Basin-Scale Leakage Risks from Geologic Carbon Sequestration:

Impact on CCS Energy Market Competitiveness

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"the economics of the CCS option for fossil fuel plant appears quite attractive."

However …

"People in the industry are quite reasonably wondering if they should invest in a [CCS] project … given the uncertainty of the regulatory situation, the potential costs of permits, and the viability of new technologies" (October 2009)

"CCS-related risks present a unique set of consequences whereby neither traditional public, nor traditional private, …risk management structures offer the perfect model for mitigating and managing such risks."

ZURICH

Risks to:
- nearby populations
- valuable subsurface resources
- potable water sources
- sensitive habitats

http://www.zurich.com/NR/rdonlyres/E2B5B53E-11DB-47AF-91E4-01ED6A2BDCA3/0/ClimateRiskChallenge.pdf

CCS will be a viable technology if:

CO_2 leakage rates are projected with a high level of certainty and low computational effort. *Will geochemical reactions alter formation integrity?*	Leakage probabilities are translated directly into liabilities. *What are the risks with respect to loss of carbon credits and damages to competing subsurface land use?*	Costs and liabilities are compared to the opportunity costs of not pursuing alternative energy sources. *Is CCS competitive in the energy market?*

Project Team

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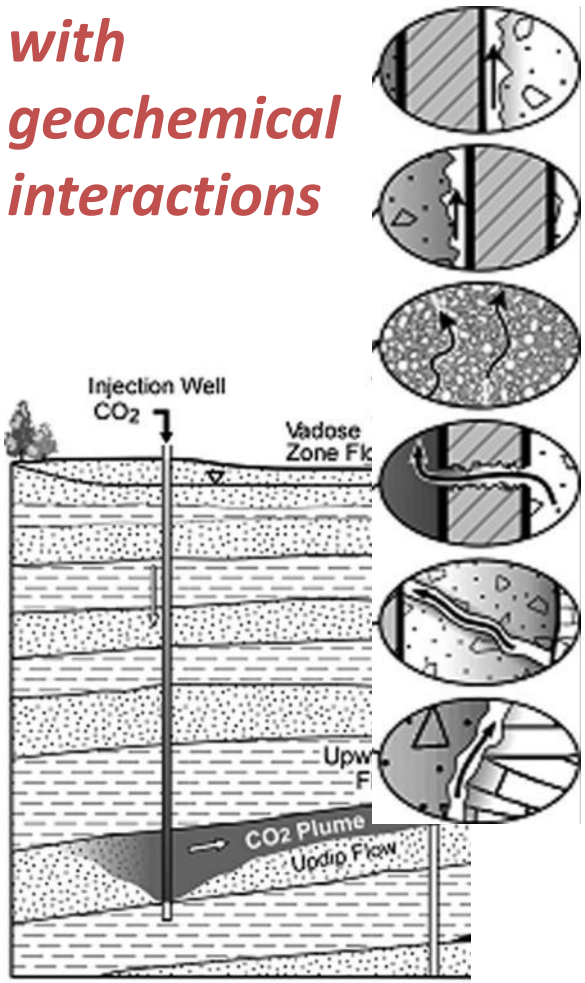
Project Overview

