NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DOE Revised Methodology for Development of Geologic Storage Potential for Carbon Dioxide

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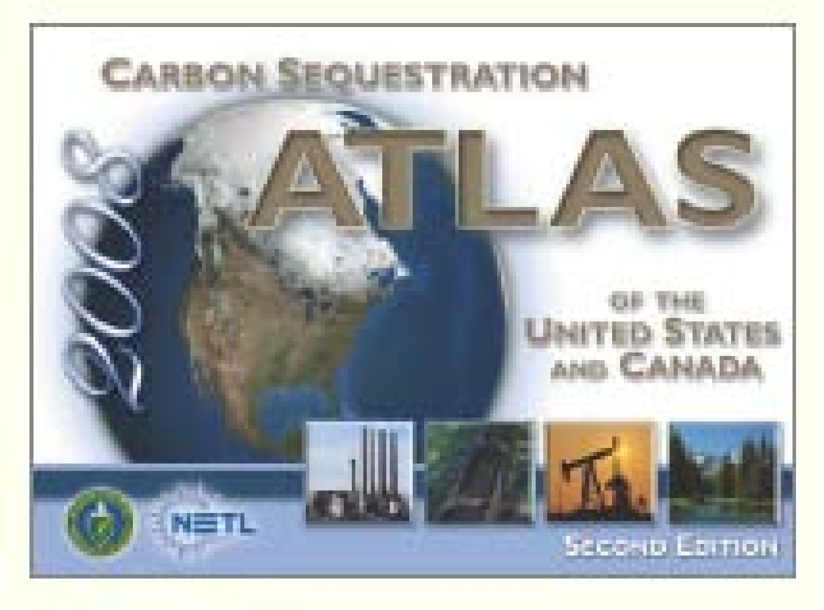
Carbon Sequestration Atlas of the United States and Canada

***Purpose*:**

- High-level assessments of potential CO_2 storage reservoirs in the United States and Canada.
- Based on physically accessible pore volume
- No consideration of regulatory or economic constraints.
- Used for broad energy-related government policy and business decisions



***Main Revisions to Methodology*:**

- Defined boundary conditions for CO_2 storage resource estimates
- Updated efficiency factors for saline formations and unmineable coal seams with improved stochastic method and documented parameters for saline formations (reporting P_{10}, P_{50}, and P_{90})

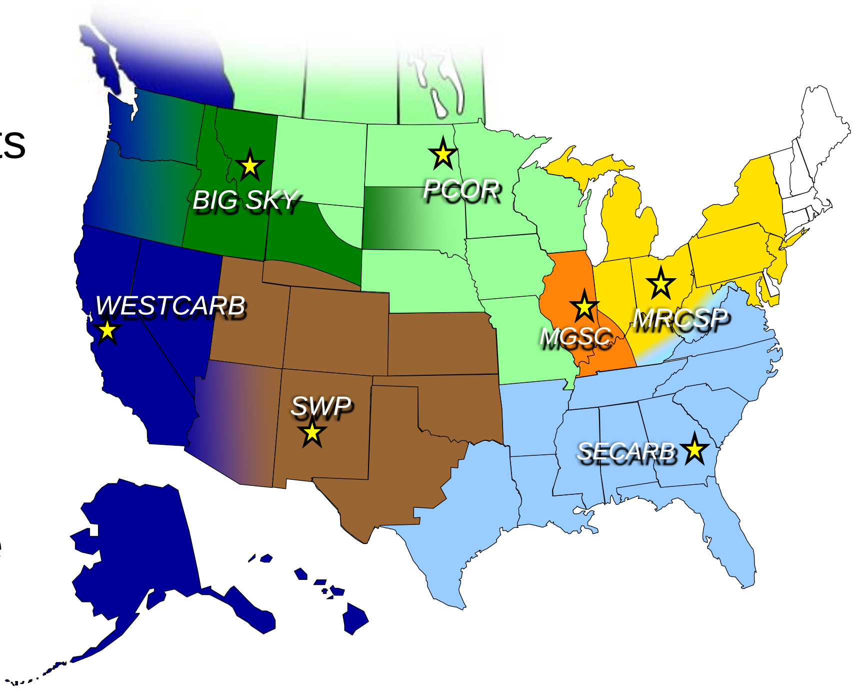
CO_2 Storage Definitions

CO_2 Storage Resource Estimates

- Available pore volume of a given formation that is accessible to CO_2 injected through drilled and completed wellbores
- Assumption that *in-situ* fluids will either be displaced by the injected CO_2 into distant parts of the same formation or neighboring formations or managed by means of fluid production, treatment, and disposal

CO_2 Storage Capacity Estimates

- Include economic and regulatory constraints.
- Educated assessment of the geologic storage potential with the highest degree of certainty when present economic and regulatory considerations are included.



