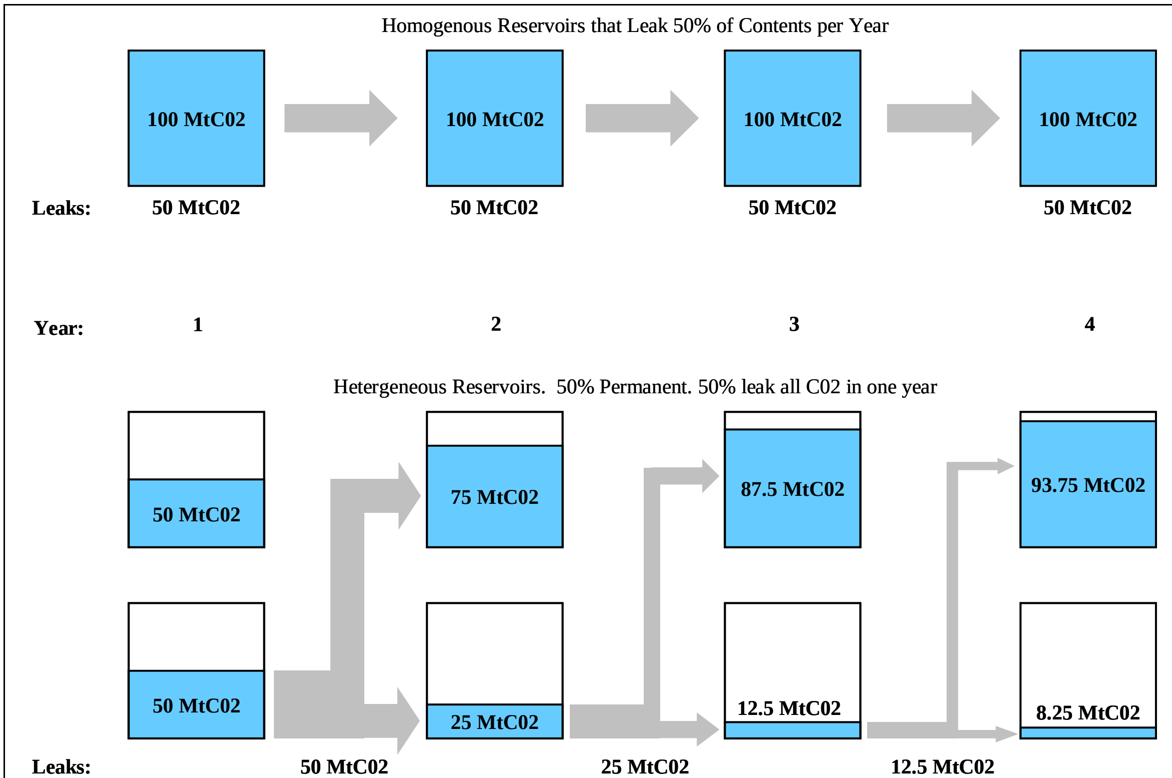
Table 3. Reference Case Stored and Captured Emissions for Various Leak Rate Distributions (Average Leak Rate = 0.20%)

	Stored ($MtCO_2$)	**$MtC0_2$ Captured to Meet S450 Emissions Standard**			
		Homogeneous	**Std Dev = .25%**	**Std Dev = 1%**	**Uniform = .19%**
2000	600	601	601	601	601
2050	6800	7170	7170	7168	7157
2100	9400	10583	10581	10567	10528
2150	6500	8475	8471	8432	8357
2200	5000	7548	7542	7468	7357
2250	2300	5211	5200	5088	4943
2300	2200	5335	5322	5170	4992

Heterogeneity across sinks would help concentrate CO_2 into sinks with the lowest leak rates even if each sink's leak rate is unknown. A simple example will demonstrate this concept (figure 3). A single reservoir with a leak rate of 50% per year that is storing 100 $MtCO_2$ will leak 50 $MtCO_2$ per year. To hold the storage constant at 100 $MtCO_2$, 50 $MtCO_2$would need to be injected every year required to store the 100 $MtCO_2$. An equivalent storage system could be two

[2] Since leak rates cannot be less than 0, the distribution is truncated when the full distribution does not fall below zero. The section of the distribution curve that had to be truncated is distributed normally and added to the truncated distribution.

sinks, one with a leak rate of 100% per year and one with a leak rate of 0%. In the first year, each would hold 50 $MtCO_2$, and 50 $MtCO_2$ would leak out from the sink with the 100% leak rate. The next year, 25 $MtCO_2$ would be injected into each sink. Therefore, the permanent sink would store 75 $MtCO_2$, and the leaky sink would store 25 $MtCO_2$. The leaks from the second year would only be 25 $MtCO_2$, because there was less CO_2 in the leaky sink. In the third year, only 12.5 $MtCO_2$ would be put into the leaky sink and therefore 12.5 $MtCO_2$ would leak. Over time, less CO_2 is being injected into the leaky sink, and more CO_2 is being injected in the permanent sink. Even though the average leak rate of the 2 sinks is 50%, as time passes, less than 50% of the CO_2 is leaking out each year. The calculated average leak rate of a heterogeneous reservoir system will drop over time, allowing for sequestration to be effective for longer than in a homogeneous reservoir system. Pacala (2001) provided the calculations for the effects of sink heterogeneity.