I. *Probabilistic leakage scenarios, with geochemical interactions*



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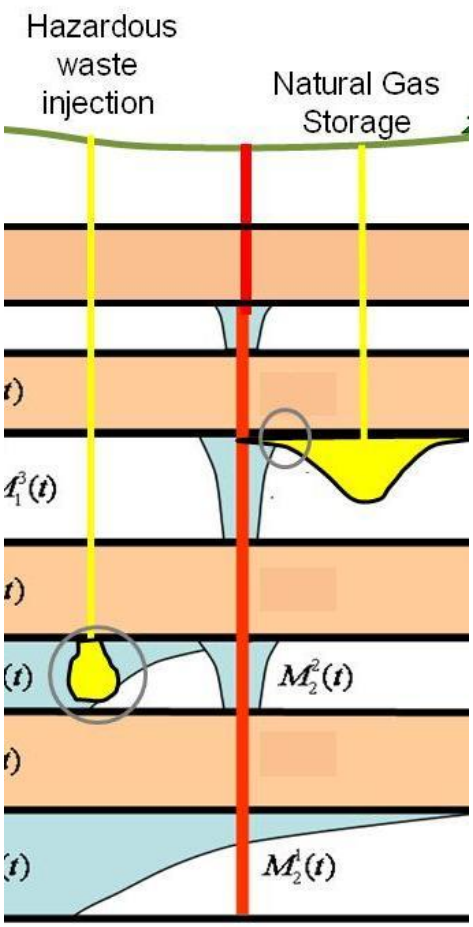