Boundary Conditions

Open

- Permeable fluid-filled reservoirs where in-situ fluids will either be displaced away from the injection location or managed

Closed

- Fluid-filled reservoirs where in-situ fluid movement is restricted by means of impermeable barriers.

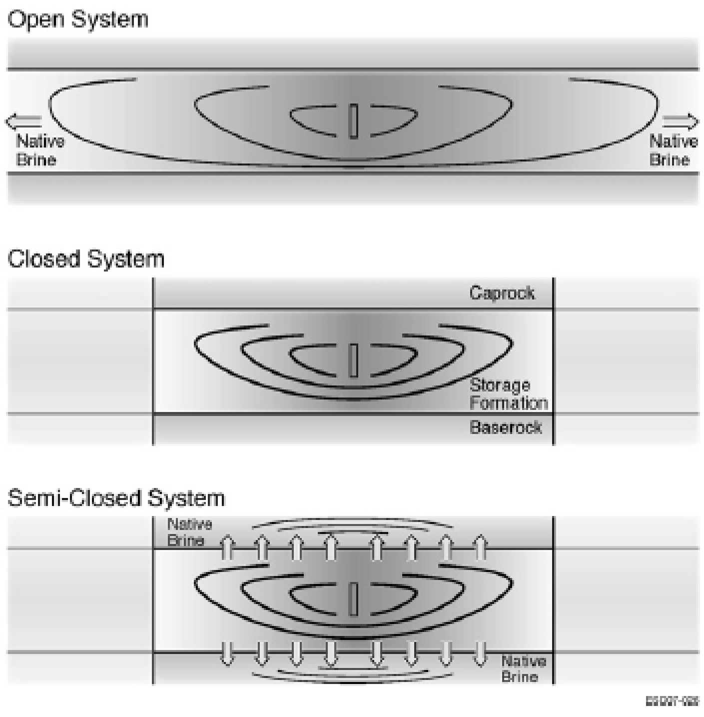


Fig. 1 – Schematic showing open systems vs. closed or semi-closed systems (not to scale).

CO_2 storage resource estimates provide an upper boundary for CO_2 storage (Realization of the full CO_2 storage resource estimate as a capacity estimate will rely on how site-specific geology, economics, and regulations restrict management of in-situ fluids)

CO_2 Storage Classification

Petroleum Industry		CO2 Geologic Storage
RESERVES	Implementation	**CAPACITY**
On Production		Active Injection
Approved for Development		Approved for Development
Justified for Development		Justified for Development
CONTINGENT RESOURCES	Site Characterization	**CONTINGENT STORAGE RESOURCE**
Development Pending		Development Pending
Development Unclarified or on Hold		Development Unclarified or on Hold
Development Not Viable		Development Not Viable
PROSPECTIVE RESOURCES	Exploration	**PROSPECTIVE STORAGE RESOURCES**
Prospect		Qualified Site(s)
Lead		Selected Areas
Play		Screened Sub-Regions

CO_2 Storage Resource Method

Volumetric Approach – in-situ fluids are displaced from the formation or managed

- *Oil and Gas Reservoir CO_2 Storage Resource Estimates*

$$G_{CO2} = \underbrace{A\, h_n\, \phi_e}_{\text{total pore volume}}\, \underbrace{(1-S_w) B\, \rho}_{\text{fluid properties}}\, \underbrace{E}_{\text{efficiency}}$$

- *Saline Formation CO_2 Storage Resource Estimates*

$$G_{CO2} = A_t\, h_g\, \phi_{tot}\, \rho E_{saline}$$

- *Unmineable Coal Seam CO_2 Storage Resource Estimates*

$$G_{CO2} = A\, h_g\, C_s\, \rho_{s,max}\, E_{coal}$$

Hundreds of Years of Storage Potential

North American CO_2 Storage Potential(Giga Tons)

