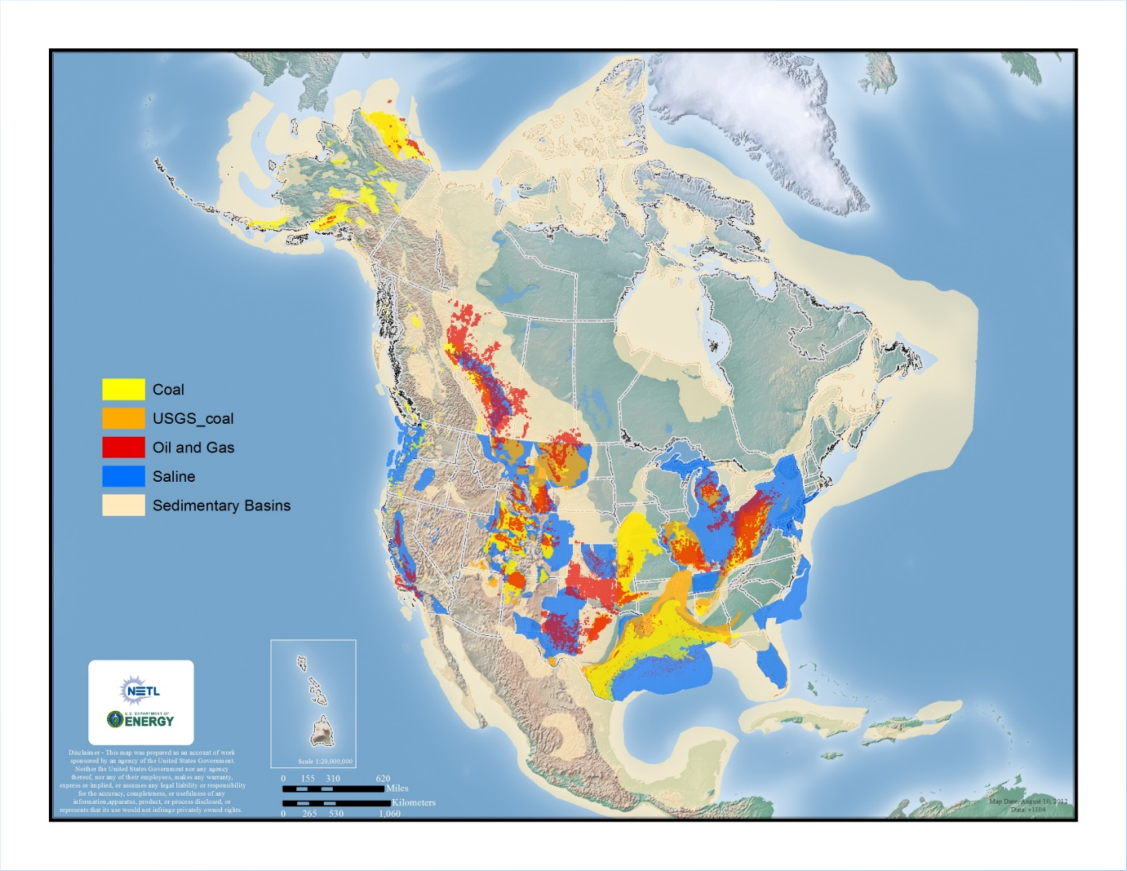
Resource Assessment Methods for CO_2 Storage in Geologic Formations

Project Number 1022403



Carbon Storage R&D
Project Review Meeting

Transforming Technology through Integration and Collaboration

August 18-20, 2015

Pittsburgh, PA

Angela Goodman

Office of Research and Development / National Energy Technology Laboratory

U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

the ENERGY lab

Science & Engineering To Power Our Future

NETL Research Presentations and Posters

TUESDAY, AUGUST 18, 2015

- **2:30 PM** Resource Assessment - Angela Goodman
- **5:25 PM** Catalytic Conversion of CO_2 to Industrial Chemicals - Doug Kauffman
- 6:15 p.m. **Poster Session (CORE R&D, NRAP, and RCSPs)**
  1. Dave Blaushild - Perfluorocarbon Tracer (PFT) Analysis to Support the South West Partnership,
  2. Liwei Zhang - Numerical simulation of pressure and CO2 saturation above the fractured seal as a result of CO2 injection: implications for monitoring network design
  3. NRAP, EDX, and NATCARB Grant Bromhal, Bob Dilmore, Kelly Rose, Maneesh Sharma

WEDNESDAY, AUGUST 19, 2015

- **1:15 PM** Monitoring the Extent of CO_2 Plume and Pressure Perturbation - Bill Harbert
- **2:05 PM** Reservoir and Seal Performance - Dustin Crandall
- **3:45 PM** Monitoring Groundwater Impacts - Christina Lopano
- 5:30 p.m. **Poster Session (SubTER, NRAP, and EFRCs)**
  1. Kelly Rose - Evaluating Induced Seismicity with Geoscience Computing & Big Data – A multi-variate examination of the cause(s) of increasing induced seismicity events
  2. NRAP, EDX, and NATCARB Grant Bromhal, Bob Dilmore, Kelly Rose, Maneesh Sharma
  3. John Tudek- EFRC
  4. Sean Sanguinito NETL CO_2 SCREEN
  5. Daniel J. Soeder, Maneesh Sharma, Mollie Kish and Chloe Wonnell: Rock Physics to Assess Depleted Gas Shales for CO2 Storage.

THURSDAY, AUGUST 20, 2015

- **11:25 AM** Shales as Seals and Unconventional Reservoirs for CO_2– Robert Dilmore

https://edx.netl.doe.gov/carbonstorage/

Presentation Outline

Resource Assessment

Develop Defensible DOE Methodology for Regional Assessments

- *Unconventional Systems*
  - ***Team Members:*** Jonathan S. Levine, Isis Fukai, Robert Dilmore, Sean Sanguinito, Daniel Soeder, Grant Bromhal, Angela Goodman
- *Oil and Gas Systems*
  - ***Team Members:*** Robert Dilmore; Russel Johns; Nic Azzolina; David Nakles; Angela Goodman
- *Offshore*
  - ***Team Members:*** Kelly Rose, Corinne Disenhof, Jenifer Bauer, Angela Goodman

Expand Methodology to Include Stochastic Approach for Key Parameters

- *Saline Systems*
  - ***Team Members:*** Sean Sanguinito, Jonathan Levine, Emily Dixon Angela Goodman

Expand Methodology to Include Geospatially Variable Key Parameters

- *Saline Systems*
  - ***Team Members:*** Kelly Rose, Corinne Disenhof, Jenifer Bauer, Angela Goodman

Benefit to the Program

- **Carbon Storage Program Major Goals**
  - Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- **Project Benefits Statement:**
  - This research project aims at developing and methods and tools for prospective CO_2 Storage at the national, regional, basin, and formation scale

Project Overview:
Goals and Objectives

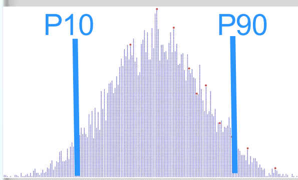
- Carbon Storage Program Major Goals:
  - Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Project Benefits Statement:
  - This research project aims at developing and maintaining tools/resources that facilitate regional- and national-scale assessment of carbon storage
- Project Objectives:
  - Resource Assessments: **Develop a Defensible DOE Methodology for Regional Assessments**
- Develop, refine, and evaluate a suite of methodologies to quantitatively assess CO_2 storage resource potential in onshore and offshore reservoirs including saline formations, oil and gas reservoirs, coal seams, and shales.

Resource Assessments and Geospatial Resources

Develop Defensible DOE Methodology for Regional Assessments

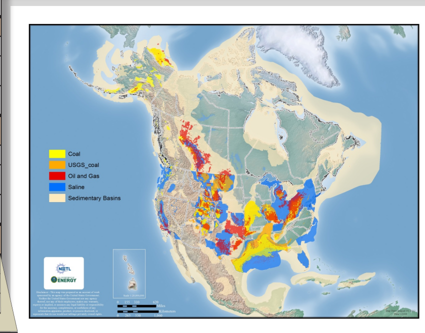
Mass Resource Estimate

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

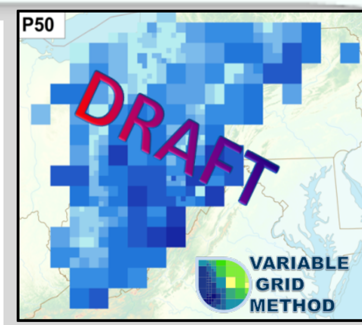


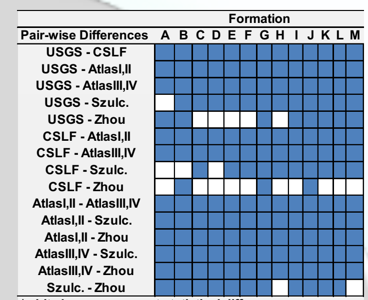
	Petroleum Industry	CO_2 Geological Storage
	Reserves	Capacity
Implementation	On Production	Active Injection
Implementation	Approved for Development	Approved for Development
Implementation	Justified for Development	Justified for Development
	Contingent Resources	Contingent Storage Resources
Site Characterization	Development Pending	Development Pending
Site Characterization	Development Unclarified or On Hold	Development Unclarified or On Hold
Site Characterization	Development Not Viable	Development Not Viable
	Prospective Resources	Prospective Storage Resources
Exploration	Prospect	Qualified Site(s)
Exploration	Lead	Selected Areas
Exploration	Play	Potential Sub-Regions

	Prospective Storage Resources	
	Project Sub-class	Evaluation Process
Exploration	Qualified Site(s)	Initial Characterization
Exploration	Selected Areas	Site Selection
Exploration	Potential Sub-Regions	Site Screening