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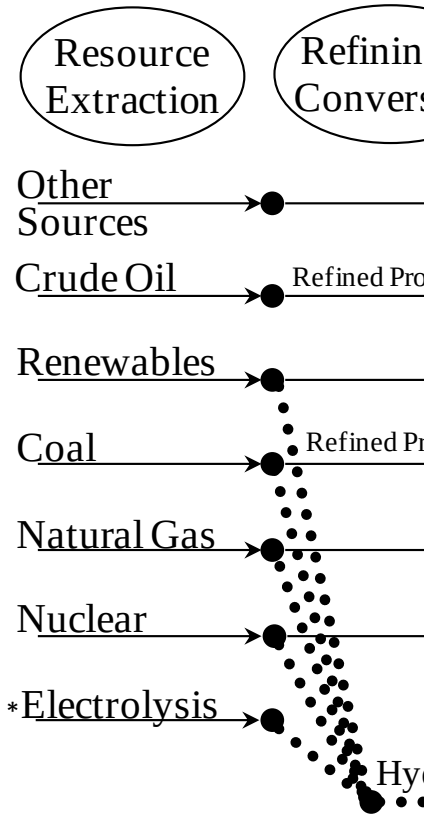
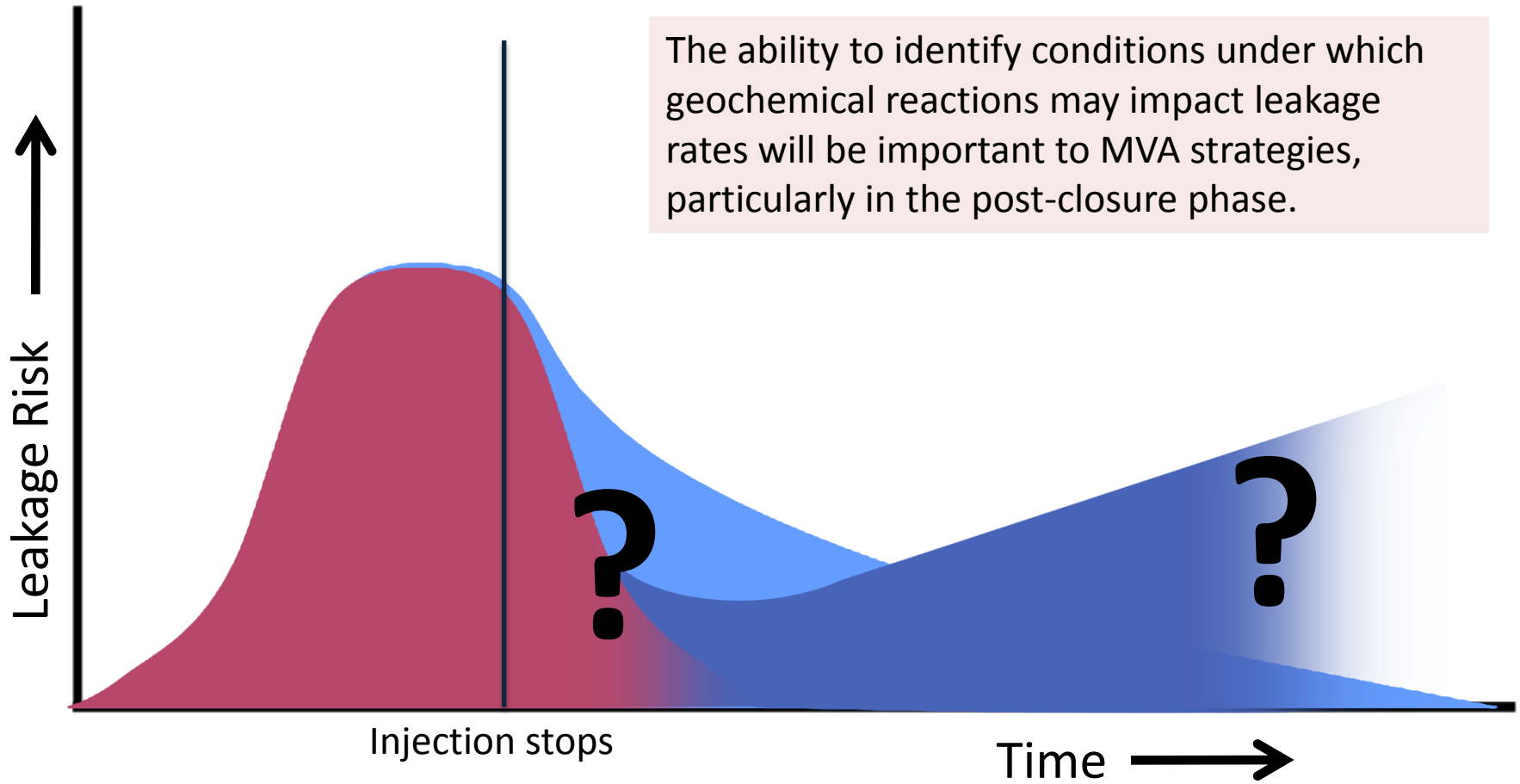