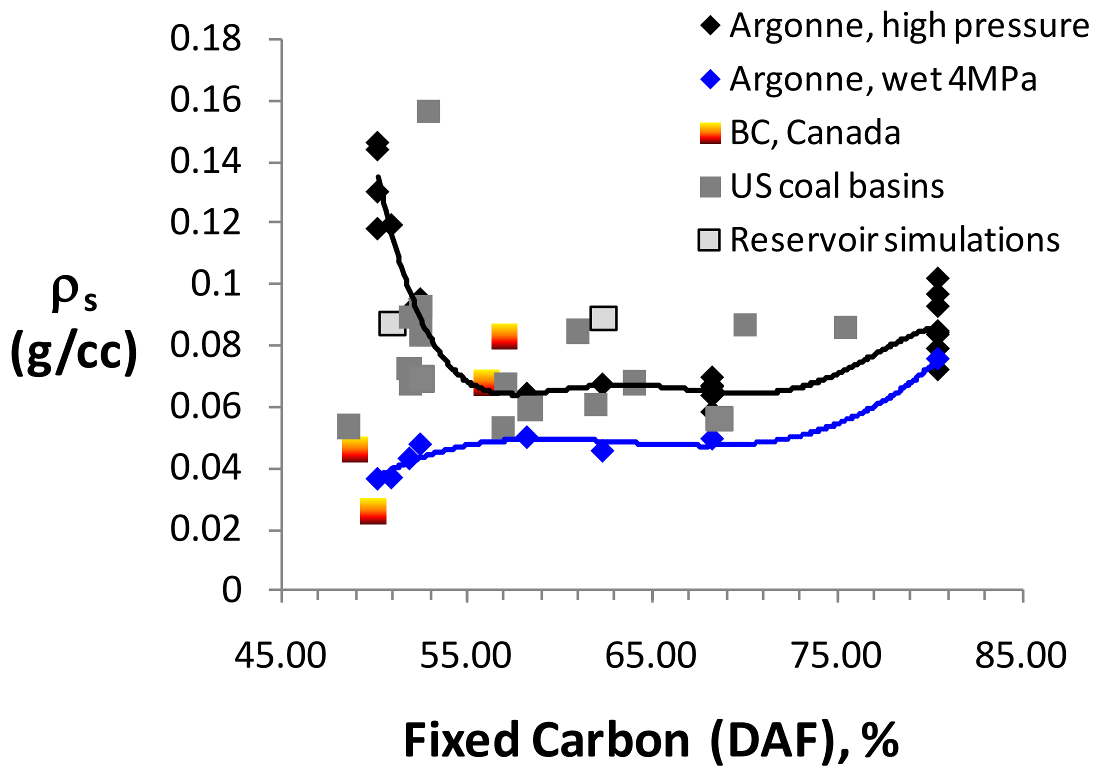
Sink Type	Low	High
Saline Formations	3300	13000
Unmineable Coal Seams	160	180
Oil and Gas Fields	140	140