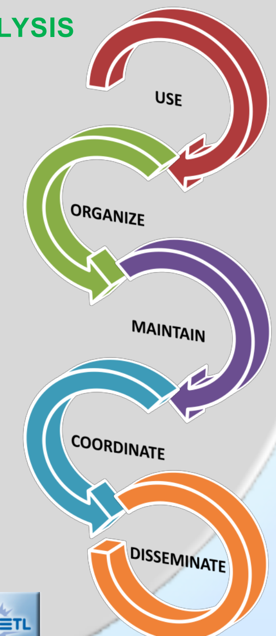
Expand Methodology to Include Geospatially Variable Key Parameters





*white boxes represent statistical differences

Spatial Statisical Data Analysis

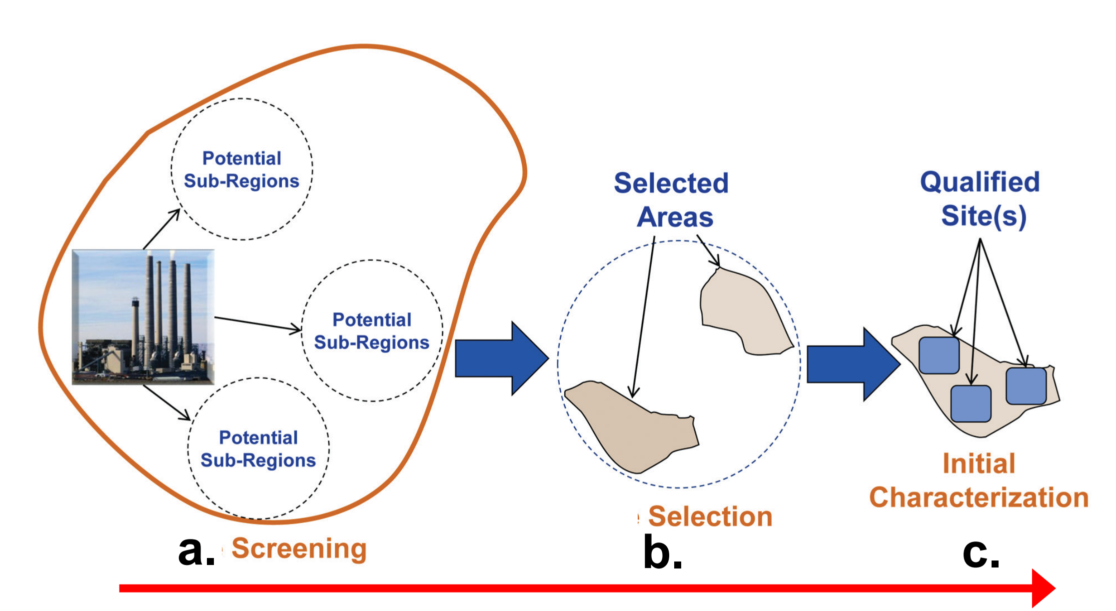


Developing methods to aid broad energy-related government policy and business decisions; provide geospatial platforms that support research and assessment; and facilitate preservation and transfer of data.

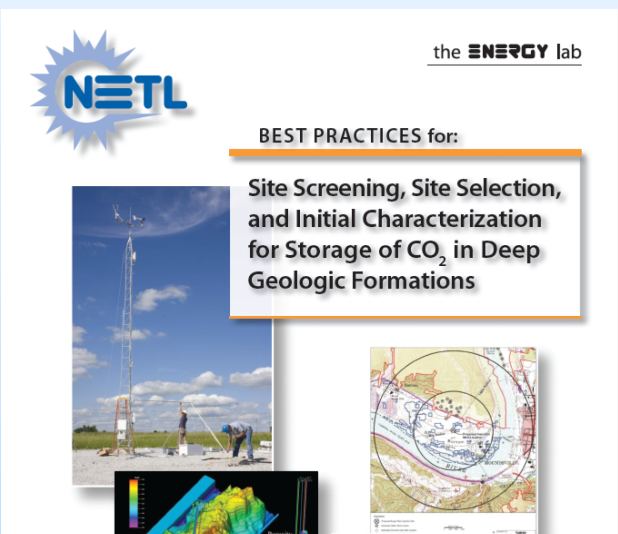
EDX Energy Data eXchange

Geospatial Platforms

Prospective Storage Resource for CO_2 storage reservoirs at the *at the Exploration Phase*.



"Project Site Maturation" through the Exploration Phase.



Petroleum Industry		CO_2 Geological Storage
Reserves	Implementation	**Capacity**
On Production		Active Injection
Approved for Development		Approved for Development
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Contingent Resources	Site Characterization	**Contingent Storage Resources**
Development Pending		Development Pending
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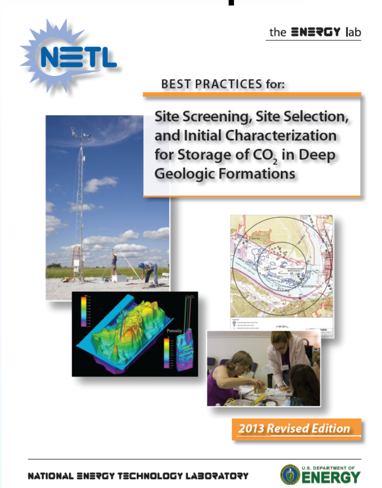
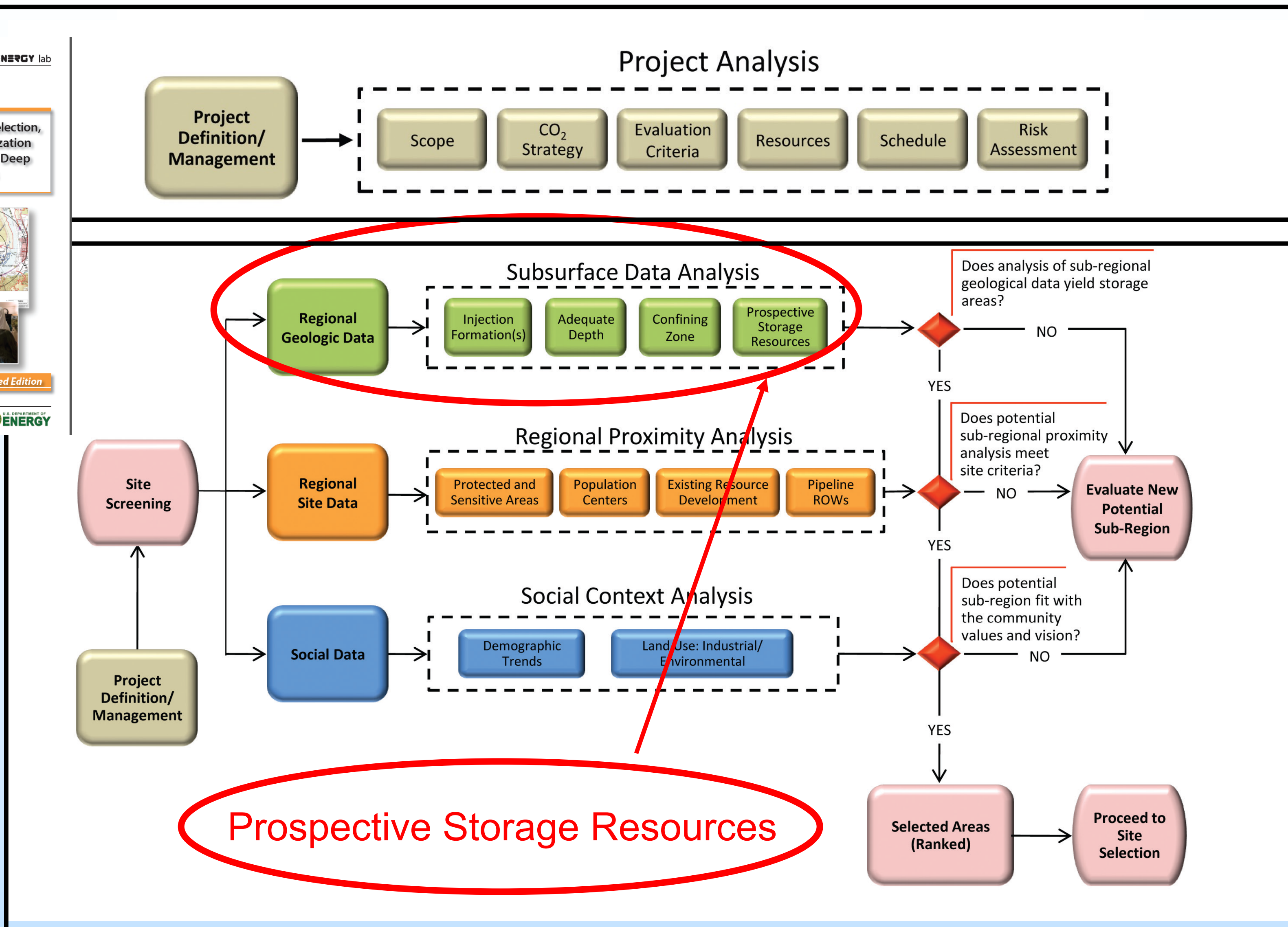
Prospective Resources	Exploration	**Prospective Storage Resources**
Prospect		Qualified Site(s)
Lead		Selected Areas
Play		Potential Sub-Regions

	Exploration	**Prospective Storage Resources**	
		Project Sub-class	**Evaluation Process**
c.		Qualified Site(s)	Initial Characterization
b.		Selected Areas	Site Selection
a.		Potential Sub-Regions	Site Screening

Process Flowchart for Site Screening





Prospective CO_2 Storage Resource Methods

Volumetric approach: *geologic properties & storage efficiency*

Subsurface Data Analysis

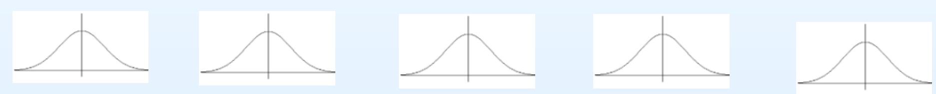
- *i. Injection Formation*
  - Oil and Natural Gas Reservoirs, Deep Saline Formations, Unmineable Coal Seams, Organic Shale, Basalt and Other Volcanic and Mafic Rocks
- *ii. Adequate Depth*
  - Sufficient depth to maintain injected CO_2 in the supercritical state
- *iii. Confining Zone*
  - Contain injected CO_2
- *iv. Prospective Storage Resources*
  - Sufficient pore volumes and can accept the change in pressure to accommodate planned injection volumes

