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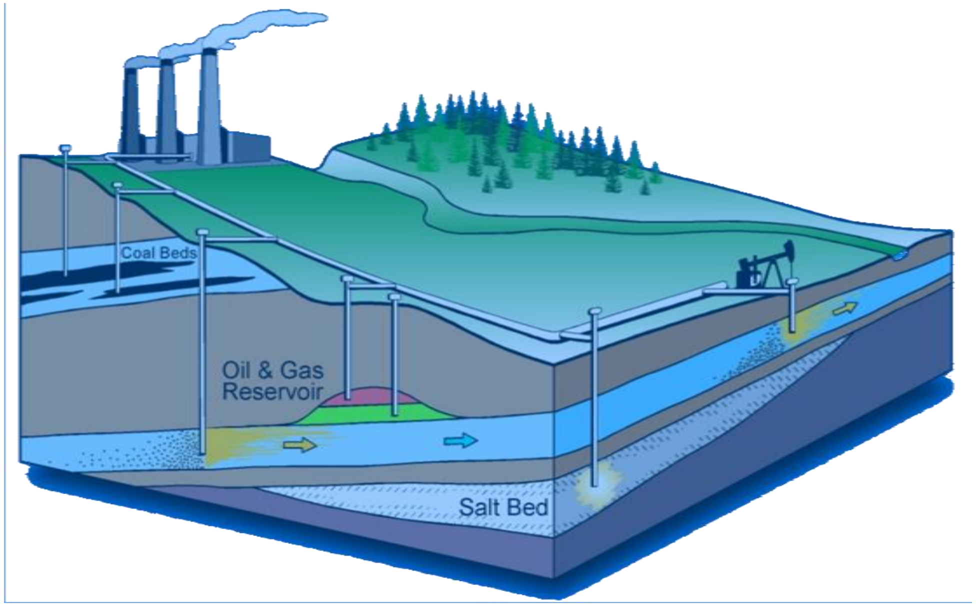
# Estimation of $CO_2$ Storage Capacity