Conservative Resource Assessment

Unmineable Coal Seam CO_2 Storage Resource Estimates

$$G_{CO2} = A\ h_g\ C_s\ \rho_{s,max}\ E_{coal}$$

$$\rho_{s,max} = n_{s,max}\ \rho_{c,dry}\ (1 - f_{a,dry})$$



Efficiency Factor for Saline Formations

$$E_{saline} = (A_n/A_t)\,(h_n/h_g)\,(\phi_e/\phi_{tot})\,E_v\,E_d$$

uncertainty in geologic parameters — $(A_n/A_t)\,(h_n/h_g)\,(\phi_e/\phi_{tot})$

effective CO_2 plume shape — E_v

accessible pore volume — E_d

Term0	Symbol	P_{10}/P_{90} Values by Lithology*			Description
		Clastics	**Dolomite**	**Limestone**	
Geologic terms used to define the entire basin or region pore volume					
Net-to-Total Area	A_n/A_t	0.2/0.8	0.2/0.8	0.2/0.8	Fraction of total basin or region area with a suitable formation.
Net-to-Gross Thickness	h_n/h_g	0.21/0.76	0.17/0.68	0.13/0.62	Fraction of total geologic unit that meets minimum porosity and permeability requirements for injection.
Effective-to-Total Porosity	ϕ_e/ϕ_{tot}	0.64/0.77	0.53/0.71	0.64/0.75	Fraction of total porosity that is effective, i.e., interconnected.
Displacement terms used to define the pore volume immediately surrounding a single well CO_2 injector.					
Areal Sweep Efficiency	E_A	N/A	N/A	N/A	Fraction of total planar area contacted by CO_2.
Vertical Sweep Efficiency	E_I	N/A	N/A	N/A	Fraction of vertical cross-sectional area contacted by CO_2.
Gravity Efficiency	Eg	N/A	N/A	N/A	Buoyancy of CO_2.
Volumetric Displacement Efficiency	E_V	0.16/0.39	0.26/0.43	0.33/0.57	Combined fraction of immediate volume surrounding an injection well that can be contacted by CO_2 and fraction of net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and in-situ water. ($E_V = E_A E_I E_g$)
Microscopic Displacement Efficiency	E_d	0.35/0.76	0.57/0.64	0.27/0.42	Fraction of pore space unavailable due to immobile *in-situ* fluids.

*Values obtained from Gorecki et. al. [9] Not applicable (N/A) is used for efficiency parameters that are included in Eq. 9, but are not included as part of the Gorecki et al. [9] report.

Log Odds Method when applied with the Monte Carlo simulation

1. Transform 'P' values of a range into corresponding 'X' values of a range

$$X = ln\left(\frac{P}{1-P}\right)$$

2. Determine the mean and standard deviation of 'X'

$$\sigma_X = \frac{X_{90} - X_{10}}{(Z_{90} - Z_{10})}$$

$$\mu_X = X_{10} - \sigma_X Z_{10}$$

3. Run Monte Carlo simulations (GoldSim) using the mean and standard deviation using normal distributions with a sample size of 5000 iterations for each.

$$E = \left({}^{1}\!/_{1+e^{X(A)}}\right)\left({}^{1}\!/_{1+e^{X(h)}}\right)\left({}^{1}\!/_{1+e^{X(\varphi)}}\right)\left({}^{1}\!/_{1+e^{X(Ev)}}\right)\left({}^{1}\!/_{1+e^{X(Ed)}}\right)$$

X_{10} and X_{90} Values Converted from P_{10} and P_{90} Values

	Clastics		Dolomite		Limestone	
	X_{10}	X_{90}	X_{10}	X_{90}	X_{10}	X_{90}
A_n/A_t	-1.4	1.4	-1.4	1.4	-1.4	1.4
h_n/h_g	-1.32	1.15	-1.59	0.75	-1.90	0.49
$Ø_e/Ø_{tot}$	0.58	1.21	0.12	0.90	0.58	1.10
E_V	-1.66	-0.45	-1.05	-0.28	-0.71	0.28
E_d	-0.62	1.15	0.28	0.58	-0.99	-0.32

μ_X and σ_X Values Calculated from X_{10} and X_{90} Values

	Clastics		Dolomite		Limestone	
	μ_X	σ_X	μ_X	σ_X	μ_X	σ_X
A_n/A_t	0	1.1	0	1.1	0	1.1
h_n/h_g	-0.09	0.97	-0.42	0.91	-0.71	0.93
$Ø_e/Ø_{tot}$	0.89	0.25	0.51	0.30	0.84	0.20
E_V	-1.05	0.47	-0.66	0.30	-0.21	0.39
E_d	0.27	0.69	0.43	0.11	-0.66	0.26

Saline Formation Efficiency Factors For Geologic and Displacement Terms
$E_{saline} = (A_n/A_t)(h_n/h_g)(\phi_e/\phi_{tot})E_v E_d$

Lithology	P_{10}	P_{50}	P_{90}
Clastics	0.51%	2.0%	5.4%
Dolomite	0.64%	2.2%	5.5%
Limestone	0.40%	1.5%	4.1%

Efficiency Factors for Saline Formations

Open Boundaries

Saline Formation Efficiency Factors

$E_{saline} = (A_n/A_t)\ (h_n/h_g)\ (\phi_e/\ \phi_{tot})\ E_v\ E_d$

A_n/A_t and h_n/h_g Terms Fixed at P_{50} Value

	Numerical method[1]			Monte Carlo Method[2]		
Lithology	**P_{10}**	**P_{50}**	**P_{90}**	**P_{10}**	**P_{50}**	**P_{90}**
Clastics	1.86%	2.70%	6.00%	1.2%	2.4%	4.1%
Dolomite	2.58%	3.26%	5.54%	2.0%	2.7%	3.6%
Limestone	1.41%	2.04%	3.27%	1.3%	2.0%	2.8%