Source: Adapted from Pacala (2001)

Figure 3. Heterogeneous Versus Homogeneous Sink System

Capacity

In the global scenario, the user can select between storage in used oil reservoirs, storage in used natural gas reservoirs or storage in both. Storage capacity data is from the International Energy Agency (IEA) (2000). In the base case, capacity is constant over 300 years, but the user can apply a growth rate to capacity so it increases over time. In a single plant scenario, capacity is user set to represent the total capacity available to the plant for disposal, but the user does not choose the type of reservoirs for storage. In the global scenario, the type of storage also determines the cost curve for sequestration.

The CSR model incorporates only geologic storage in its calculations of capacity effectiveness. Given the state of the estimates for other types of carbon sinks (deep saline formations, oceans, etc.) capacity estimations may be several orders of magnitude greater than those presented in this model (Herzog 2001). Therefore the lifetime of a global sequestration strategy may last far longer than the estimations of the CSR model.

Table 4. Reference Capacity and Years Effective

	Oil Wells	Natural Gas Wells	Both
Capacity (MtC0$_2$)	126000	797000	923000
Effective Years	40	123	140

Note: Global Reference Scenario capturing difference between S750 and S450 scenarios

Sequestration Cost

Sequestration cost is defined as the cost per ton for capturing and sequestering CO_2 from fossil-fuel based power production. In the global scenario, cost is a function of the type of storage capacity and is based on IEA (2000). Separate curves are calculated for natural gas reservoirs and oil reservoirs. If both oil and gas capacities are available for storage, then the two cost curves are aggregated assuming sequestration would occur in the cheapest reservoirs first. Given that the cost curve is a function of CO_2 stored, the cost of sequestration increases as existing capacity is used. For many scenarios, the amount of CO_2 stored is greater than existing geologic capacity. Therefore projections for the cost of sequestration are calculated beyond geologic capacity limits, based on base case estimates, or user-specific levels. Projections to the cost curve represent the possible costs of other forms of sequestration.

Table 5. Global Sequestration Costs for Existing Geologic Capacity

	Sequestration Cost ($/Ton)		
MtCO$_2$ Stored	**Oil**	**Gas**	**Combined**
1	30	53	30
100	55	65	54
500	-	69	68

The cost of sequestration for the single plant scenario is the sum of capture cost, transport and disposal costs, and metering costs. Capture cost (C_{CAP}), or the cost of CO_2 avoided per ton, is calculated using plant characteristics (table 2) and the following equation (Rao and Rubin 2002).

$$C_{CAP} = \frac{COE_{Cap} - COE_{\mathrm{Re}\,f}}{EMIS_{\mathrm{Re}\,f} - EMIS_{Cap}}$$

where:
COE_{Cap} = Cost of Electricity with Capture ($/kWh)
COE_{Ref} = Cost of Electricity Reference ($/kWh)
$EMIS_{Ref}$ = Emissions Rate for Reference Plant (ton/kWh)
$EMIS_{Cap}$ = Emission Rate for Capturing Plant (ton/kWh)

Transport and disposal cost (C_{TD}) includes pipeline transmission costs (C_{PT}), disposal well costs (C_{DW}), and the cost of surface facilities (C_{SF}). The following section describes the equations and assumptions used to calculated transport and disposal costs. The equations given were developed by Ogden (2002) and Williams (2002). The assumptions used in the equations are summarized in table 6.

$$C_{TD} = C_{PT} + C_{DW} + C_{SF}$$

$$C_{PT} = (C_b((FR_c / FR_b)^{-0.52})((TD_{ss} / TD_b)^{1.24}))$$

where: C_b = Base Cost of Pipeline Transmission
FR_c = Current Flow Rate
FR_b = Base Flow Rate
TD_{ss} = Source to Sink Distance
TD_b = Pipeline Length

$$C_{DW} = \frac{(TC_{DW}(CRF)) + (TC_{DW}(OM))}{SC}$$

where: OM = O&M
SC = Tons of $C0_2$ Sequestered

$$TC_{DW} = Wells * (CC_i + (VC * Depth))$$

where: TC_{DW} = Total Cost of Disposal Wells
CC_i = Initial Capital Cost
VC = Variable Cost
$Wells$ = Number of Disposal Wells = $\frac{Flow_{Well}}{FR_c}$
where: $Flow_{Well}$ = Flow Rate per Well