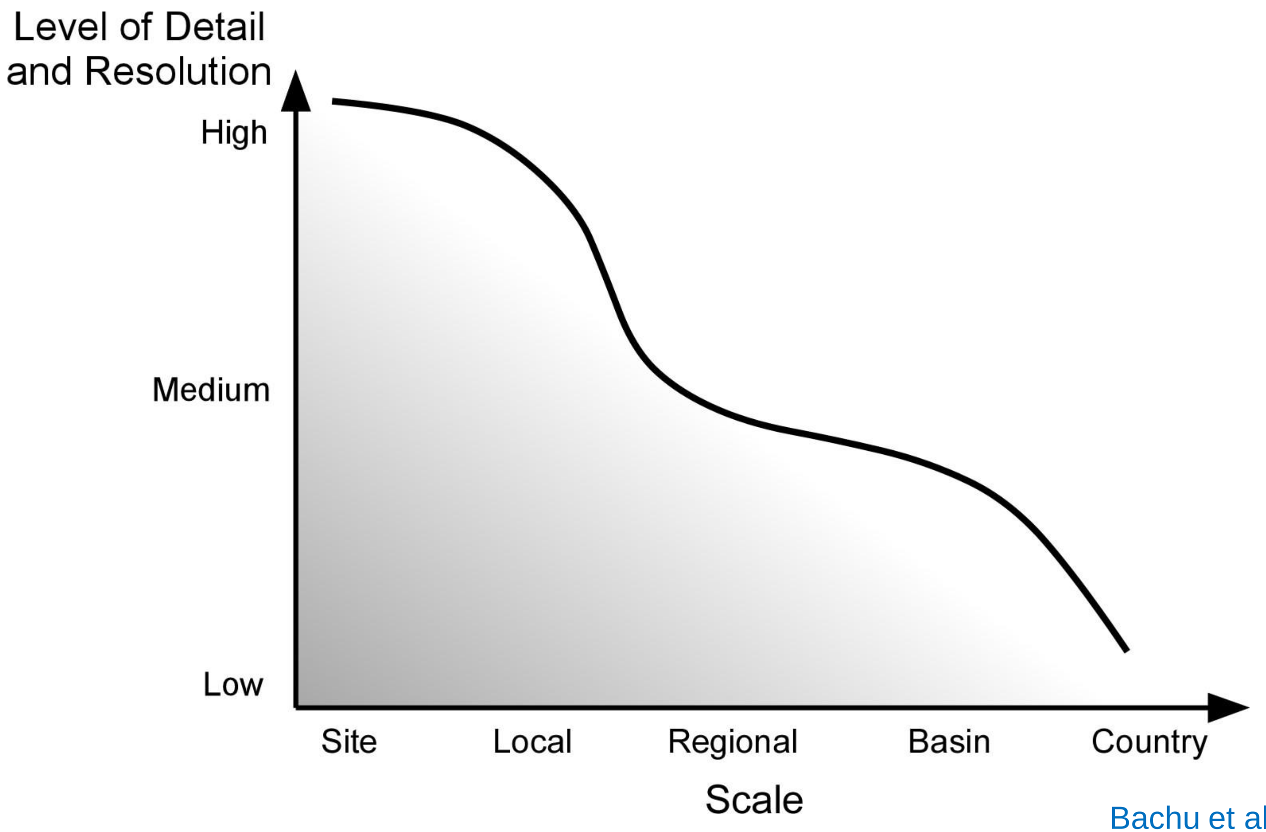


# Assessment Scales and Resolution

- **Country**: high level, minimal data
- **Basin**: identify and quantify storage potential
- **Regional**: increased level of detail, identify prospects
- **Local**: very detailed, pre-engineering site selection
- **Site**: engineering level for permitting, design and implementation

Note: Depending on the size of a country in relation to its sedimentary basin(s), the order of the top two or three may interchange

# Relationship Between Assessment Scale and Level of Detail and Resolution

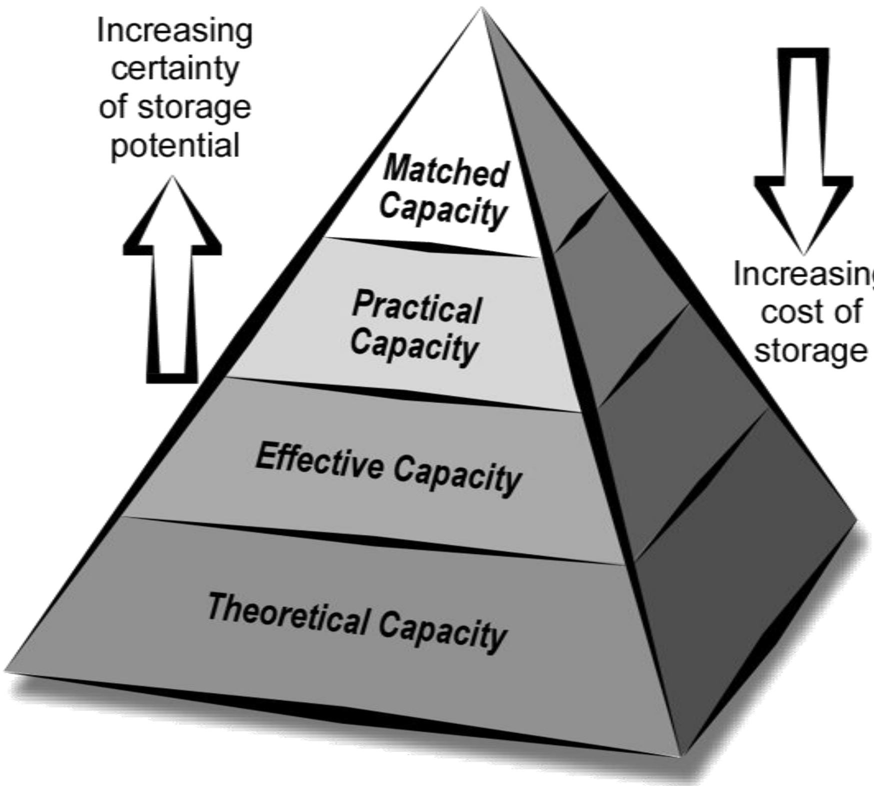



Bachu et al., IJGGC, 2007

# Assessment Types

- **Theoretical**: physical limit of the system
- **Effective**: accounts for geological and engineering cut-offs
- **Practical**: accounts for technical, legal and regulatory, infrastructure and economic barriers
- **Matched**: obtained by source-sink matching (SSM)

# Techno-Economic Resource-Reserves Pyramid for $CO_2$ Storage Capacity




Bachu et al., IJGGC, 2007

# History - 1

- Up to 2004, different methods were used by various researchers, based mainly on basin surface area, average basin thickness and an arbitrary fraction for storage, considering $CO_2$ trapping in free phase or in solution to full saturation, with the following results:
  - Inconsistent methodologies that did not allow comparison
  - Significant discrepancies in assessments
  - Country-scale capacity assessments greater than world-wide assessments
  - Inability to properly advise decision makers about storage potential and resources

- Deficiencies brought to light during the writing of the IPCC Special Report on CCS (2005) and at the CSLF meeting in 2004, where consequently a Task Force on Estimating $CO_2$ Storage Capacity was established.