Leakage risk curve – possible effects of geochemical interactions with caprocks and well-cements

The ability to identify conditions under which geochemical reactions may impact leakage rates will be important to MVA strategies, particularly in the post-closure phase.

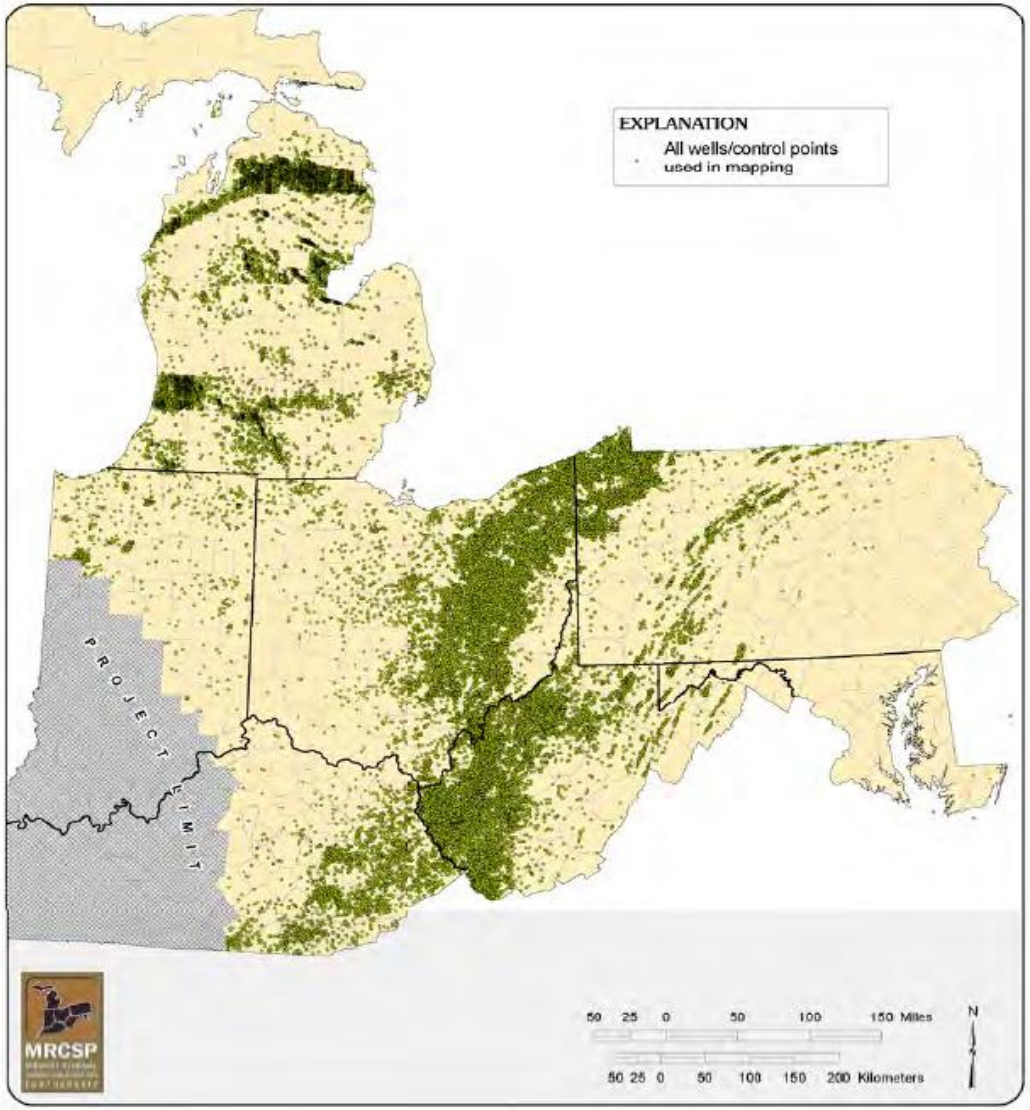


Leakage risk due to pressure changes

Mineral dissolution may enlarge flow pathways over time

Geochemical-induced sealing may reduce leakage risk

The Michigan Basin – Geographic focus of this study



Mount Simon Sandstone identified as an important sequestration formations in MI Basin & Ottawa Co. (*Barnes et. al, 2009*)

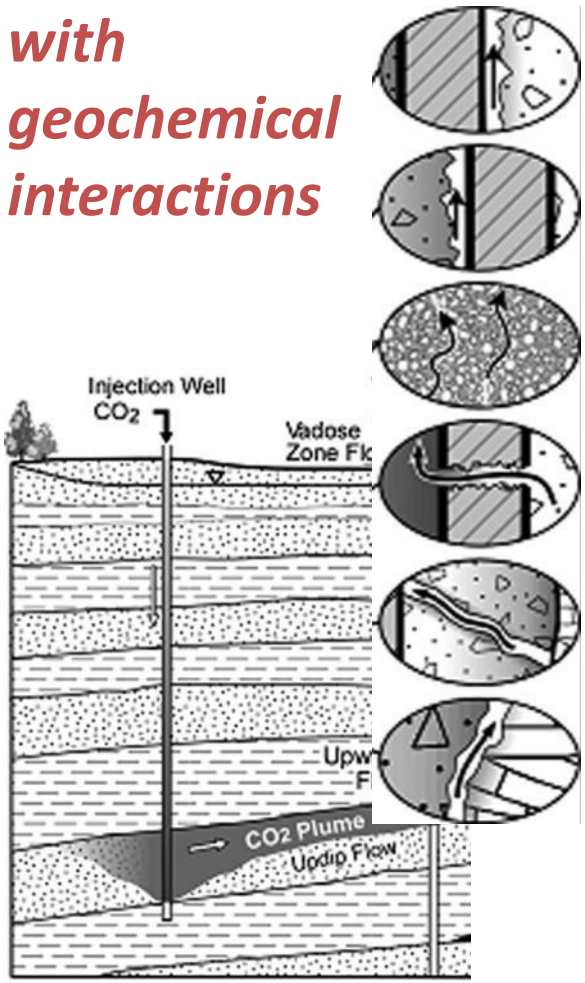
Eau Clair Formation serves as primary seal –low porosity dolomite, but heterogeneous