1. Gorecki et. al.[9] 2. this work

Saline Formation Efficiency Factors For Displacement Terms

$E_{saline} = (A_n/A_t)^*\ (h_n/h_g)^*\ (\phi_e/\phi_{tot})^*\ E_v\ E_d$

Lithology	**P_{10}**	**P_{50}**	**P_{90}**
Clastics	7.4%	14%	24%
Dolomite	16%	21%	26%
Limestone	10%	15%	21%

*(A_n/A_t), (h_n/h_g), and (ϕ_e/ϕ_{tot}) values known directly

Closed Boundaries

E_{comp} 0.35 and 1% (Zhou, Birkholzer, Gorecki, Okwen, van de Meer, Economides)

**closed reservoirs would lower total efficiencies by a factor of 1/3 to 1/6*

Original E factor :
1 and 4% (P_{15}-P_{85})

2008 CO2 Resource Estimates by Partnership

	Saline Formations	
	Low	**High**
	Billion Metric Tons of CO_2	Billion Metric Tons of CO_2
Big Sky	460.9	1,831.5
MGSC	29.2	116.6
MRCSP	49.6	199.1
PCOR	185.6	185.6
SECARB	2,274.6	9,098.4
SWP	92.4	368.9
WESTCARB	204.5	818.2
Total	3,297.0	12,618.0

Efficiency Factors for Coal Seams

$E_{coal} = (A_n/A_t)\,(h_n/h_g)\,E_A\,E_L\,E_g\,E_d$

- $(A_n/A_t)\,(h_n/h_g)$: *uncertainty in geologic parameters*
- $E_A\,E_L\,E_g$: *effective CO_2 plume shape*
- E_d: *accessible pore volume*

Term	Symbol	P_{10}/P_{90} Values	Description
Geologic terms used to define the entire basin or region pore volume			
Net-to-Total Area	A_n/A_t	0.6/0.8	Fraction of total basin or region area that has bulk coal present.
Net-to-Gross Thickness	h_n/h_g	0.75/0.90	Fraction of coal seam thickness that has adsorptive capability.
Displacement terms used to define the pore volume immediately surrounding a single well CO_2 injector.			
Areal Displacement Efficiency	E_A	0.7/0.95	Fraction of the immediate area surrounding an injection well that can be contacted by CO_2.
Vertical Displacement Efficiency	E_L	0.8/0.95	Fraction of the vertical cross section (thickness), with the volume defined by the area (A) that can be contacted by a single well.
Gravity	Eg	0.9/1.0*	Fraction of the net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and the in-situ water in the cleats.
Microscopic Displacement Efficiency	E_d	0.75/0.95	Reflects the degree of saturation achievable for in-situ coal compared with the theoretical maximum predicted by the CO_2 Langmuir Isotherm.

*0.999 used due to inability to divide by zero when using Log Odds Method.

Coal Seam Efficiency Factors $E_{coal} = (A_n/A_t)\,(h_n/h_g)E_A\,E_L\,E_g\,E_d$		
P_{10}	P_{50}	P_{90}
21%	37%	48%

Coal Seam Efficiency Factors for Displacement Terms $E_{coal}= (A_n/A_t)^*\,(h_n/h_g)^*\,E_A\,E_L\,E_g\,E_d$		
P_{10}	P_{50}	P_{90}
39%	64%	77%

$^*(A_n/A_t)$ and (h_n/h_g) values known directly

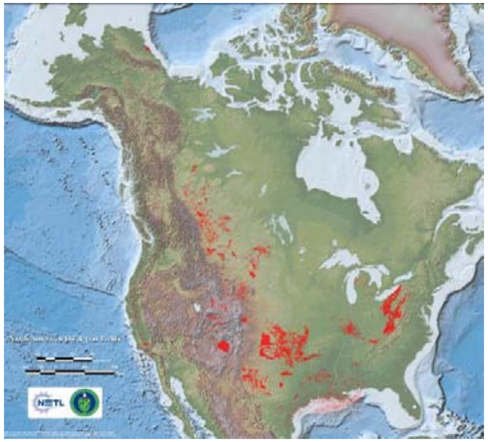
Original E factor: 28 and 40% (P_{15}-P_{85})