- First findings of the CSLF Task Force were presented to CSLF ($1^{st}$ report) and at GHGT-8 in 2006, then published in IJGGC in 2007 (Bradshaw et al., 2007)

# History - 2

- The CSLF Task Force devised consistent volumetric-based methodology for estimating $CO_2$ storage capacity at the country and basin scales, widely accepted in Europe and elsewhere, for deep saline aquifers, coal beds and hydrocarbon reservoirs, introducing storage efficiency coefficients C but with no numerical values provided (results published in 2nd CSLF report and in IJGGC, 2007, Bachu et al., 2007)

- In parallel and independently, the US Regional Partnerships developed similar methodology for the volumetric estimation of $CO_2$ storage capacity in deep saline aquifers, coal beds and hydrocarbon reservoirs, with values for storage efficiency coefficients E for P15, P50 and P85 developed by using Monte-Carlo simulations. These were used for estimating $CO_2$ storage capacity in the US, resulting in the first edition of the Atlas of $CO_2$ Storage Capacity in US and Canada

- CSLF and USDOE methodologies are equivalent, as shown in the 3rd report to CSLF in 2008 by the Task Force, with the CSLF methodology providing explicitly for residual gas saturation in the formulae

# $CO_2$ Storage Capacity

Both CSLF and USDOE have shown that $CO_2$ storage capacity has to be calculated individually for oil and gas reservoirs, coal beds and deep saline aquifers, rather than for full sedimentary basins, according to:

$$M_{CO2} = E \times V_{CO2} \times \rho_{CO2}(P, T)$$

Where $M$ is mass, $V$ is the pore space in the rock mass of area $A$, thickness $h$ and porosity $\varphi$, $\rho_{CO2}$ is $CO_2$ density and $P$ and $T$ are in-situ pressure and temperature. The irreducible water saturation, $S_{wirr}$, can be explicitly factored on the above equation (CSLF), but because of lack of data, particularly at the formation scale, it is actually included in the efficiency coefficient $E$ (USDOE). For coal beds, $\rho_{CO2}$ is at standard conditions of pressure and temperature.

The challenge is in estimating the value of the storage efficiency coefficient $E$!

# Estimation of $CO_2$ Storage Capacity

By storage medium and by scale of assessment:

- In oil and gas reservoirs
- In unmineable coal beds
- In deep saline aquifers

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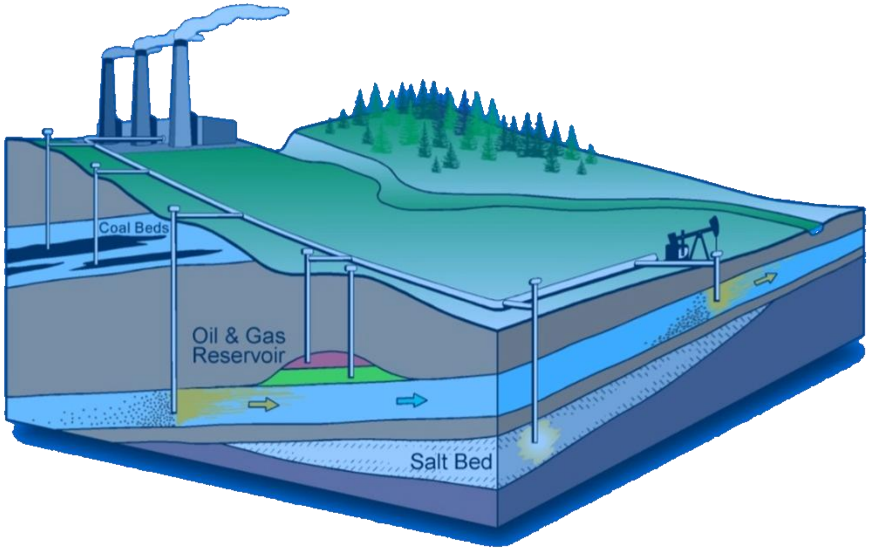
# Estimation of $CO_2$ Storage Capacity in Oil and Gas Reservoirs

It is done at the reservoir or pool level, which are spatially discrete



# Theoretical Mass $CO_2$ Storage Capacity in Depleted Oil Reservoirs

## Theoretical Capacity

$$M_{CO2t} = \rho_{CO2r} \quad [\, R_f \quad OOIP / B_f - V_{iw} + V_{pw}]$$

or

$$M_{CO2t} = \rho_{CO2r} \quad [R_f \quad A \quad h \quad \phi \quad (1 - S_w) - V_{iw} + V_{pw}]$$