Mass Resource Estimate

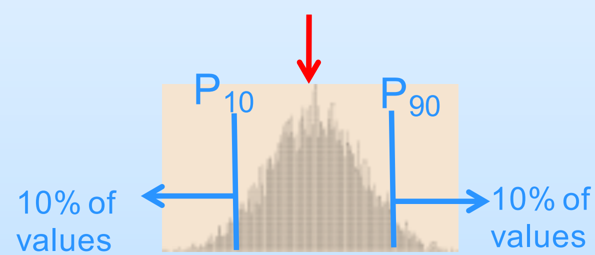
$$G_{Storage} = Ah\phi\,\rho\,E$$

$$E = E_A\,E_h E_\phi\,E_v\,E_d$$

E_A E_h E_ϕ E_v E_d



$$\frac{1}{(1+e^{(-E_A)})} * \frac{1}{\left(1+e^{(-E_h)}\right)} * \frac{1}{\left(1+e^{(-E_\phi)}\right)} * \frac{1}{(1+e^{(-E_V)})} * \frac{1}{(1+e^{(-E_D)})}$$



Prospective Storage for Saline Formations at the *National and Regional Scale*

Term	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	$E_{An/At}$	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	$E_{hn/hg}$	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	$E_{\phi e/\phi tot}$	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.					
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.
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 from IEA (2009)/Gorecki (2009)

Saline Formation Efficiency Factors For Geologic and Displacement Terms

$E_{saline} = E_{An/At}\ E_{hn/hg}\ E_{\phi e/\ \phi tot}\ E_v\ E_d$

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%

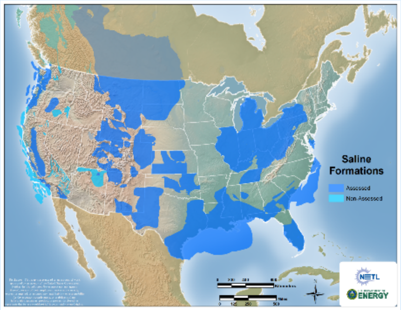
Saline Formation Efficiency Factors For Displacement Terms

$E_{saline}{}^{*} = E_v\ E_d$

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

*$E_{An/At}$, $E_{hn/hg}$, and $E_{\phi e/\ \phi tot}$ values are known directly

IEA, 2009/13. Development of Storage Coefficients for CO2 Storage in Deep Saline Formations, IEA Green house Gas R&D Programme (IEA GHG) October.



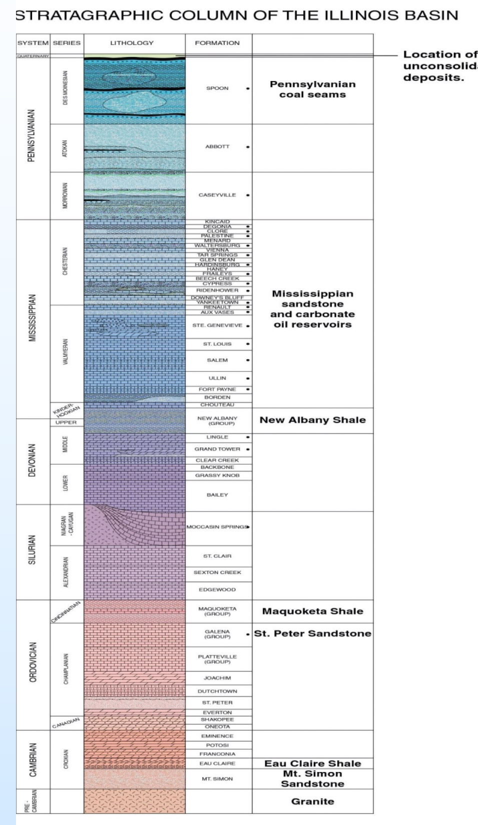
Prospective Storage for Saline Formations at the *Basin and Formation Scale* *(in development)*

- Refine estimates at the National and Regional Scale
- Builds upon existing Volumetric Approach
- Based on intrinsic geologic subsurface data

Beta Version

NETL CO_2 SCREEN

Storage CO_2 Resource Estimation Excel aNalysis



- Provide user-friendly platform for estimating prospective CO_2 in saline formations at the national, regional, basin, and formation scale
- Provide a consistent, flexible method to calculate prospective CO_2 that based on more detailed geologic attributes
- Allow for direct comparison of prospective CO_2 storage estimates between RCSP's, government agencies, and independent research studies

Beta Version

NETL CO_2 SCREEN

Storage CO_2 Resource Estimation Excel aNalysis

NETL CO_2 SCREEN

Instructions:

- [1] Type general information into cells I7:I9
- [2] Storage Efficiency Values
  - Option One: Choose the lithology and depositional environment using the drop-down list in cell I17 (yellow). This will autopopulate storage efficiency P_{10} and P_{90} values in cells I21:I25 and J21:J25 (yellow)
  - Option Two: Enter user specific P_{10} and P_{90} values in cells K21:K25, and L21:L25 (light red)
- [3] Formation Data
  - Option One: Skip to step 4 to enter user specific data
  - Option Two: Enter formation data in "Formation Data" tab and follow instructions to autopopulate values
- [4] Storage Parameters
  - Directly enter user specified storage parameters (light red)

- GoldSim will import values from cells O21:O25, P21:P25, J42, J44:J47, and K44:K47 (red font: make sure each cell contains a value)
- Do not alter spreadsheet cell layout as this may cause errors when syncing with GoldSim Player
- After data is input, save and close spreadsheet before running GoldSim Player

*** (Area, Thickness, Porosity)**

These will be treated as gross estimates requiring application of efficiency terms. To use "net" values manually enter 1 for respective P_{10} and P_{90} efficiency terms.

† (Pressure, Temperature)

Ranges are limited by the lookup table in GoldSim

Pressure must range between 0.1 and 60 MPa

Temperature must range between 1 and 180°C

Reference Values		
z_{90}	z_{10}	z_{90}-z_{10}
1.28155157	-1.2815516	2.56310313

Data Inputs

[1]

General Information	
Researcher Name	Jane Scientist
Formation Name	Oriskany Formation
Date	8/15/2015

[2]

Storage Efficiency Values

Autopopulate: Choose lithology and depositional environment

User Specified: Directly enter P_{10} and P_{90} values

Lithology and Depositional Environment	Clastics: Shallow Shelf

	Autopopulated		User Specified					
	P_{10}	P_{90}	P_{10}	P_{90}	X_{10}	X_{90}	μ_X	σ_X
Net-to-Total Area	0.20	0.80	0	0	-1.39	1.39	0.00	1.08
Net-to-Gross Thickness	0.21	0.76	0	0	-1.32	1.15	-0.09	0.97
Effective-to-Total Porosity	0.62	0.78	0	0	0.49	1.27	0.88	0.30
Volumetric Displacement	0.18	0.63	0	0	-1.52	0.53	-0.49	0.80
Microscopic Displacement	0.39	0.82	0	0	-0.45	1.52	0.53	0.77

[3]

Formation Data

If user requires processing of data go to "Formation Data" tab to enter multiple storage parameter values which will autopopulate aggregated means and standard deviations for step 4 below. If user already has processed data, proceed to step 4

[4]

Storage Parameters

Autopopulate: Calculated from step 3

User Specified: Directly enter storage parameters

		Autopopulated		User Specified	
Total Area*	(km^2)	100		100	
		Mean	Std Dev	Mean	Std Dev
Gross Thickness*	(m)	50	0	50	0
Total Porosity*	(%)	10.00	0	10	0
Pressure†	(MPa)	20	0	20	0
Temperature†	(°C)	100	0	100	0

Beta Version

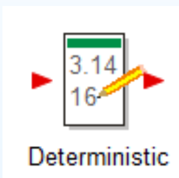
NETL CO_2 SCREEN

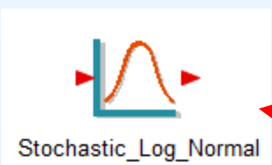
Storage CO_2 Resource Estimation Excel aNalysis

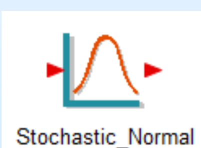
Storage Parameters

Autopopulate: Calculated from step 3

User Specified: Directly enter storage parameters







		Autopopulated		User Specified	
Total Area*	(km^2)	100		100	
		Mean	**Std Dev**	**Mean**	**Std Dev**
Gross Thickness*	(m)	50	0	50	0
Total Porosity*	(%)	10.00	0	10	0
Pressure†	(MPa)	20	0	20	0
Temperature†	(°C)	100	0	100	0

- Enter mean and standard deviation storage parameters for geologic formation of interest

Beta Version

NETL CO_2 SCREEN

Storage CO_2 Resource Estimation Excel aNalysis

Storage Efficiency Values

Autopopulate: Choose lithology and depositional environment

User Specified: Directly enter P_{10} and P_{90} values

Lithology and Depositional Environment	Clastics: Shallow Shelf

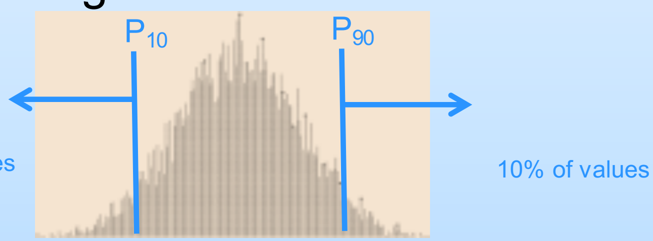
	Autopopulated		**User Specified**					
	P_{10}	**P_{90}**	**P_{10}**	**P_{90}**	**X_{10}**	**X_{90}**	**μ_X**	**σ_X**
Net-to-Total Area	0.20	0.80	0	0	-1.39	1.39	0.00	1.08
Net-to-Gross Thickness	0.21	0.76	0	0	-1.32	1.15	-0.09	0.97
Effective-to-Total Porosity	0.62	0.78	0	0	0.49	1.27	0.88	0.30
Volumetric Displacement	0.18	0.63	0	0	-1.52	0.53	-0.49	0.80
Microscopic Displacement	0.39	0.82	0	0	-0.45	1.52	0.53	0.77