Recent survey of hydrogeologic units and groundwater salinity in Lake Michigan Basin (*USGS Report 2009-5060*)

Digitized well data available thru Michigan State Survey

Thrust I: Probabilistic representation of CO_2 leakage on a basin scale

I. *Probabilistic leakage scenarios, with geochemical interactions*



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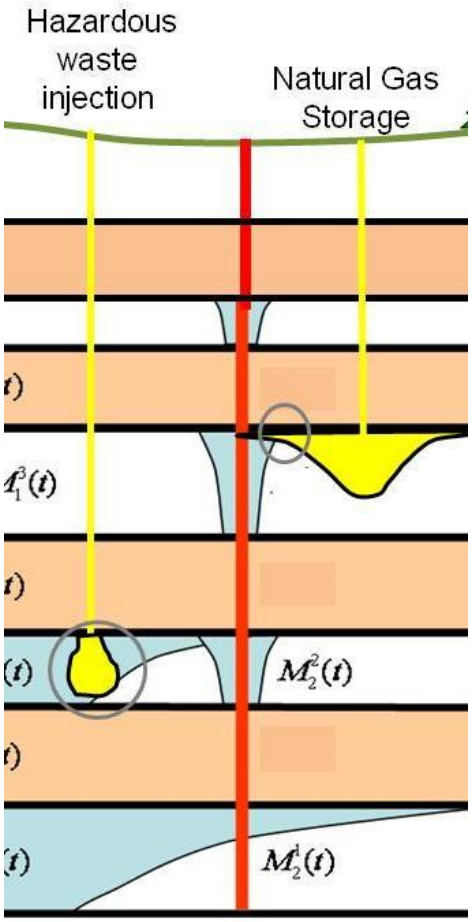

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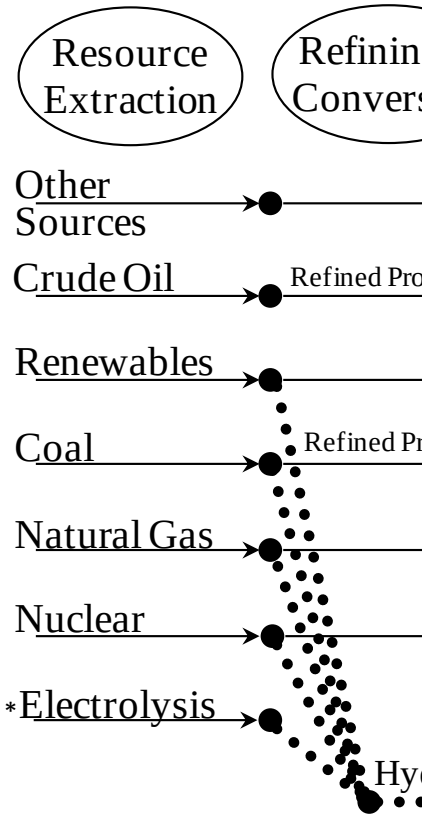
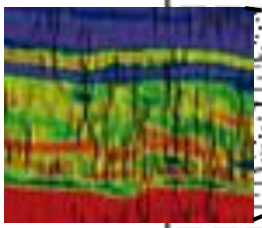
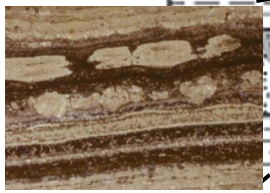