CRF = Capital Recovery Factor = $\frac{DR}{1-(1+DR)^{-PL}}$

where: PL = Disposal Plant Lifetime
DR = Discount Rate
(Note: CRF equation is taken from Drennen et al. (2002))

$$C_{SF} = 0.138(FR_c - Flow_{\max})^{0.253}$$

where: $Flow_{max}$ = Maximum Flow Rate

Metering costs account for the costs associated with monitoring and metering the CO_2 after it has been sequestered in geologic sinks. The CSR model allows the user to set an initial metering cost, along with a metering cost growth rate. The reference case assumes metering costs of 0.2 $/ton over the span of the model (Benson 2004).

Table 6. Summary of Single Plant Sequestration Assumptions

	Initial Value	Growth Rate	Source
Base Cost of Pipeline Transmission ($/ton)	3.5	-	Ogden 2002
Base Flow Rate (ton/hr)	446	-	Ogden 2002
Source to Sink Distance (km)	100	0	Ogden 2002
Pipeline Length (km)	100	0	Ogden 2002
O&M (%)	4	-	Williams 2002
Initial Capital Cost of Disposal Wells (million $)	1	0	Ogden and Williams 2002
Variable Cost of Disposal Wells (million $/km)	1.25	0	Ogden 2002
Flow Rate per Well (tons/hr)	104	-	Ogden and Williams 2002
Sink Depth (km)	3	0	User Set
Disposal Plant Life	20	0	User Set
Discount Rate	2	0	User Set

The reference case assumes costs are associated with an existing coal plant with capture technology. Capture costs (66.7 $/ton) make up a majority of the total sequestration cost, and pipeline costs (5.5 $/ton) are the next most expensive component in 2000. Disposal costs (0.4 $/ton), surface facilities (0.4 $/ton) and metering (0.2 $/ton) make up smaller portions of the total sequestration costs in 2000. Disposal costs and pipeline costs change over time due to the influences of CO_2 flow rate.

Permit price

The price of a CO_2 permit is the market clearing price for a ton of CO_2. Assuming that a Kyoto-style, global permit trading system is in place over the course of the model, a permit could be sold for each ton of CO_2 that is sequestered, offsetting sequestration cost. In the CSR model, permit price can follow several paths. The user can choose to have permit price change according to an annual growth rate, or increase at the discount rate. If permit price is set to increase at the discount rate, the NPV cost per ton sequestered would be constant for the duration of the sequestration scenario. A maximum permit price can be set by the user to account for ‘backstop technology’ or the use of non fossil fuel energy sources (Herzog 2001). When economic effectiveness is calculated as a comparison to permit price, changes to the price will have significant impacts on the economic effectiveness statistic (table 7). The lower that permit price, the less economically effective sequestration will be compared to permanent sequestration using permits. For example, sequestration in leaky sinks has an economic effectiveness of 99% at permit prices of 50 $/ton. At this permit price, sequestration in leaky sinks would cost, at current price levels, an almost identical amount as permanent sequestration over 300 years. The model also calculates the average cost per ton of all future payments. At permit prices of 50 $/ton, leaky sequestration and permanent sequestration would both cost 2 $/ton.

Table 7. Permit Price Sensitivity Analysis

Permit Price ($/Ton)	Economic Effectiveness (%)	Leaky (NPV$/Ton)	Permanent (NPV$/Ton)
10	20	2	0.4
20	39	2	0.8
30	59	2	1
40	79	2	1
50	99	2	2
60	118	2	2

Note: Global Reference Scenario - Assumes homogeneous sink system with an average leak rate of 0.2%, and economic effectiveness is a comparison with permits. Discount is a constant 5%

Discount rate

The user can change assumptions (initial value, growth rate, maximum value) for the discount rate. The economic effectiveness statistic is highly sensitive to the choice of discount rate (table 8). The higher the discount rate, the less important payments in the future become. As the discount rate increases, economic effectiveness also increases. At a discount rate of 10% the net present value of the sequestration scenario actually becomes less than the net present value of permanent sequestration using permits. This result is even more intriguing because leaky sequestration requires more CO_2 to be captured than is needed to be stored.

Table 8. Discount Rate Sensitivity Analysis

Discount Rate (%)	Economic Effectiveness (%)	Leaky (NPV$/Ton)	Permanent (NPV$/Ton)
1	38	36	13
2	53	12	6
3	64	6	4
4	72	3	2
5	79	2	2
6	84	1	1
7	89	1	0.9
8	94	0.8	0.7
9	98	0.6	0.6
10	101	0.5	0.5

Note: Global Reference Scenario – Assumes homogeneous sink system with an average leak rate of 0.2%, and economic effectiveness is a comparison with permits. Permit price is assumed to be a constant 40 $/ton.