- $M_{CO2t}$: Theoretical storage capacity
- $\rho_{CO2r}$: $CO_2$ density at initial reservoir conditions
- $R_f$: Recovery factor
- *OOIP*: Original Oil in Place
- $B_f$: Formation factor

- $A$: Reservoir area
- $h$: Reservoir thickness
- $\phi$: Porosity
- $S_w$: Water saturation
- $V_{iw}$: Volume of injected water
- $V_{pw}$: Volume of produced water

# Theoretical Mass $CO_2$ Storage Capacity in Depleted Gas Reservoirs

## Theoretical Capacity

$$M_{CO2t} = \rho_{CO2r} \times R_f \times (1 - F_{IG}) \times OGIP \times \frac{P_S \times Z_r \times T_r}{P_r \times Z_S \times T_S}$$

- $M_{CO2t}$: Theoretical storage capacity
- $\rho_{CO2r}$: $CO_2$ density at initial reservoir conditions
- $R_f$: Recovery factor
- *OGIP*: Original Gas in Place
- $F_{IG}$: Fraction of (re-)injected gas

- *P*: Pressure
- *T*: Temperature (°K)
- *Z*: Z-factor (gas compressibility)
- *r,s*: reservoir; surface subscripts

# Effective Mass $CO_2$ Storage Capacity in Depleted Oil and Gas Reservoirs

## Effective Capacity

$$M_{CO2e} = C_m \quad C_b \quad C_h \quad C_w \quad C_a \quad M_{CO2t} \equiv C_e \quad M_{CO2t}$$

- $M_{CO2t}$: Theoretical storage capacity
- $M_{CO2e}$: Effective storage capacity
- $C$: Efficiency coefficients

*Subscripts*

- *m*: mobility
- *b*: buoyancy
- *h*: heterogeneity
- *w:* water saturation
- a: aquifer strength
- t: theoretical
- e: effective

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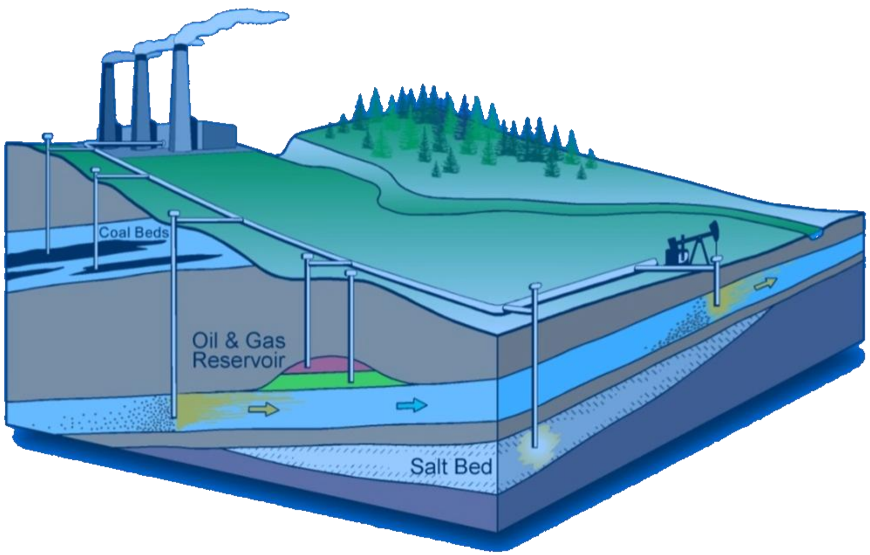
# Estimation of $CO_2$ Storage Capacity in Unmineable Coal Seams

It is done at the coalbed level, which is spatially continuous



# Regional-Scale Mass $CO_2$ Storage Capacity in Coal Beds

## Theoretical Capacity

$$IGIP = \rho_{CO2} \times A \times h \times \rho_{coal} \times G_c \times (1 - f_a - f_m)$$