- Values are transformed from P to X values using log-odds normal distribution

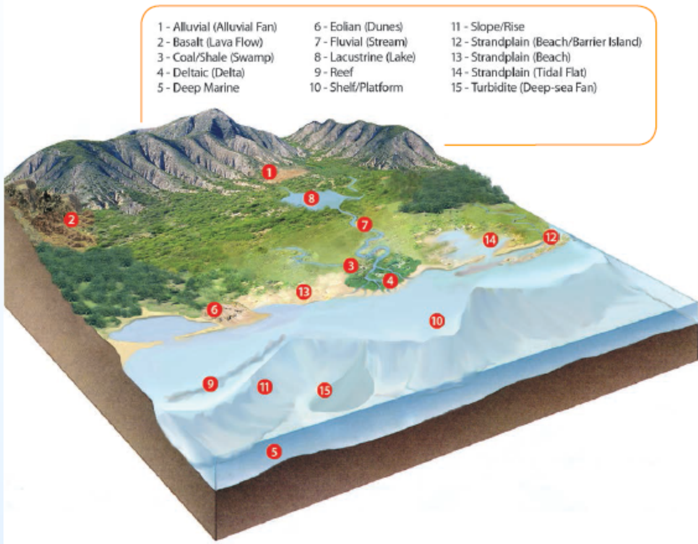
$$X = ln\left(\frac{p}{1-p}\right)$$

- Mean (μ_X) and standard deviation (σ_X) are calculated using:

$$\sigma_X = \frac{X_{90} - X_{10}}{Z_{90} - Z_{10}} \quad \text{and} \quad \mu_X = X_{10} - \sigma_x Z_{10}$$

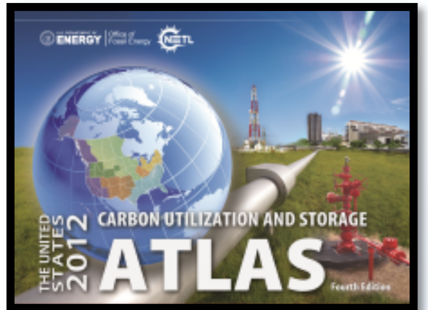


Geologic Storage Formation Classes



		Matrix of Field Activities in Different Reservoir Classes (2012)										
		High Potential Reservoirs					Medium Potential Reservoirs				Lower/Unknown Potential Reservoirs*	
Large-Scale Field Projects[a]	Saline	-	-	1	1	-	1	-	1	-	-	-
	EOR	1	-	-	-	1	2	-	-	-	-	-
Small-Scale Field Projects[b]	Saline	2	1	1	1	-	-	-	1	-	-	1
	EOR	1	1	3	1	2	1	-	1	-	6	0
Reservoir Class		Deltaic	Shelf Clastic	Shelf Carbonate	Strandplain	Reef	Fluvial Deltaic	Eolian	Fluvial & Alluvial	Turbidite	Coal	Basalt (LIP)

Notes:
The number in the cell is the number of investigations by NETL per geologic storage formation classification.
* Potential reservoirs were inferred from petroleum industry and field data from the Carbon Storage Program.
[a] Large-Scale Field Projects – Injection of more than 1,000,000 tons of CO_2.
[b] Small-Scale Field Projects – Injection of less than 500,000 tons of CO_2 for EOR and 100,000 tons for saline formations.



Lithology	Depositional Environment
Clastics	Clastics
Dolomite	Dolomite
Limestone	Limestone
Clastics	Alluvial fan
Clastics	Delta
Clastics	Eolian
Clastics	Fluvial
Clastics	Peritidal
Clastics	Shallow shelf
Clastics	Shelf
Clastics	Slope basin
Clastics	Strand plain
Limestone	Peritidal
Limestone	Reef
Limestone	Shallow shelf

IEA, 2009/13. Development of Storage Coefficients for CO2 Storage in Deep Saline Formations, IEA Green house Gas R&D Programme (IEA GHG) October.

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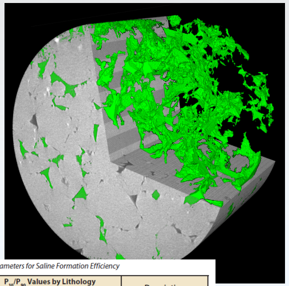
Storage Efficiency and Experimental Measurement of Relative Permeability and Wettability

- Wettability controls pore-scale saturation and relative permeability
- These control sweep efficiency and maximum initial saturation, thus residual saturation
- **Reservoir Management Session at 2:05 PM** Reservoir and Seal Performance - Dustin Crandall WEDNESDAY, AUGUST 19, 2015
  - Set of relative permeability core flood experiments and contact angle+IFT for lithology and depositional environments

Simulating flow through pore and fracture networks



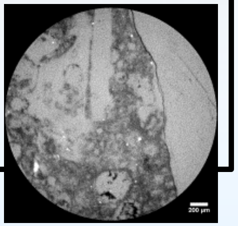
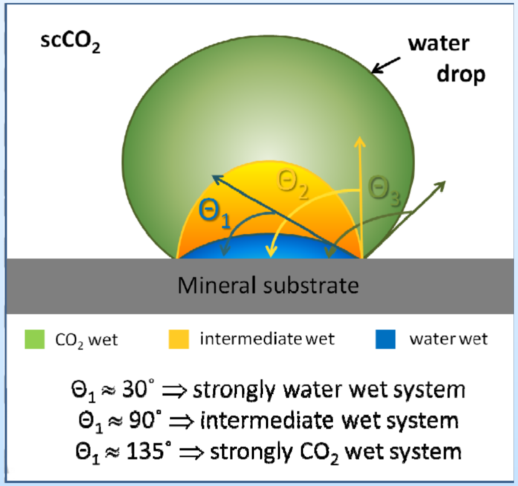


Table 4: *Parameters for Saline Formation Efficiency*

Term	Symbol	P_{10}/P_{90} Values by Lithology			Description
		Clastics	Dolomite	Limestone	
Displacement terms used to define the pore volume immediately surrounding a single well CO_2 injector					
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.
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 from IEA (2009)



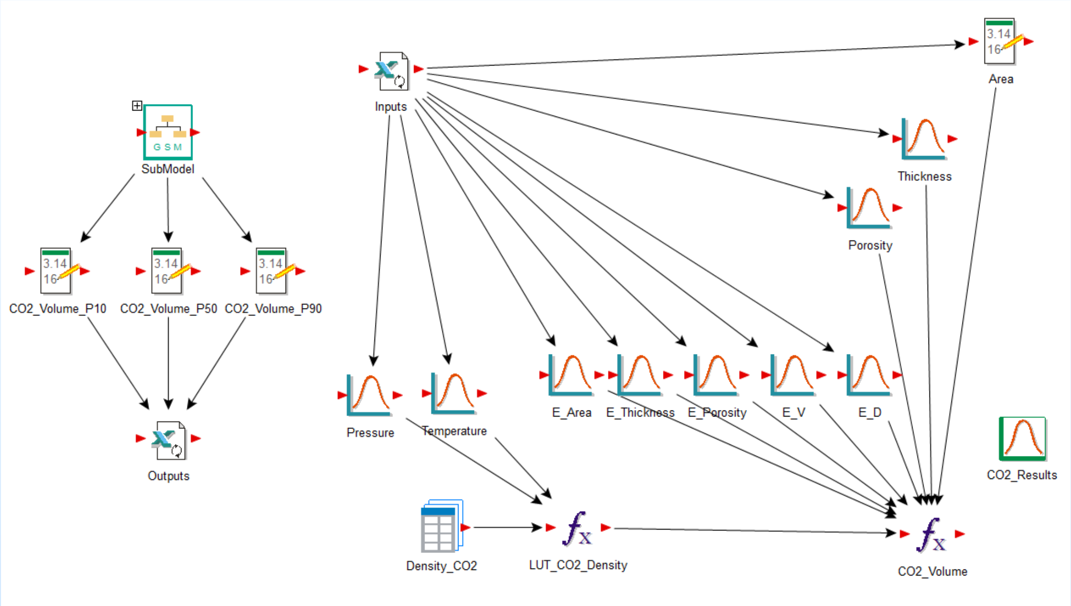
Beta Version

GoldSim Model and Output

GoldSim performs Monte Carlo sampling (n=10,000) using the following equation:

$$CO_2 = \frac{1}{\left(1+e^{(-E_{hg})}\right)} * \frac{1}{\left(1+e^{(-E_{\phi tot})}\right)} * \frac{1}{(1+e^{(-E_V)})} * \frac{1}{(1+e^{(-E_D)})} * A_t * h_g * \phi_{tot} * \rho$$

It calculates the statistical P_{10}, P_{50}, and P_{90} probability values of volumetric CO_2 and exports it in the format to the right



Estimated CO_2 Storage Capacity

	Oriskany Formation	8/15/2015	
CO_2 Storage Statistics			
P10	0.018347	Mt	
P50	0.073574	Mt	
P90	0.211128	Mt	
P10	0.000018	Gt	
P50	0.000074	Gt	
P90	0.000211	Gt	
Information			
Lithology and Depositional Environment	Clastics: Shallow Shelf		