Global Reference Scenario S450 Concentration Level

The CSR Models global reference case determines the effectiveness of a sequestration system that would allow combustion of fossil fuels consistent with the S750 climate stabilization level, but release emissions at the S450 level. The emissions curves assume linear growth rates between the input variables. The CO_2 is stored in heterogeneous natural gas and oil reservoirs, with an assumed standard deviation between the sinks' leak rates of 1%. Permit price has been set at a constant 40 $/ton, and the discount rate set at a constant 2%. The cost of sequestration is determined by the aggregate natural gas and oil curve, and the cost of sequestration beyond capacity limits increases at a similar rate as existing capacity curve. Economic effectiveness is calculated by comparing sequestration in leaky reservoirs to permanent sequestration through the buying of permits.

The CSR model shows that at low leak rates, there is enough global capacity to store CO_2 for 140 years (figure 4). The top graph shows the cumulative amount of CO_2 that would potentially be stored (red), the amount of CO_2 captured in order to sequester the necessary amount of CO_2 (green) and total amount of global storage capacity (blue line). In the 140th year of sequestration, potential CO_2 stored is greater than total capacity.

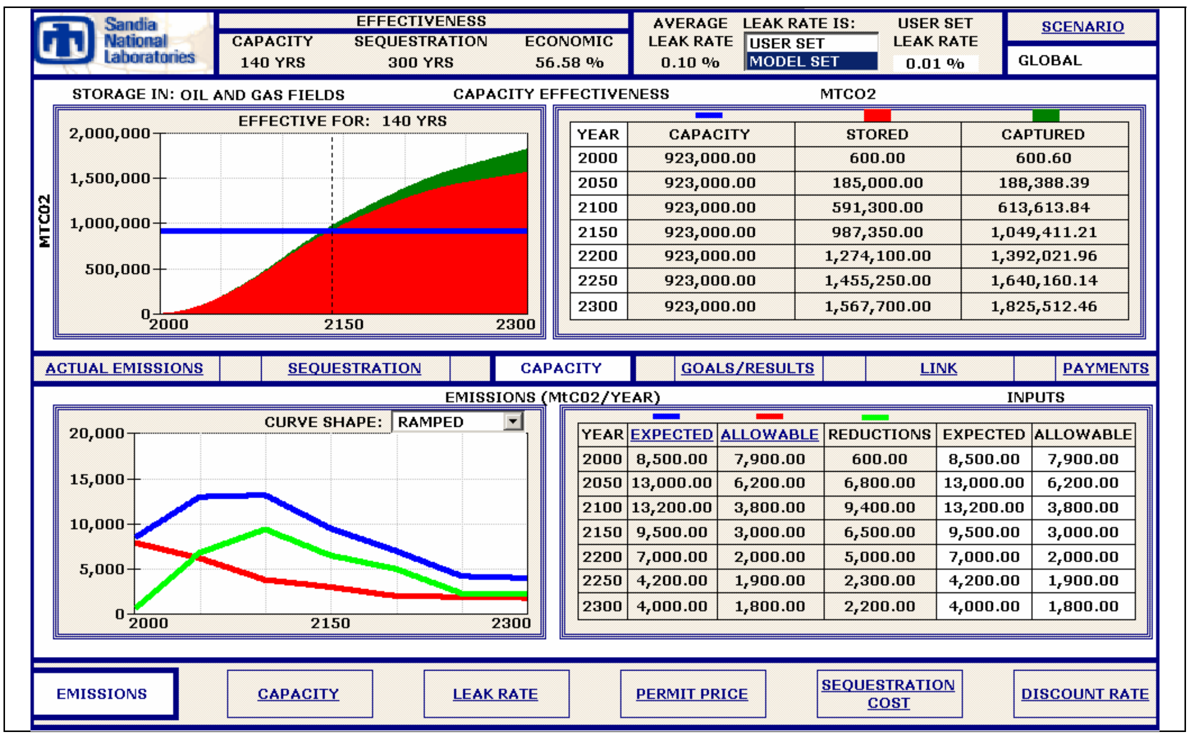


Figure 4. CSR Model's Capacity and Emissions Screen

Table 9 shows the effectiveness of this sequestration scenario at various leak rates. When the leak rate increases to a significantly high level, capacity actually lasts longer. So much CO_2 is leaking out of the sinks that there are not enough emissions to maintain the required amount of CO_2 in the reservoirs. As a result, the reservoirs storing the CO_2 do not reach capacity. At a leak rate of 0.7%, capacity would be effective for 300 years but actual emissions could not be held below the S450 scenario limit after 97 years.