## Effective Capacity

$$PGIP = R_f \times C \times IGIP$$

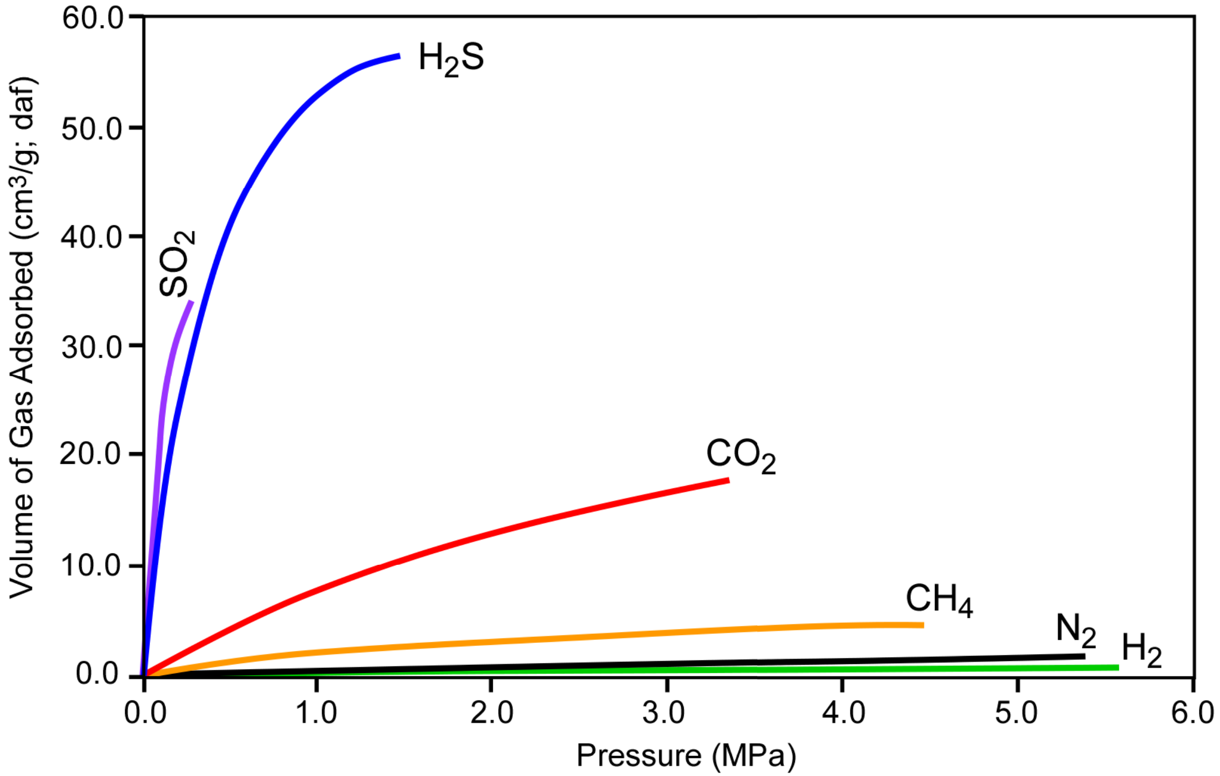
- *IGIP*: Initial Gas in Place
- (or storage capacity)
- *A*: Area of the coal bed ($m^2$)
- *h*: Net thickness of the coal bed (m)
- $\rho_{coal}$: Coal density, ~1.4 $t/m^3$
- $\rho_{CO2}$ $CO_2$ density at STP, = 1.78 $kg/m^3$

- $G_c$: Gas content ($cm^3/g$ or $m^3/t$)
- $f_a$: Ash fraction
- $f_m$: Moisture (water) fraction
- $R_f$: Recovery factor
- C: Completion factor

# Coal Gas Content

$$G_{CS} = V_L \times \frac{P}{P + P_L}$$

- P: Pressure
- $P_L$: Langmuir pressure
- $V_L$: Langmuir volume



# Storage Efficiency Coefficients (%) for Storage in Coal Seams

| Case | $P_{10}$ | $P_{50}$ | $P_{90}$ |
|---|---|---|---|
| When area and thickness are uncertain | 21 | 37 | 48 |
| When area and thickness are certain | 39 | 64 | 77 |