U.S. DEPARTMENT OF ENERGY

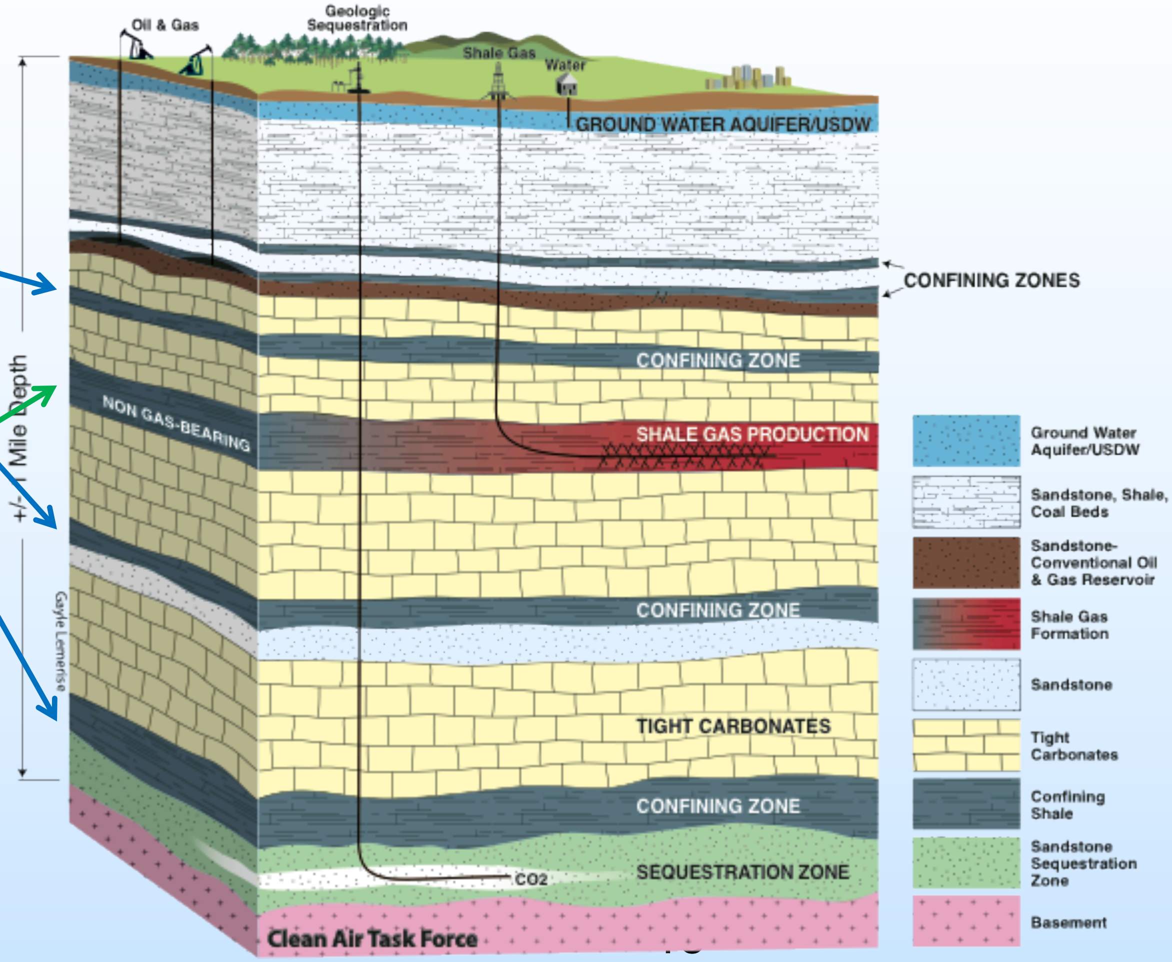
WEDNESDAY, AUGUST 19, 2015

Sean Sanguinito NETL CO2 SCREEN) 5:30 p.m. **Poster Session (SubTER, NRAP, and EFRCs)**

Prospective Storage for Shale Formations at the *National and Regional Scale*

Shales as Seals

Shales as Storage Reservoirs



*Sources: **HF illustration from National Energy Technology Laboratory (NETL), 2011),** Micro CT images by Rebecca Rodriguez, ORISE; Shale image from Reference: Lacazette , A. and Engelder, T. (1992) Fluid-driven cyclic propagation of a joint in the Ithaca Siltstone, Appalachian Basin, New York: p. 297 - 323 in B. Evans and T.-F. Wong (editors): Fault Mechanics and Transport Properties of Rocks; a festschrift in honor of W. F. Brace: Academic Press, San Diego.; NETL Carbon Storage Atlas IV (2012)*

Prospective Storage Resource for CO_2 storage in shale at the *national scale at the Exploration Phase*.

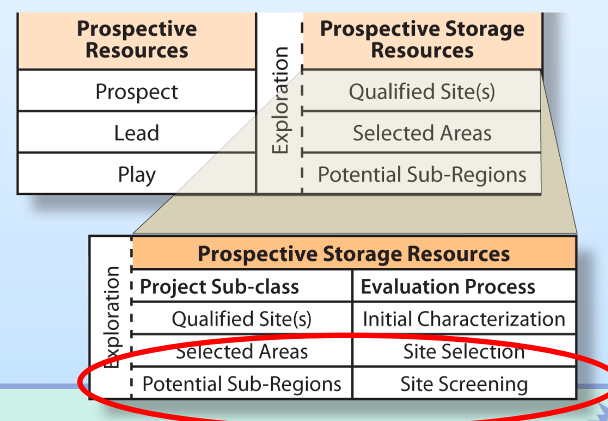
- Develop *National* Scale Prospective Method
- Builds upon existing Volumetric Approach
- Based on highly-limited data availability

- Produce a universally-applicable method capable of being applied to *all* U.S. shale basins — even pre-production formations lacking detailed geophysical data — to provide prospective CO_2 resource at a national level.

- Applied by RCSPs and external stakeholders

Pierre Shale core recovered at the surface in SD
Photo by Dan Soeder, 2014

DOE CO_2 Storage Classification

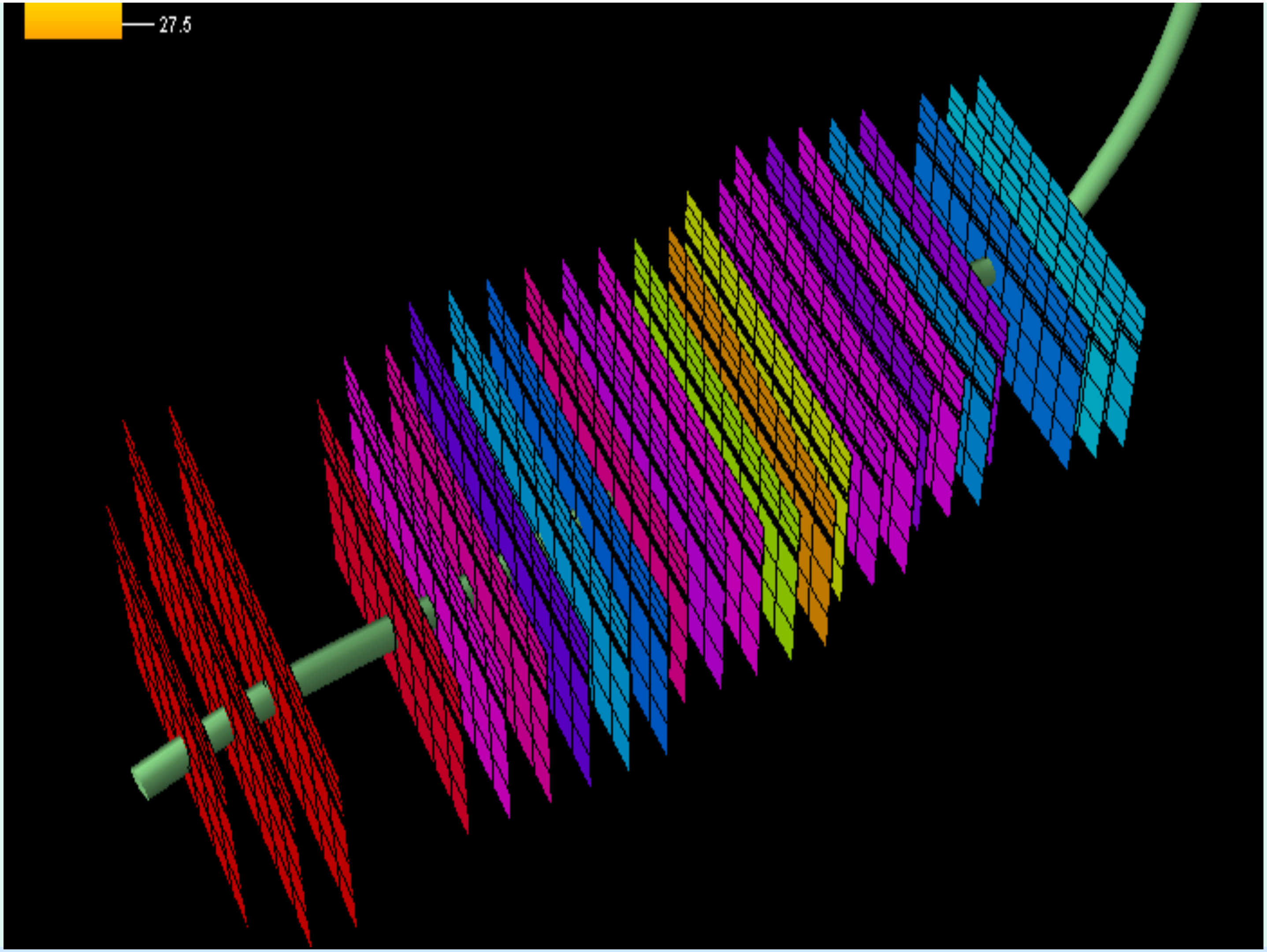


Shales Considered for Prospective CO_2 Storage

- **Prospective** – shale formations where hydrocarbons are/were produced
  - Existing reduced-cost infrastructure and site characterization
  - Favorable transport properties: both artificially induced hydraulic fractures and a natural fracture network
  - Pore space and sorption site availability
  - Pressure and temperature conditions adequate to keep the CO_2 liquid or supercritical
  - Suitable seal system

- **Potentially Prospective** – shale formations having similar geologic characteristics as prospective formations including dense-phase CO_2 conditions, but have not (yet) produced hydrocarbons
  - Indication of favorable transport properties, specifically a pre-existing natural fracture network.
  - Category includes many gray shale formations, i.e. TOC < 2%, which have not generally been used for hydrocarbon production but could be in the future.