The maximum leak for which sequestration is effective for the length of the model (300 years) is 0.1%. At this leak rate, sequestration is 57% as economically effective as buying the 40

$/ton permits. Since the capacity assumptions used in this model only account for geologic storage, it is possible that storage capacity in other forms will add to the lifetime of the sequestration scenario.

Table 9. Global Scenario's Effectiveness at Various Leak Rates

Leak Rate	Effectiveness		
	Capacity	Sequestration	Economic
0.01	140 years	300 years	60%
0.1	140 years	300 years	57%
0.2	140 years	184 years	53%
0.3	140 years	152 years	50%
0.4	140 years	129 years	47%
0.5	164 years	114 years	44%
0.6	218 years	103 years	42%
0.7	300 years	97 years	40%

The CSR model calculates the actual emissions released as a result of a sequestration scenario. When sequestration fails (from a performance standpoint), more emissions are released than are allowed, even though 100% of the fossil fuel emissions are sequestered. Table 10 summarizes actual emissions for the global reference scenario at various leak rates.

Table 10. Global Reference Scenario Actual Emissions at Various Leak Rates

Leak Rate (%)	Actual Emissions ($MtCO_2$/Year)						
	2000	2050	2100	2150	2200	2250	2300
0.01	7900	6200	3800	3000	2000	1900	1800
0.1	7900	6200	3800	3000	2000	1900	1800
0.2	7900	6200	3800	3000	2468	2788	2970
0.3	7900	6200	3800	3000	3725	4219	4508
0.4	7900	6200	3800	3897	5001	5680	6086
0.5	7900	6200	3800	4886	6280	7144	7668
0.6	7900	6200	3800	5875	7559	8608	9248
0.7	7900	6200	4121	6864	8837	10070	10827

Using NPV calculations, the total cost of the sequestration is calculated. Permanent sequestration costs, both total costs and marginal costs, are the same regardless of the leak rate, but the cost of leaky sequestration increases with the leak rate (table 11). The reference scenario shows that the average cost of permanent sequestration is 6 $/ton at all leak rates. Changes in leak rate do not have an effect of the cost of permanent sequestration because the cost of sequestering leaks does not need to be accounted for. Sequestration in leaky sinks will get as high as 11 $/ton for the reference scenario when sequestering in reservoirs with acceptable leak rates (leak rates less than or equal to 0.1%). The total NPV cost of the reference scenario storing in sinks with an average leak rate of 0.1% is $17 trillion. That same scenario could be achieved for a NPV cost of $10 trillion if permits sequestered the CO_2 permanently.

Table 11. Global Reference Scenario Costs at Various Leak Rates

Leak Rate	Total Cost (Trillion NPV $)		Marginal Cost (NPV $/ton)	
	Leaky	Permanent	Leaky	Permanent
0.01	16	10	10	6
0.1	17	10	11	6
0.2	18	10	11	6
0.3	20	10	12	6
0.4	20	10	13	6
0.5	21	10	13	6
0.6	21	10	14	6
0.7	21	10	14	6

Capturing CO_2 on a global scale would be a massive undertaking. Due to the often high parasitic loads on power generation when capturing CO_2, substantial amounts of replacement capacity would be required to offset these losses. The CSR model calculates the number of additional plants needed, assuming that all electric capacity comes from the same generation technology (492 MW natural gas plants with capture technology). For the global scenario and assuming that reservoirs had an average leak rate of 0.1%, 2,366 new plants would need to be built in addition to 4,118 plants that would already be operational in that year. In 2150, 1,651 plants would need to be added on top if of the existing 2,964 plants. Table 12 summarizes the number of additional plants needed at various leak rates.

Table 12. Additional Power Plants Needed for Sequestration at Various Leak Rates

Leak Rate (%)	Additional New Natural Gas Plants Needed						
	2000	2050	2100	2150	2200	2250	2300
0.01	151	1706	2366	1651	1283	612	590
0.1	151	1747	2497	1869	1562	928	927
0.2	151	1793	2463	2109	1868	1273	1293
0.3	151	1839	2790	2353	2182	1631	1678
0.4	151	1885	2938	2600	2501	1996	2072
0.5	151	1931	3086	2848	2821	2362	2468
0.6	151	1978	3233	3095	3141	2728	2863
0.7	152	2024	3381	3342	3461	3094	3258
Existing Plants	2652	4055	4118	2964	2184	1311	1248

Note: all worldwide electric capacity is assumed to be new natural gas plants. It takes 0.09 mWh for these plants to capture 1 ton of CO_2

The reference global scenario shows that assuming the world emits CO_2 along a 'business as usual path' (S750 curve), carbon sequestration could be successful at holding emissions to the S450 curve, but this scenario is unlikely due to lack of geologic storage capacity. Assuming that the necessary additional capacity is found and utilized (644,700 $MtCO_2$), sequestration would be effective for 300 years if the average leak rate was at 0.1% or below. Sequestration would be relatively expensive, with an NPV cost of $17 trillion or 11 $/ton. If permit prices stay at a constant 40 $/ton, then buying permits as a form of permanent sequestration would only cost $9 trillion (NPV) or 6 $/ton.