$P_x$ -> there is (1-x)% certainty that this resource exists

Goodman et al., IJGGC, 2011

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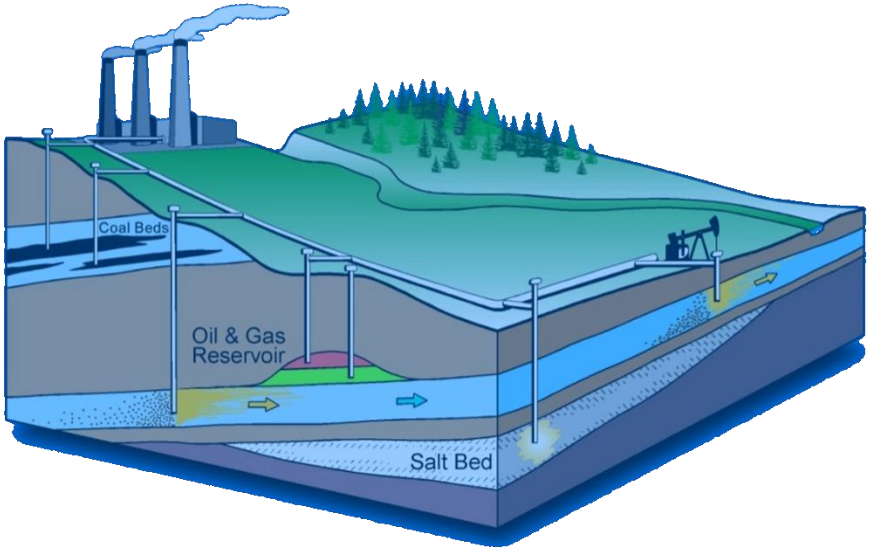
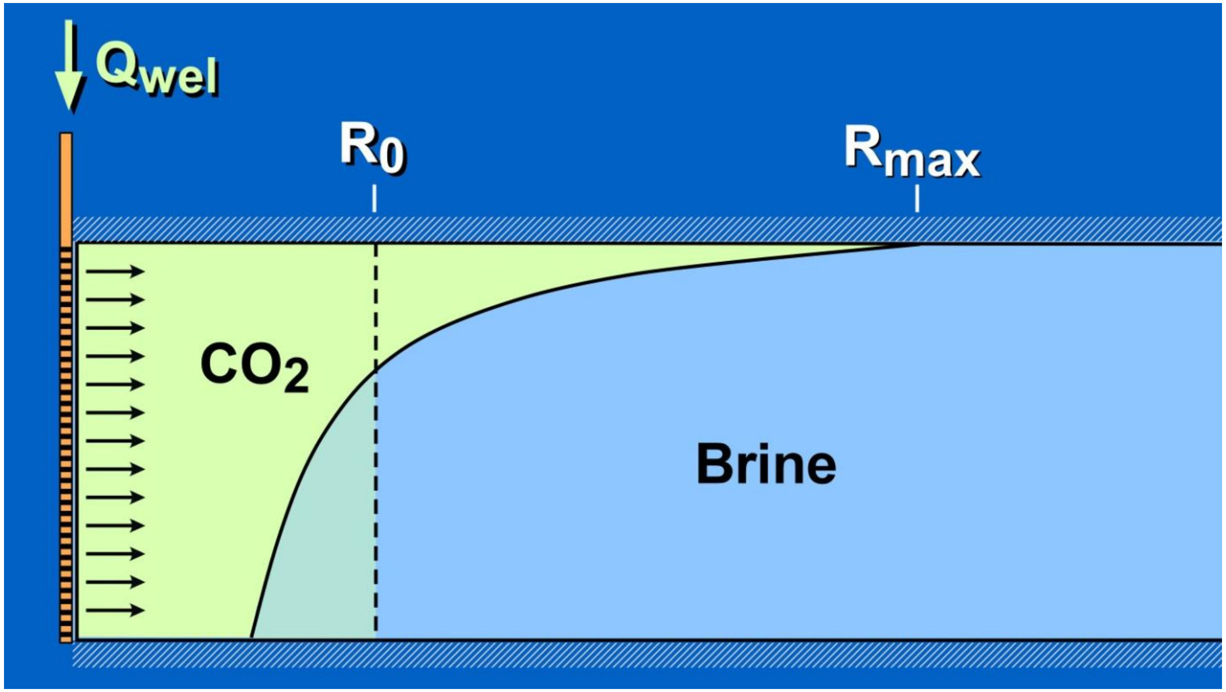
# Estimation of $CO_2$ Storage Capacity in Deep Saline Aquifers

**It is done at the aquifer level, which is spatially discrete in stratigraphic and structural traps, and is spatially continuous in laterally open aquifers**



# Spread of a $CO_2$ Plume and Storage Efficiency




Storage efficiency coefficient $E = V_{CO2}/(\pi R^2_{max})$

# Storage Efficiency Coefficient Dependencies

- *E* decreases with increasing buoyancy (low $CO_2$ density)
- *E* decreases with increasing mobility (low $CO_2$ viscosity)

  $CO_2$ density and viscosity increase with increasing temperature

- *E* increases with increasing capillary forces
- *E* increases with increasing medium heterogeneity

- Relative permeability and irreducible gas saturation affect storage efficiency

# Volumetric $CO_2$ Storage Capacity in Structural and Stratigraphic Traps and Open Deep Saline Aquifers

## Theoretical Volumetric Capacity

$$V_{CO2t} = V_{trap} \quad \phi \quad (1 - S_{wirr}) \equiv A \quad h \quad \phi \quad (1 - S_{wirr})$$

or, if the spatial variability is known

$$V_{CO2t} = \iiint \phi (1 - S_{wirr}) dxdydz$$

## Effective Volumetric Capacity

$$V_{CO2e} = E \quad V_{CO2t}$$

- $V_{CO2t}$: Theoretical storage volume
- $V_{CO2e}$: Effective storage volume
- $V_{trap}$: Trap volume
- $\phi$: Porosity