- **Likely Non-Prospective** - characteristics that preclude future CO_2 storage based on current requirements
  - Pressures and temperatures not adequate
  - No extensive natural fracture network (extremely low organic content)
  - Likely to serve as sealing layers rather than injection layers
  - NOT considered in the method



SOURCE: Range Resources: http://thepacoalition.com/wp-content/uploads/2011/06/The-Marcellus-Experience-Part-11.pdf

Estimating CO_2 Storage Resource of Shales

induced hydraulic fractures → natural fracture network → matrix pores → sorption sites (clay or kerogen)

High — CO_2 Storage Efficiency: — Low

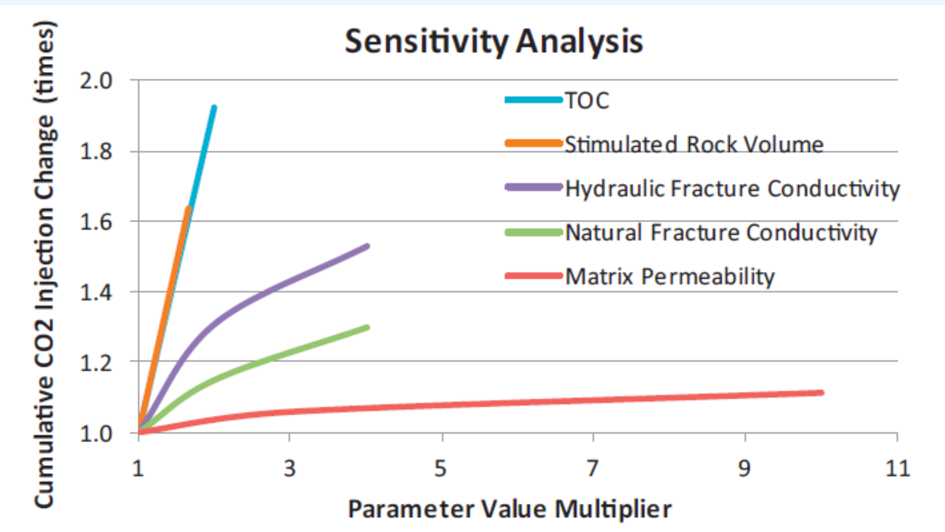


Fig. 15. Comparison of influences from all tested parameters on CO_2 storage performance.

Liu, Ellett, Xiao, Rupp International Journal of Greenhouse Gas Control, 7, 2013, 111-126

Prospective CO_2 Storage Resource Method for Shales

Represents the physically accessible CO_2 storage volume

Volumetric Equation:

$$G_{CO_2} = \underbrace{A_t E_A h_g}_{\text{Net Volume}} E_h \rho_{CO_2}\left[\phi E_\phi + (1-\phi)E_S\right]$$

Net Volume

(1) *void phase* storage in Stimulated Reservoir fractures, natural fractures and matrix pores

(2) *Solid phase* storage on kerogen & clay components

Efficiency: ***fraction*** **of the total formation volume that will be accessed for CO_2 storage**

Accounts for storage limitations that may prevent CO_2 from accessing 100% of the theoretical storage volume
(*e.g. Goodman et al., 2011*)

NETL

Prospective CO_2 Storage Resource Method for Shales

Volumetric Equation:

Expand to separate measureable sub-surface physical phenomena

$$G_{CO_2} = A_t E_A h_g E_h \rho_{CO_2} [E_{if}(\phi_{if} + [E_{nf}(\phi_{nf} + [E_m(\phi_m + [(1 - \phi_{if} - \phi_{nf} - \phi_m)E_S])])])]$$

Net Volume

Induced Fractures

Natural Fractures

Matrix Pores

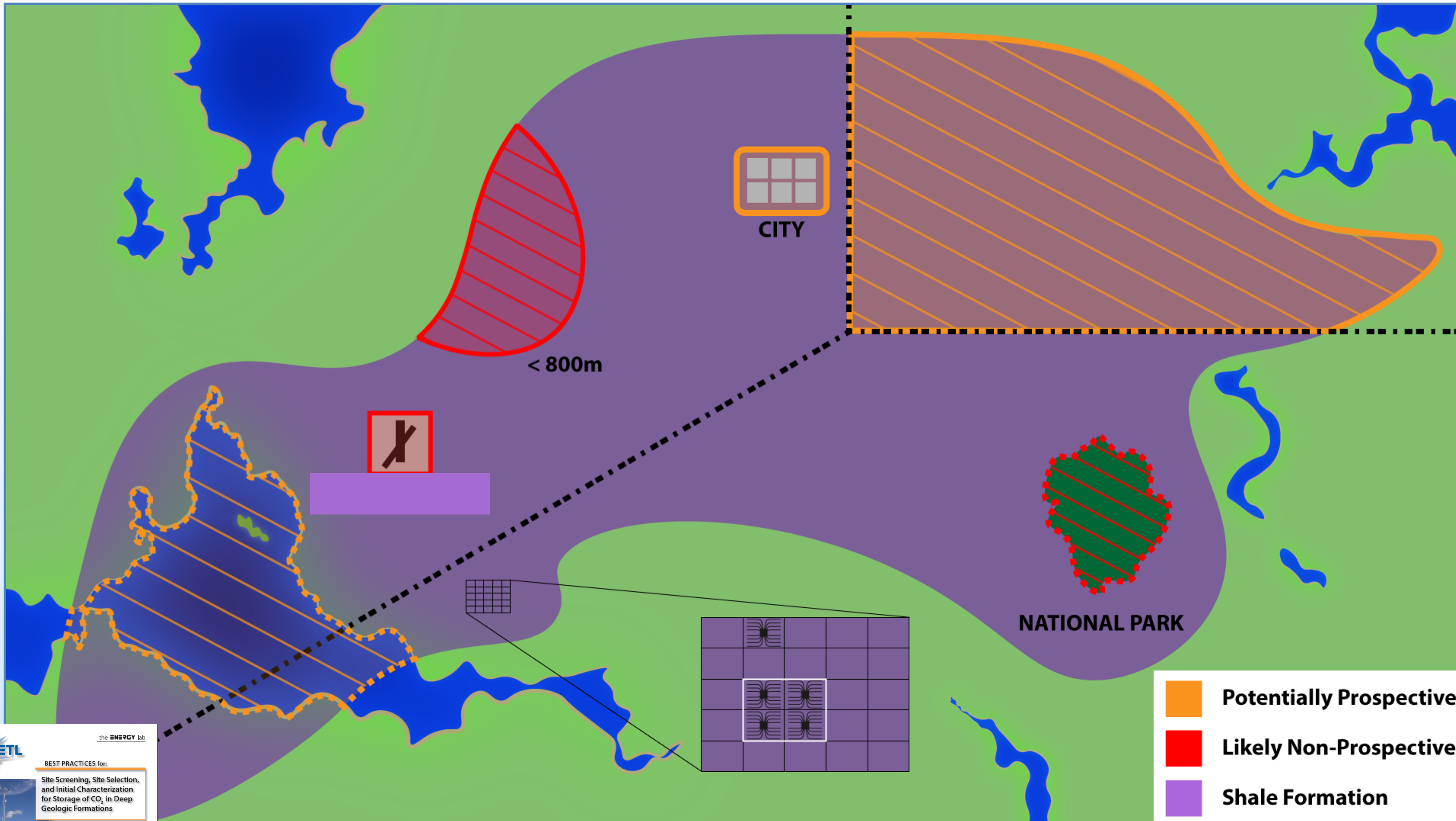
Sorption

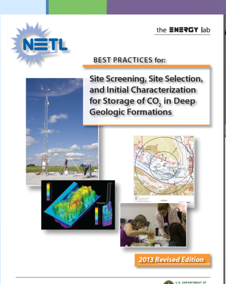
Kerogen and Clays

$$E_s = (\rho^{STP}_{CO_2} / \rho_{CO_2})(C^c_{co2} C^s_c \mathrm{E}_C + C^k_{co2} C^s_k \mathrm{E}_k)\rho_{s,g}.$$

Area Efficiency Term(E_A)

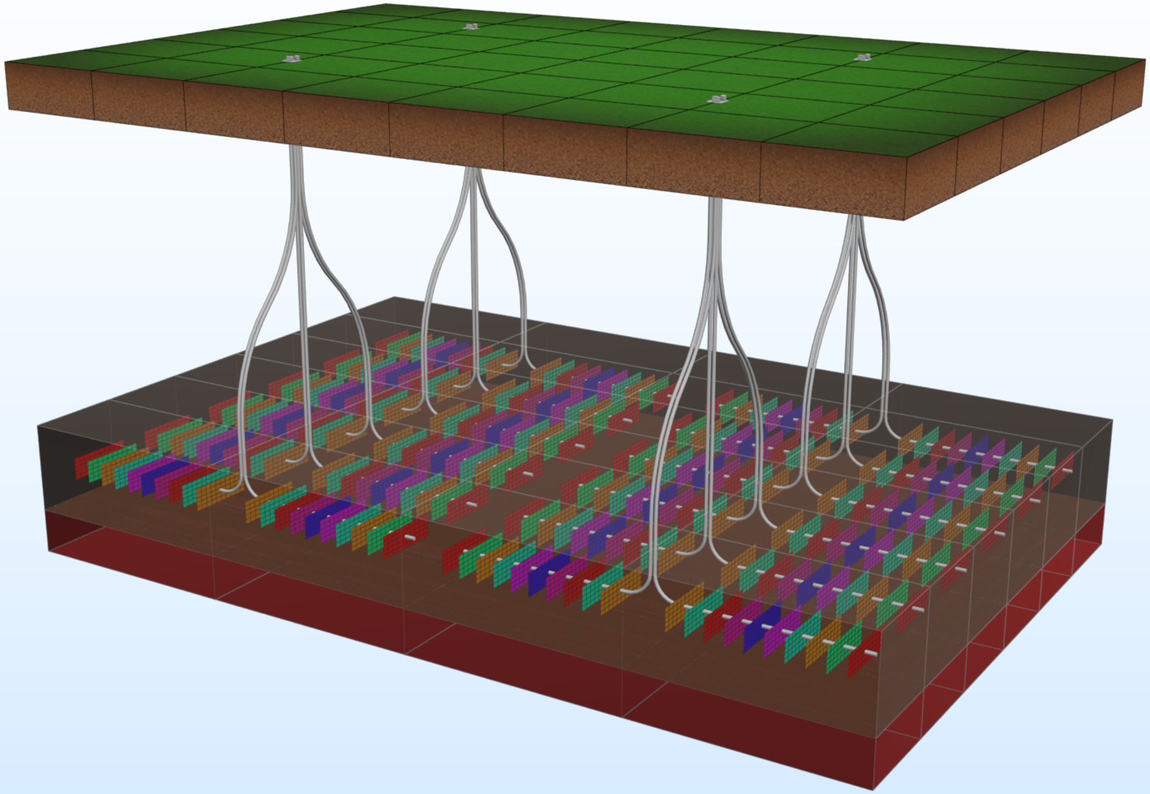
$$A_t E_A h_g E_h$$





Thickness Efficiency Term(E_h)