Global Scenario S550 Concentration Level

Storage capacity is sufficient to meet a S550 (table 1) concentration scenario for 233 years. The CO_2 is stored in heterogeneous natural gas and oil reservoirs, with an assumed standard deviation between the reservoirs' leak rates of 1%. Permit price and discount rate are both constant through the course of the model at 40 $/ton and 2% respectively. An aggregate natural gas and oil sequestration cost curve is used, and the cost of sequestration beyond capacity limits grows at a similar rate as the existing capacity curve. Economic effectiveness is calculated by comparing sequestration in leaky reservoirs to buying permits.

The most significant result of the S550 scenario is that there is enough capacity in gas and oil reservoirs for capacity to remain effective for 233 years (figure 5 and table 13). In order for capacity to be effective for 300 years in the S550 scenario, 120,450 $MtCO_2$ of additional storage capacity would be needed.

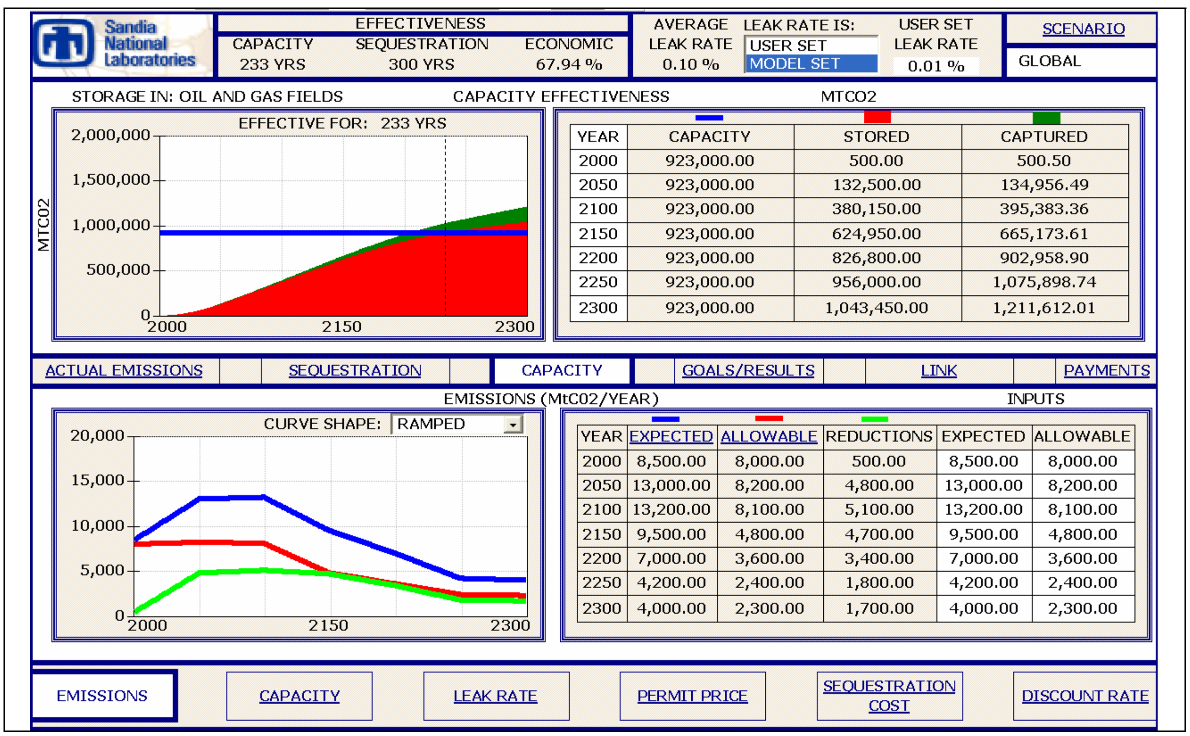


Figure 5. S550 Scenario Capacity and Emission Screen

The S550 scenario also allow for sequestration to occur in reservoirs with higher leak rates than the S450 scenario while still remaining effective. For all leak rates below 0.24%, enough CO_2 could be sequestered to hold actual emissions at an S550 concentration level. If the average leak rate of the storage system was high (0.7 %), sequestration would be effective but emissions would be limited to S550 levels for just 158 years.