- $S_w$: Irreducible water saturation
- $A$: Average trap area
- $h$: Average trap height
- $E$: Storage efficiency coefficient

# Site-Scale Storage Efficiency Coefficients for Deep Saline Aquifers - 1

No dissolution and precipitation effects are considered over the time scale of $CO_2$ injection operations (operational or engineering time scale)

- Zhou et al. (2008), van der Meer and Egbert (2008) and Ehlig-Economides and Economides (2010) considered closed systems, where accommodation space is provided through water and pore compressibility only, arriving at values for the storage coefficient *E*

$$E = (\beta_p + \beta_w)\Delta p_{av} < 1\%$$

- Birkholzer et al. (2009) and Cavanagh et al. (2010) showed that, if caprock permeability is ≤ $10^{-19}$ $m^2$ (0.1 μD) then the system can be considered as being closed, but if caprock permeability is ≥ $10^{-18}$ $m^2$ (1 μD), then $E > 1\%$ as a result of additional accommodating space created by the displacement of formation water into the caprock at very low velocity but over a very large area

# Site-Scale Storage Efficiency Coefficients for Deep Saline Aquifers - 2

- Kopp et al. (2009a,b) calculated storage capacity for deep saline aquifers considering relative-permeability, capillary forces, buoyancy and viscosity effects, and the data in the US National Petroleum Council database and arrived statistically at values for *E* that vary between 1.17% and 3.6% depending on geothermal gradient, depth, and absolute and relative permeability

- Okwen et al. (2010) developed an analytical expression for the storage efficiency coefficient *E* in the absence of capillary forces (sharp interface between $CO_2$ and formation water) and arrived at the following values:
  - For negligible buoyancy
    - 15%-20% for low mobility ratios between $CO_2$ and formation water, and
    - 3% to 4% for high mobility ratios between $CO_2$ and formation water
  - For non-negligible buoyancy
    - 1% to 17% depending on buoyancy, for low mobility ratios, and
    - 0.1% to 2% depending on buoyancy, for high mobility ratios

# IEA-GHG
# Regional-Scale Storage Efficiency Coefficients

- Gorecki et al. (2009), commissioned by IEA-GHG, introduced the concept that the storage efficiency coefficient $E$ has a geological volumetric term $E_{Geol}$ that expresses the pore space available for storage, a volumetric displacement term $E_v$ that expresses the portion of the pore space occupied by $CO_2$ as a result of macroscopic displacement in a heterogeneous porous medium, and a microscopic displacement term $E_d$ that expresses the effect of microscopic (pore-scale) displacement processes:

$$E = E_{geol} \quad E_v \quad E_d$$

Using a database of hydrocarbon reservoir properties for >20,000 reservoirs from around the world, Gorecki et al. (2009) calculated probabilistic values $P_{10}$, $P_{50}$ and $P_{90}$ for the storage efficiency coefficient $E$ for various depositional environments using Monte Carlo simulations of $CO_2$ plume spread for various conditions of depth, pressure, temperature, structure, permeability anisotropy, irreducible water saturation and injection rate.

# IEA-GHG Regional-Scale Storage Efficiency Coefficients for $CO_2$ Storage in Deep Saline Aquifers

At the regional scale, Gorecki et al. (2009) arrived at the following values for $E$

| Lithology | E (%) @ $P_{10}$ | E (%) @ $P_{50}$ | E (%) @ $P_{90}$ |
|---|---|---|---|
| Clastics | 1.86 | 2.70 | 6.00 |
| Dolomite | 2.58 | 3.26 | 5.54 |
| Limestone | 1.41 | 2.04 | 3.27 |

$P_x$ -> there is (1-x)% certainty that this resource exists

# USDOE
# Efficiency Coefficients for $CO_2$ Storage in Deep Saline Formations

Goodman et al. (2011) used log-odds normal distributions for the data used by Gorecki et al. (2009) to arrive at more robust estimates of the value of the $CO_2$ storage efficiency coefficient *E* at the formation scale (reproduced below), values used in the 3rd edition of the National Atlas of $CO_2$ Storage Capacity for US and Canada.