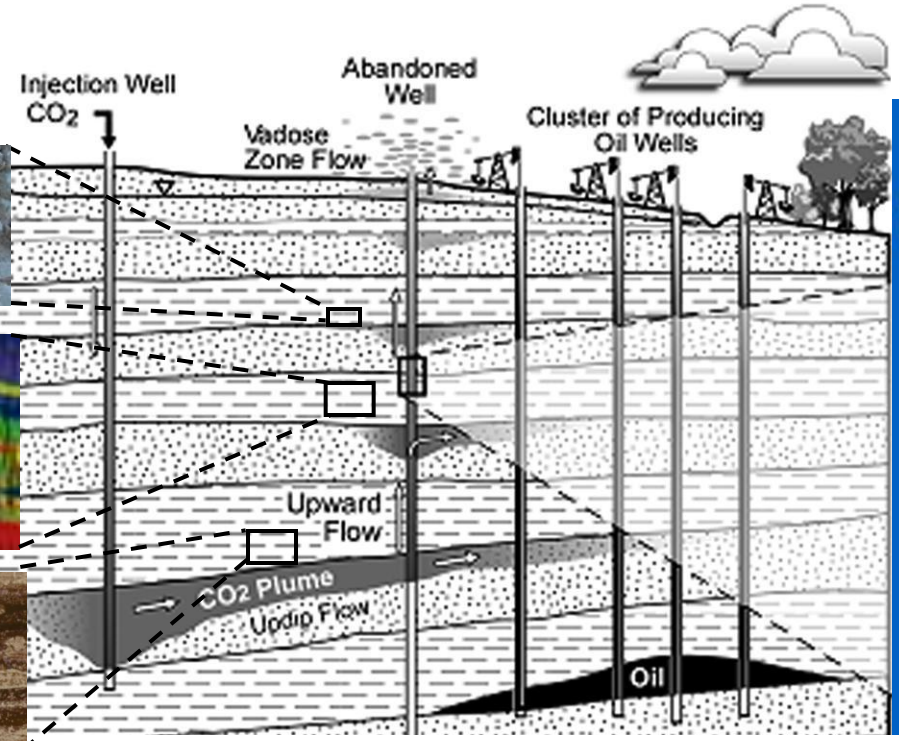
March 2010

Under what conditions and within what timeframe does geochemistry impact hydrodynamics?

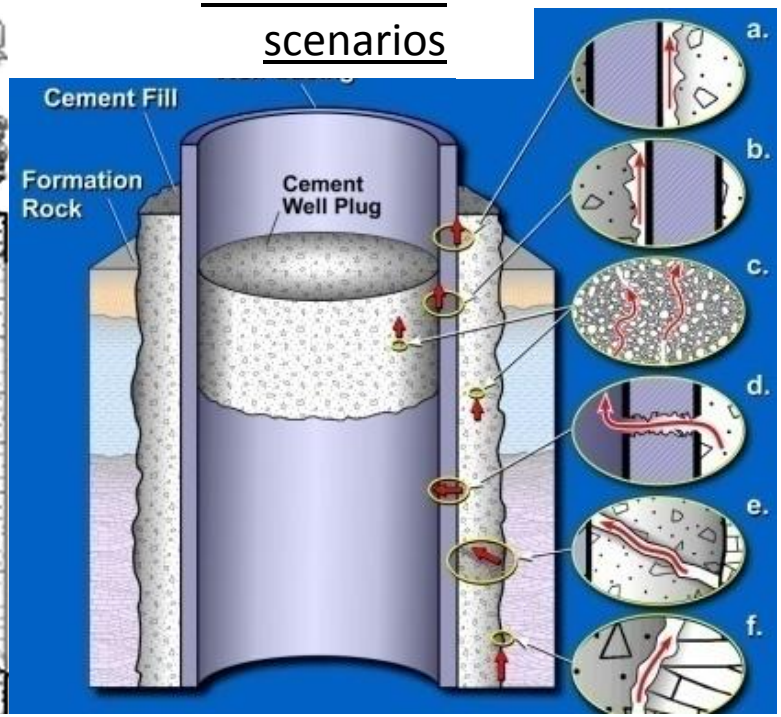
Caprock scenarios







Well cement scenarios



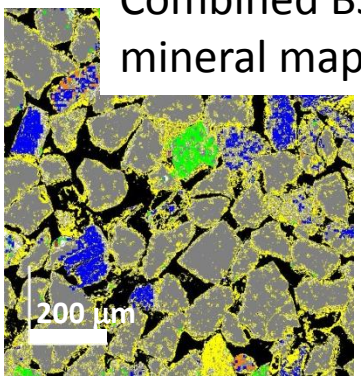
Possible leakage pathways include faults, fracture networks & discontinuities in caprocks, and seams, fissures & diffusion in wells.