Table 13. S550 Scenario's Effectiveness at Various Leak Rates

Leak Rate	Effectiveness		
	Capacity	Sequestration	Economic
0.01	233 years	300 years	72%
0.1	233 years	300 years	68%
0.2	233 years	300 years	64%
0.3	233 years	237 years	61%
0.4	233 years	209 years	58%
0.5	300 years	188 years	56%
0.6	300 years	171 years	53%
0.7	300 years	158 years	52%

Table 14 shows the actual emissions that occur when sequestration is used to limit S750 expected emissions to an S550 concentration scenario. Note that at higher leak rates, actual emissions as a result of sequestration may actually be higher than emissions would be had sequestration not taken place. In the S550 scenario 4000 $MtC0_2$ is emitted in 2300. If sequestration had taken place in a reservoirs with leak rates of greater than 0.4%, then actual emissions will be higher than the 'business as usual' projection. When considering a system of sequestration, one must decide whether it is worth the cost to sequester CO_2 in the present, while causing higher than expected emissions in the future.

Table 14. S550 Scenario Actual Emissions at Various Leak Rates

Leak Rate (%)	Actual Emissions ($MtCO_2$/Year)						
	2000	2050	2100	2150	2200	2250	2300
0.01	8000	8200	8100	4800	3600	2400	2300
0.1	8000	8200	8100	4800	3600	2400	2300
0.2	8000	8200	8100	4800	3600	2400	2300
0.3	8000	8200	8100	4800	3600	2773	3003
0.4	8000	8200	8100	4800	3600	3733	4053
0.5	8000	8200	8100	4800	4076	4694	5106
0.6	8000	8200	8100	4800	4905	5656	6157
0.7	8000	8200	8100	4800	5735	6617	7208

Single Natural Gas Plant Scenario

The CSR model allows the user to run a single plant sequestration scenario in addition to the global scenario. In this scenario, a new natural gas combined cycle plant is allowed to emit only 1 million tons of CO_2 per year and is storing CO_2 in a hypothetical sink with 700 million tons of capacity. The average leak rate of the sink is heterogeneous with a standard deviation of 1%. Carbon permits are selling at a constant 30 $/ton for the life of the model, and the discount rate is set at a constant 10%. Since the plants have a lifetime of 25 years, 12 identical plants would need to be built in order to continue the sequestration scenario for 300 years.

Figure 6 shows the CSR model's results and plant characteristics screen. The maximum leak rate where sequestration is effective for 300 years is 0.1%. At this leak rate, economic effectiveness is 72% when compared to sequestration in permanent reservoirs. In this example, the model compares economic effectiveness to sequestration in a perfectly secure reservoir (leak rate = 0%). Both permanent and leaky sequestration scenarios are able to store 662 million tons of CO_2 in 300 years, but storage in leaky reservoirs would require the capture of 759 million tons of CO_2. The total cost of the leaky scenario (NPV $30 million) is greater than the total cost of perfect sequestration (NPV $20 million) and the average cost of a sequestered ton of CO_2 is 0.04 $/ton for leaky sequestration and 0.03 $/ton for permanent sequestration. The average NPV cost of sequestration is low is because the permit price of 30 $/ton is almost as high as the total sequestration cost (32 $/ton in 2000). Much of the sequestration cost is offset by the cost of the CO_2 credits received as a result of sequestration. If the permit price was set to 0 $/ton, then the cost of leaky sequestration would average 1.1 $/ton, assuming a leak rate of 0.01%.