2008 CO2 Resource Estimates by Partnership		
	Unmineable Coal Seams	
	Low	High
	Billion Metric Tons of CO_2	Billion Metric Tons of CO_2
Big Sky	12.1	12.1
MGSC	1.7	2.4
MRCSP	0.8	0.8
PCOR	10.7	10.7
SECARB	43.8	63.0
SWP	0.7	1.8
WESTCARB	86.8	86.8
Total	157.0	178.0

Summary

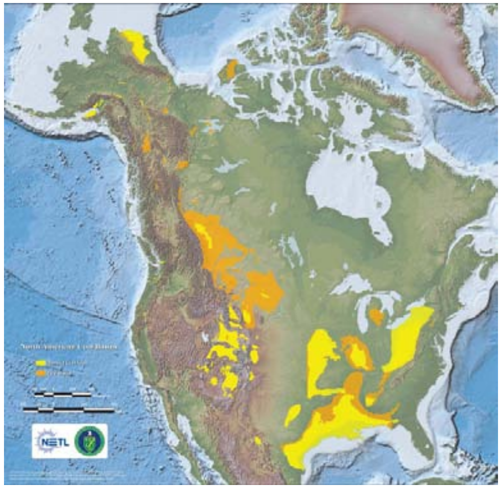
- **Complete revision of CO_2 storage resource methodology for November 2010 Carbon Sequestration Atlas**

- ***Main Revisions to Methodology*:**
  - Defined boundary conditions for CO_2 storage resource estimates
  - Updated efficiency factors for saline formations and unmineable coal seams with improved stochastic method and documented parameters for saline formations



Oil and Gas Fields

Saline Formations



Unmineable Coal Seams

Volumetric Resource Estimates

Unmineable Coal Seams

Parameter	Units*	Description
G_{CO2}	M	Mass estimate of CO_2 resource of one or more coal beds.
A	L^2	Geographical area that outlines the coal basin or region for CO_2 storage calculation.
h_g	L	Gross thickness of coal seam(s) for which CO_2 storage is assessed within the basin or region defined by A.
C_s	%	Fraction of CO_2 that is stored per unit of coal under reservoir conditions as opposed to under ideal (maximum) pressure conditions (e.g., as defined by Langmuir volume constant or alternative)
$\rho_{s,max}$	M/L^3	Density of sorbed CO_2 averaged over coal bulk volume; assumes 100% CO_2 saturated coal conditions.
E	L^3/L^3	CO_2 storage efficiency factor that reflects a fraction of the total coal bulk volume that is contacted by CO_2.

Volumetric Resource Estimates

Oil and Gas Reservoirs

Parameter	Units*	Description
G_{CO2}	M	Mass estimate of oil and gas formation CO_2 storage resource estimate.
A	L^2	Area that defines the oil or gas formation that is being assessed for CO_2 storage calculation.
h_n	L	Oil and gas column height in the formation.
ϕ_e	L^3/L^3	Effective porosity in volume defined by the net thickness.
S_w	L^3/L^3	Average water saturation within the total area (A) and net thickness (h_n).
B	L^3/L^3	Formation volume factor; converts standard oil or gas volume to subsurface volume (at formation pressure and temperature). B = 1.0 if CO_2 density is evaluated at anticipated reservoir pressure and temperature.
ρ	M/L^3	Density of CO_2 evaluated at pressure and temperature that represents storage conditions in the formation averaged over h_n.
E	L^3/L^3	CO_2 storage efficiency factor that reflects a fraction of the total pore volume from which oil and/or gas has been produced and that can be filled by CO_2.

Volumetric Resource Estimates

Saline Formations

Paramete r	Units*	Description
G_{CO2}	M	Mass estimate of saline formation CO_2 storage resource estimate.
A_t	L^2	Geographical area that defines the basin or region being assessed for CO_2 storage calculation.
h_g	L	Gross thickness of saline formations for which CO_2 storage is assessed within the basin or region defined by A.
ϕ_{tot}	L^3/L^3	Effective porosity in volume defined by the net thickness.
ρ	M/ L^3	Density of CO_2 evaluated at pressure and temperature that represents storage conditions anticipated for a specific geologic unit averaged over h_g.
E	L^3/L^3	CO_2 storage efficiency factor that reflects a fraction of the total pore volume that is filled by CO_2.