$$A_t E_A h_g E_h$$



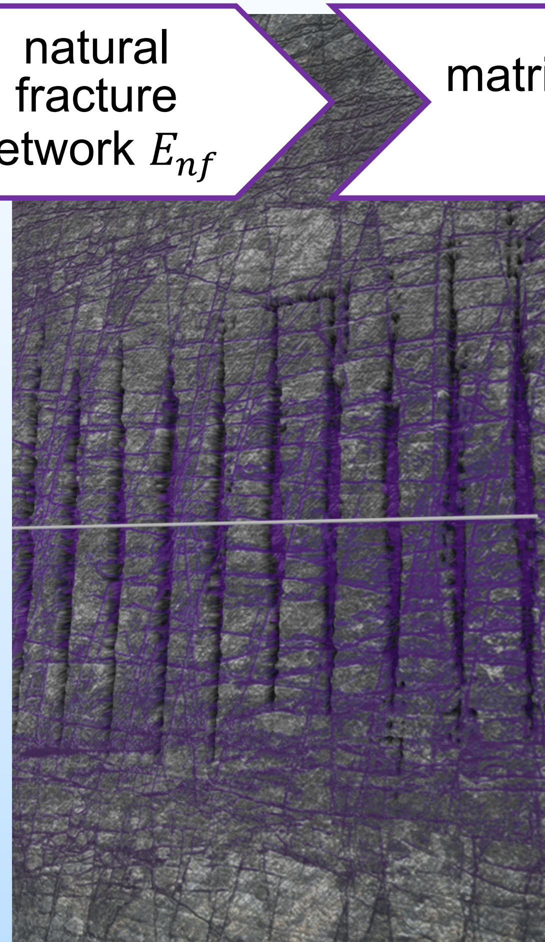
Transport of CO_2 from the Well into the Surrounding Formation E_{if}, E_{nf}, E_m, E_c, and E_k

induced hydraulic fractures E_{if}

natural fracture network E_{nf}

matrix pores E_m

sorption sites (clay or kerogen) E_c, and E_k



Shale: Potential to Store CO_2

Advantages

1. Existing well infrastructure and engineered fracture systems
2. CO_2: CH_4 adsorption ≈3:1 *(at 7Mpa)*
3. Close proximity to CO_2 sources

Challenges

1. Low permeability: *100-500 nanodarcys*
2. Matrix porosity: *accessible?*
3. Heterogeneity
4. Sensitivity to stress
5. Fracture variability: *engineered vs. natural*

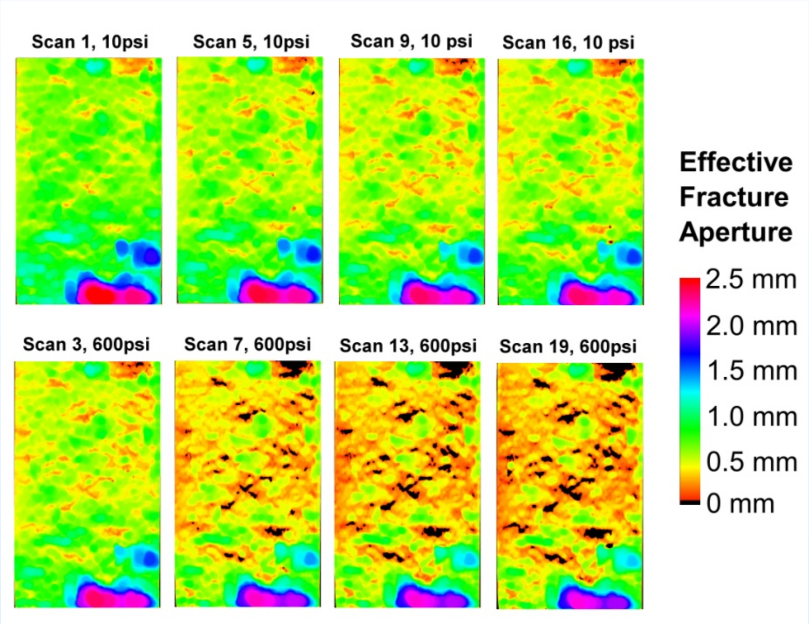
Picture of Utica Shale from the Ohio Oil and Gas Association

Characterize fracture conductivity change in response to shale swelling with CO_2

Does CO_2 sorption lead to swelling in shales, reducing effective fracture aperture and fracture hydraulic conductivity?

THURSDAY, AUGUST 20, 2015

11:25 AM Shales as Seals and Unconventional Reservoirs for CO_2– Robert Dilmore



Source: *Crandall, D. Gill, M., McIntyre, D.L., and Bromhal, G.S. (2013)* ***Coupling Mechanical Changes of a Fracture to Hydraulic Changes*** *SPE 165695-MS. prepared for SPE Eastern Regional Meeting held in Pittsburgh, Pennsylvania, USA, 20–22 August 2013. © 2013, SPE*

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EDXtools provide access to data and information assembled as custom themes of high interest. EDXtools are standard, static, frameworks; however, the data presented within them may update and change with time, thus offering fresh and current information. EDXtools may accommodate spatial and/or non-spatial data. Some EDXtools are designed to allow the EDXtool to communicate with EDX servers to allow for searching, querying, and displaying data.

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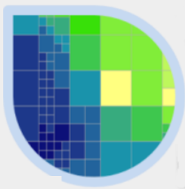
Global CO_2 Storage Portal

NETL

National Energy Technology Laboratory's (NETL) Carbon Storage Database Link Library, GLOBAL CO_2 STORAGE PORTAL, is a map-based application that provides quick access to the primary on-line sources of Carbon Storage Atlases associated with stationary CO_2 sources and potential geologic sinks for countries around the world.

Keywords: Carbon Storage | NETL | Atlas | CO2 | geologic sinks

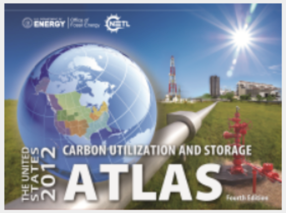


Variable Grid Method

NETL

NETL's Variable Grid Method (VGM) is a novel approach that leverages GIS capabilities to simultaneously visualize and quantify spatial data trends and underlying data uncertainty. The flexible VGM approach utilizes a range of spatial datasets and uncertainty quantifications, which can be calculated using data related to sample density, sample variance, interpolation error, multiple simulations, etc., to create an integrated visualization of data and uncertainty. The intuitive manner of the VGM helps communicate the relationship between uncertainty and spatial data to effectively guide research, support advanced computation analyses, and helps inform research, management and policy decisions. The VGM approach is being developed into a Python Add-in extension and toolbar for ArcGIS, providing users the capabilities to utilize the VGM for their datasets, analysis, and models in support of their decision making needs. The VGM approach was developed as part of NETL's Offshore portfolio. It was further matured and utilized in projects associated with both NETL's Unconventional Resources and Carbon Storage portfolios.

Keywords: Geospatial | Analytics | VGM



NATCARB

NETL

The National Carbon Sequestration Database (NATCARB) is a geographic information system (GIS)-based tool for viewing carbon capture, use and storage (CCUS) potential across the United States. Through a graphical user interface, NATCARB displays locations and associated metadata about stationary CO_2 sources and potential geologic sinks. Users can access, query and model, analyze, display, and download CO_2 storage resource data.

Keywords: Geospatial

TBD: *NETL CO_2 SCREEN*

Beta Version

Synergy Opportunities

– All methodologies undergo review by the Regional Carbon Sequestration Partnerships (RCSPs), field experts, and the peer-review process prior to being released in the Atlas.
– Incorporation of Experimental and Modeling parameters need to refine and improve storage efficiency factors

Summary: Prospective CO_2 Storage

Develop Defensible DOE Methodology for Regional Assessments

- *Unconventional Systems*
  - *Method will be ready for RCSP review in the near term followed by peer review*
  - *Future work – application to formations across the U.S.*
  - *Future work - Modeling effort for storage efficiency ranges*
- *Oil and Gas Systems*
  - *Method will be ready for RCSP review in the near term followed by peer review*
- *Offshore*
  - *Future – work beginning on developing a method for prospective storage in the offshore*

Expand Methodology to Include Stochastic Approach for Key Parameters

- *Saline Systems*
  - *Method and tool will be ready for RCSP review in the near term followed by peer review*

Expand Methodology to Include Geospatially Variable Key Parameters

- *Saline Systems*
  - *Application to the Oriskany Formation is in progress*

Accomplishments to Date

- NETL CO_2 SCREEN ***(Storage CO_2 Resource Estimation Excel aNalysis)*** Beta Version

The US-DOE storage method for the national and regional scale supplies a basic volumetric equation with broad national to regional scale storage efficiencies. As this method meant to be applied to regions when little to not geologic data are available, the method is not well suited when improved geologic parameters are known. This tool provides a US-DOE basin scale method and tool for estimating prospective CO_2 storage in saline formations when greater level of geologic characterization is available.