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# Storage Efficiency Coefficients (%) for Storage in Deep Saline Aquifers

**At regional scale**

| Lithology | $P_{10}$ | $P_{50}$ | $P_{90}$ |
|---|---|---|---|
| Clastics | 1.2 | 2.4 | 4.1 |
| Dolomite | 2.0 | 2.7 | 3.6 |
| Limestone | 1.3 | 2.0 | 2.8 |

**At local scale**

| Lithology | $P_{10}$ | $P_{50}$ | $P_{90}$ |
|---|---|---|---|
| Clastics | 3.1 | 6.1 | 10.0 |
| Dolomite | 5.1 | 6.9 | 9.2 |
| Limestone | 3.5 | 5.2 | 7.3 |

$P_x$ -> there is (1-x)% certainty that this resource exists

After Goodman et al., IJGGC, 2011

# Volumetric $CO_2$ Storage Capacity in Residual-Gas Traps in Deep Saline Aquifers

$$V_{CO2t} = \Delta V_{trap} \quad \phi \quad S_{CO2t}$$

- $V_{CO2t}$: Theoretical storage volume
- $\Delta V_{trap}$: Volume occupied by $CO_2$ at irreducible gas saturation
- $\phi$: Porosity
- $S_{CO2t}$: *Saturation of trapped $CO_2$*

- It is a time-dependent process, as the $CO_2$ plume migrates
- Storage capacity can be determined by numerical simulations only, based on real relative-permeability data

# Mass $CO_2$ Storage Capacity in Solution in Deep Saline Aquifers

## Theoretical Capacity

$$M_{CO2t} = A \times h \times \phi \times (\rho_S X_S^{CO2} - \rho_0 X_0^{CO2})$$

or, if the spatial variability is known

$$M_{CO2t} = \iiint \phi (\rho_S X_S^{CO2} - \rho_0 X_0^{CO2}) dxdydz$$

## Effective Capacity $M_{CO2e} = C_c \quad M_{CO2t}$

- $M_{CO2t}$: Theoretical storage capacity
- *A:* *Aquifer area*
- *h:* *Aquifer thickness*
- $\phi$: Porosity
- *ρ:* *Water density*
- $X^{CO2}$: *Carbon content in formation water*
- $C_c$: *Capacity coefficient*
- *s,0:* *saturation and initial, subscripts*

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# Applicability of Methodologies for Estimating $CO_2$ Storage Capacity to Various Assessment Scales

| Storage Mechanism | Trapping Mechanism | Temporal Nature[1] | Coefficients Needed[2] | Assessment Scale | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Country | Basin | Regional | Local | Site-Specific |
| Oil & Gas Reservoirs | Stratigraphic and Structural | No | Yes | √ | √ | √ | √ | √ |
| | Enhanced Oil Recovery | No | Yes | - | - | - | √ | √ |
| Coal Beds | Adsorption | No | Yes | √ | √ | √ | √ | √ |
| Deep Saline Aquifers | Stratigraphic and Structural | No | Yes | √ | √ | √ | √ | √ |
| | Residual Gas | Yes | ? | - | - | - | √ | √ |
| | Solubility | Yes | Yes | - | - | - | √ | √ |
| | Mineral Precipitation | Yes | Yes | - | - | - | √ | √ |
| | Hydrodynamic | Yes | Yes | - | - | - | √ | √ |

[1] – A trapping mechanism has a temporal nature if the physical or chemical storage process continues after cessation of injection

[2] – Various coefficients need to be estimated to cascade the storage capacity estimate down from theoretical to effective and to practical. These coefficients have to be determined based on field experience and/or numerical simulations

# Issues

- The storage capacity coefficients (or storage efficiency coefficients) have been estimated only through numerical simulations and there is debate in regard to their values
- At actual injection sites, injection limitations and regulatory limits on pressure build-up, $CO_2$ buoyancy and sweep, and other processes will actually limit the storage capacity to what is called “dynamic storage capacity”, which is less, sometimes considerably, than the “static” storage capacity estimated using the methods described
- Pressure interference between various storage sites may limit injectivity and capacity, or may reduce the space available for a given storage operation
- Well configurations will affect injectivity, $CO_2$ behavior in the aquifer or reservoir, and storage capacity
- Other energy and mineral resources that have primacy over $CO_2$ storage will limit further storage capacity by excluding pore space from availability

# Concluding Remarks

- Any assessment of $CO_2$ storage capacity should carefully consider the processes involved, their spatial and temporal scales, the resolution of the assessment, and the available data and their quality

- Proper communication to decision makers of the assumptions made and methodologies used is essential in establishing sound policy and making the best decision regarding CCS implementation

# Concluding Remarks

To the best knowledge of the author, these are the only regional (or formation) scale values for storage efficiency coefficients available in the literature

Site-scale storage capacity is/should be evaluated using detailed numerical simulations

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