Will acidic fluids enlarge or self-seal flow pathways?

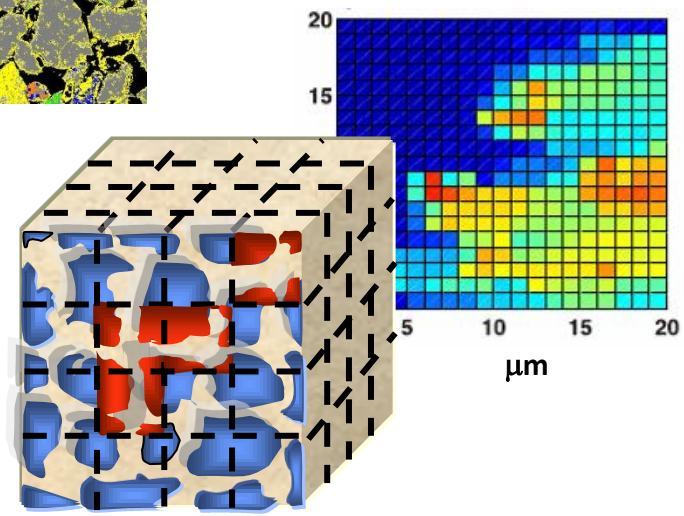
Pore-scale leakage scenario modeling will produce simplified geochemical rules as inputs for the basin scale model

Mineral phases and their accessible reactive surface area

Modified reaction rates at mineral surfaces



Combined BSE-EDX mineral map



3-D reactive transport modeling with full geochemistry within a network flow model

Source: Peters, Chem. Geol. 2009;
Li et al. 2006 & 2007A & B;

Determine minimum number of geochemical parameters to represent leakage pathway self-sealing and erosion

Including full geochemical considerations in basin scale models is computationally prohibitive

Reactions

$$CaAl_2Si_2O_8(s) + 8H^+ \rightleftharpoons Ca^{2+} + 2Al^{3+} + 2H_4SiO_4$$
$$Al_2Si_2O_5(OH)_4(s) + 6H^+ \rightleftharpoons 2Al^{3+} + 2H_4SiO_4 + H_2O$$

$$H_2O \rightleftharpoons H^+ + OH^-$$
$$H_2CO_3^* \rightleftharpoons HCO_3^- + H^+$$
$$HCO_3^- \rightleftharpoons CO_3^{2-} + H^+$$
$$H_4SiO_4 \rightleftharpoons H_3SiO_4^- + H^+$$
$$H_3SiO_4^- \rightleftharpoons H_2SiO_4^{2-} + H^+$$
$$Al^{3+} + OH^- \rightleftharpoons Al(OH)^{2+}$$
$$Al(OH)^{2+} + OH^- \rightleftharpoons Al(OH)_2^+$$
$$Al(OH)_2^+ + OH^- \rightleftharpoons Al(OH)_3$$
$$Al(OH)_3 + OH^- \rightleftharpoons Al(OH)_4^-$$

Rate laws that are highly non-linear and pH-dependent

$$r_A = (k_H\{H^+\}^{1.5} + k_{H_2O} + k_{OH}\{OH^-\}^{0.33})(1 - \Omega_A)$$

$$\Omega_A = \frac{\{Ca^{2+}\}\{Al^{3+}\}^2\{H_4SiO_4\}^2}{\{H^+\}^8 K_{eq,A}}$$

$$r_K = (k_H\{H^+\}^{0.4} + k_{OH}\{OH^-\}^{0.3})(1 - \Omega_K^{0.9})$$

$$\Omega_K = \frac{\{Al^{3+}\}^2\{H_4SiO_4\}^2}{\{H^+\}^6 K_{eq,K}}$$

Complex interactions between dissolution/precipitation kinetics and porous media properties