- Shale Prospective Method

U.S. DOE Method for Estimating the Prospective CO_2 Storage Resource of Shale Formations at National and Regional Scales

- **Global CO_2 Storage Portal**

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- **Variable Grid Method**

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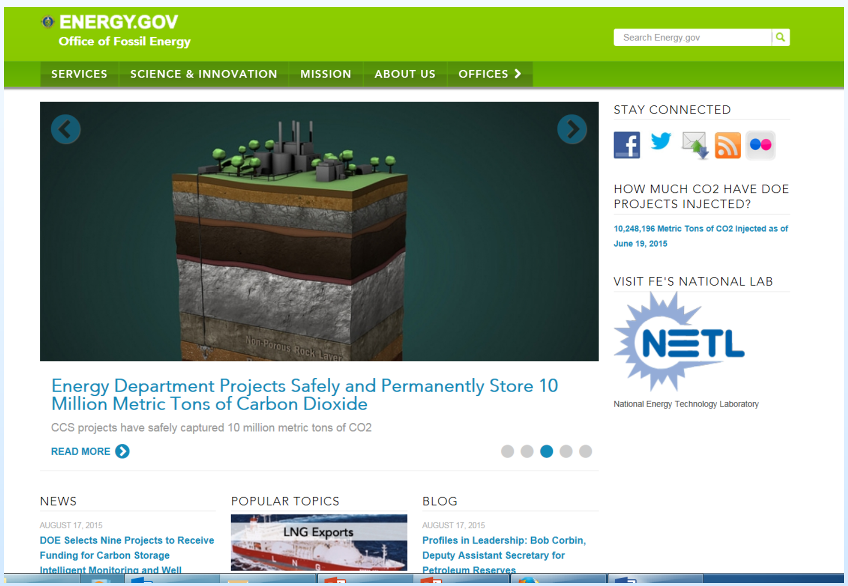
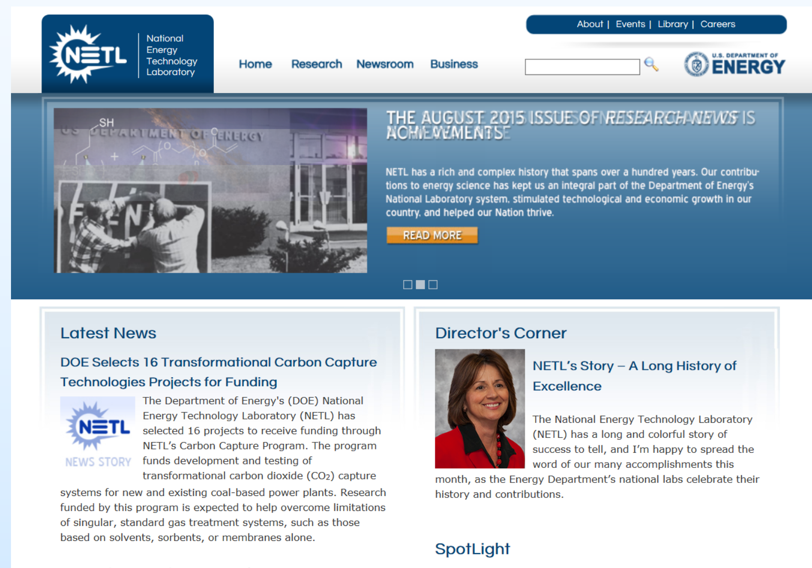
Research Team

Team Members:

Robert Dilmore, Daniel Soeder, Grant Bromhal, Kelly Rose, Angela Goodman, Sean Sanguinito, Emily Dixon, Jonathan Levine, Corinne Disenhof, Jenifer Bauer, Maneesh Sharma, Russel Johns, Nic Azzolina, David Nakles, Isis Fukai,





Office of Fossil Energy

http://energy.gov/fe/office-fossil-energy

National Energy Technology Laboratory

www.netl.doe.gov

Appendix

– These slides will not be discussed during the presentation, but are mandatory

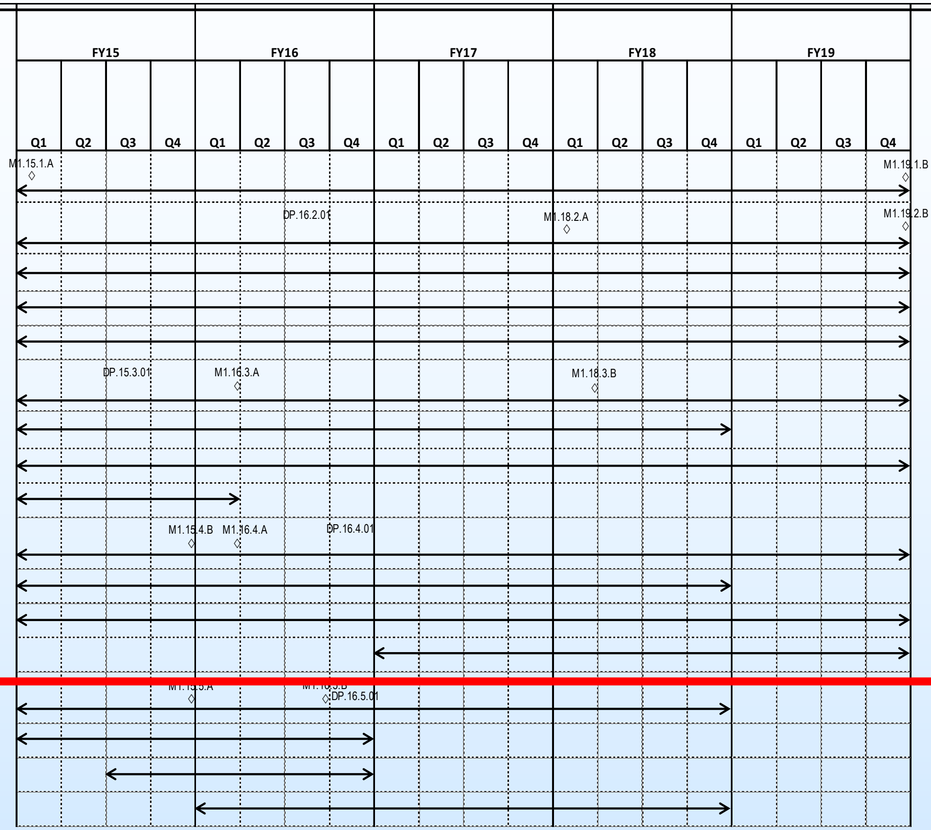
Organization Chart

Task 5.0 Resource Assessments (TTT: Angela Goodman)

- **Subtask 5.1 Develop Defensible Department of Energy Methodology for Regional Assessment (Angela Goodman)**
- **Subtask 5.2 Expand Methodology to Include Stochastic Approach for Key Parameters (Angela Goodman)**
- **Subtask 5.3 Expand Methodology to Include Geospatially Variable Key Parameters (Kelly Rose)**

Gantt Chart

FY15 Carbon Storage (Project Period: 10/01/14 – 09/30/19)	Project Dates For each Task, Subtask, Sub-subtask of your WBS **Start** Reflects the date the work is scheduled to begin	 **Finish** Reflects the date the work is scheduled for completion
1. Project Management and Planning	**10/1/2014**	**9/30/2019**
2. Reservoir and Seal Performance	**10/1/2014**	**9/30/2019**
2.1 Understanding Relative Permeability, Residual Saturation, and Porosity in Reservoirs to Reduce Uncertainty in Long-Term CO_2 Storage and Efficiency	10/1/2014	9/30/2019
2.2 Improve Characterization of Physical Changes in Reservoir and Seal Rock due to CO_2	10/1/2014	9/30/2019
2.3 Determine Impact of Microbial Induced Changes on Reservoir Performance	10/1/2014	9/30/2019
3. Shales as Seals and Unconventional Reservoirs	**10/1/2014**	**9/30/2019**
3.1 Understanding Permeability, Residual Saturation, and Porosity in Shale to Reduce Uncertainty in Long-Term CO_2 Storage and Efficiency	10/1/2014	9/30/2018
3.2 Improve Characterization of Physical Changes in Shale with Exposure to CO_2	10/1/2014	9/30/2019
3.3 Field Activity to Obtain, Log, Ship, and Store Shale Core from South Dakota	10/1/2014	12/31/2015
4. Monitoring Groundwater Impacts	**10/1/2014**	**9/30/2019**
4.1 Develop and Demonstrate Monitoring Tools and Protocols for Groundwater Systems	10/1/2014	9/28/2018
4.2 Assess Impacts: Natural Groundwater Variability	10/1/2014	9/30/2019
4.3 Fundamental Controls on Groundwater Composition	10/1/2016	9/30/2019
5. Resource Assessments	**10/1/2014**	**9/30/2018**
5.1 Develop Defensible Department of Energy Methodology for Regional Assessment	10/1/2014	9/30/2016
5.2 Expand Methodology to Include Stochastic Approach for Key Parameters	4/1/2015	9/30/2016
5.3 Expand Methodology to Include Geospatially Variable Key Parameters	10/1/2015	9/30/2018



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- Goodman, A. Method for Assessing CO2 Storage Potential of Organic-Rich Shale Formations Accepted for presentation at the GHGT-12 Conference, Austin, TX, Oct 5–9, 2014; Paper # 1205.00
- Data Driven Application of DOE Method for CO_2 Storage in Saline Formations Angela Goodman, Kelly Rose, Jennifer Bauer, Corinne Disenhof, Sean Sanguinito, Emily Dixon, Jonathan Levine, and Robert Dilmore Carbon Capture, Utilization & Storage *Gordon Research Conference* Defining the Frontiers May 31 - June 5, 2015 Stonehill College Easton, MA
- .