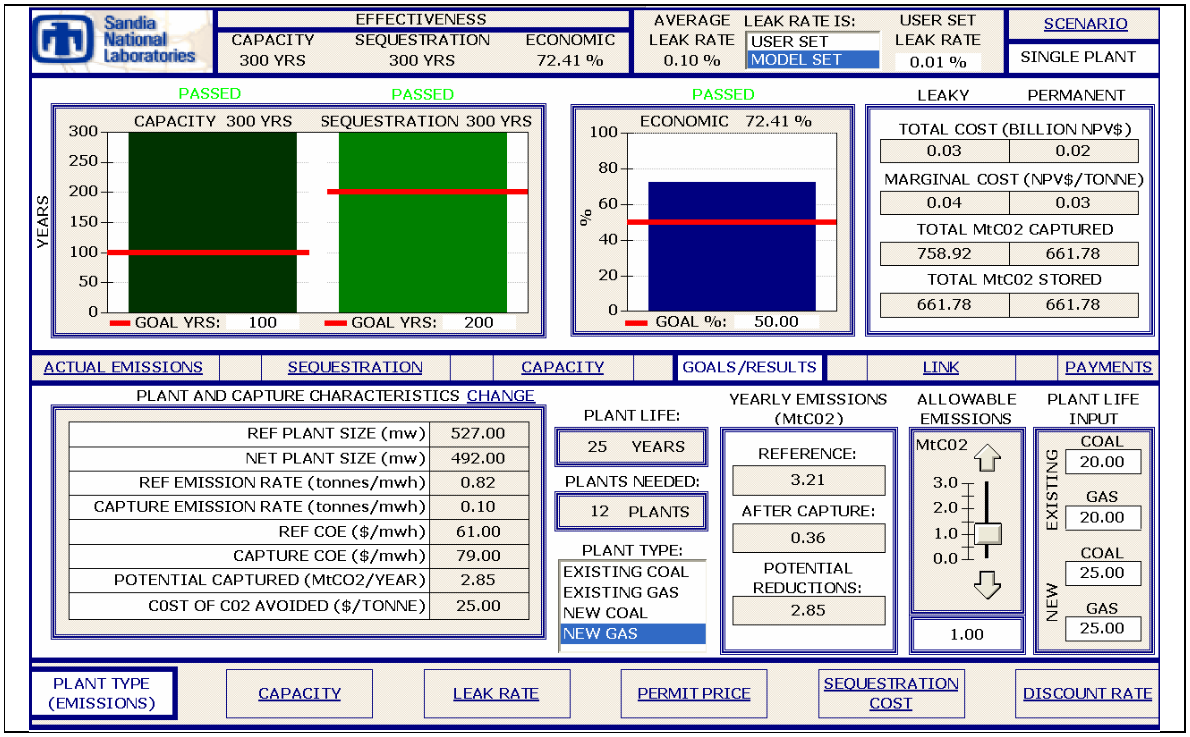


Figure 6. CSR Single Plant Results and Plant Characteristics Screen

The calculation for sequestration cost in the single plant scenario allows the user to change many assumptions about sequestration. Holding all sequestration cost variables constant, but increasing the distance between plant and sink will increase the cost of the scenario. The base case assumption is that the plant is located 100 kilometers from the sink, so pipeline cost is calculated at between 4 $/ton to 5 $/ton for the 300 year period. If the plant is located 200 kilometers from the sink, then pipeline costs range from 11 $/ton in 2000 to 10 $/ton in 2300. The increased pipeline costs also affect the total cost of the sequestration scenario. The net present value costs of sequestration increase from $30 million to $190 million if the distance from source to sink increases from 100 km to 200km (table 15).

Table 15. Source to Sink Distance Sensitivity Analysis

Source to Sink Distance (km)	Pipeline Costs ($/ton)				Total Sequestration Cost (Million NPV $)	
	2000	2100	2200	2300	Leaky	Permanent
100	5	5	4	4	30	20
150	8	7	7	7	100	100
200	11	11	10	10	190	180
250	15	14	13	13	270	260
300	18	17	17	16	360	350

Leak rate is the major factor driving whether sequestration will be effective in a single plant scenario. Table 16 shows the effects of leak rate on the actual emissions created by a single natural gas plant limited to 1 million tons of CO_2 emissions per year. Sequestration in reservoirs with leak rates greater than 0.1% will limit the emissions of a natural gas plant, but it will not be able to hold emissions at the desired level.

Table 16. Single Plant Scenario Leak Rate's Influence on Actual Emissions

Leak Rate (%)	Actual Emissions ($MtCO_2$/Year)						
	2000	2050	2100	2150	2200	2250	2300
0.01	1	1	1	1	1	1	1
0.1	1	1	1	1	1	1	1
0.2	1	1	1	1	1.2	1.4	1.6
0.3	1	1	1	1.3	1.6	2.0	2.3
0.4	1	1	1.2	1.7	2.1	2.5	2.9

Conclusion

The Carbon Sequestration and Risk model shows that a global system of storing CO_2 in geologic sinks is limited by storage capacity. A sequestration scenario that restricts CO_2 to a S450 concentration scenario from the 'business as usual' S750 concentration scenario with sequestration in oil and natural gas reservoirs will have enough capacity to last 140 years. If other forms of capacity were utilized (oceans, saline wells, etc.) this scenario could be effective for 300 years if the average leak rate of the storage system is below 0.1%, the leak rate is heterogeneous across the sinks and has a standard deviation of 1%. If emissions are restricted to the more lenient S550 atmospheric concentration curve, then geologic storage capacity would last 233 years and could be maintained for 300 years if the average leak rate of the storage system was below 0.24% and other storage capacity was used. Meeting the S450 scenario with storage in leaky sinks would be economically similar to permanently sequestering CO_2 through the purchase of 50 $/ton carbon permits, while the S550 scenario would be economically similar to the purchase of 37 $/ton carbon permits. Sequestration on a smaller scale (a single new natural gas plant with emissions limited to 1 $MtCO_2$/year) would be effective for 300 years if the sinks have capacity greater than 662 $MtCO_2$ and an average leak rate of 0.1% or below. Sequestration in sinks 100 km from the plant would cost $30 million (NPV), but sequestration in sinks 200 km from the plant would increase costs to $190 million (NPV).

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