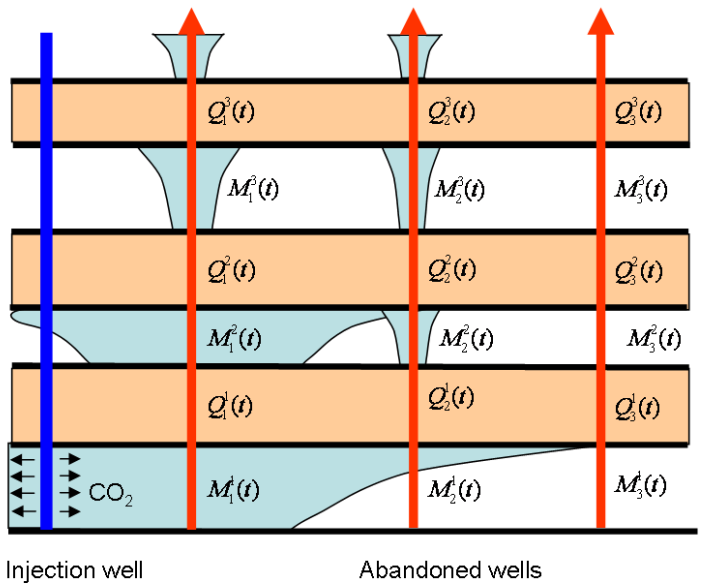
$$S_{i,Ca^{2+}} = r_{A,i}\mathscr{A}_{A,i}, \qquad S_{i,Al_T} = 2r_{A,i}\mathscr{A}_{A,i} + 2r_{K,i}\mathscr{A}_{K,i},$$

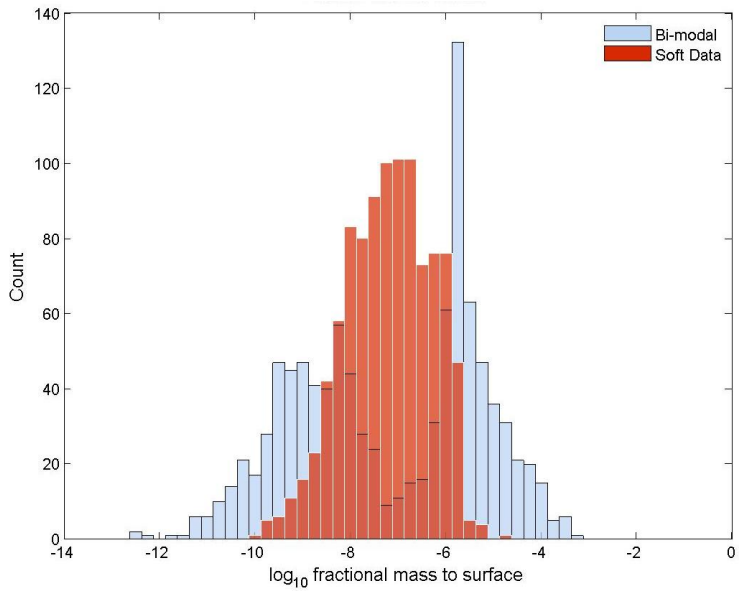
$$S_{i,Si_T} = 2r_{A,i}\mathscr{A}_{A,i} + 2r_{K,i}\mathscr{A}_{K,i}, \qquad S_{i,H_T} = -6r_{A,i}\mathscr{A}_{A,i} - 4r_{K,i}\mathscr{A}_{K,i},$$

Composition-dependent transport properties

$$D^*_{ij,C_T} = \frac{D_{H_2CO_3^*}([H_2CO_3^*]_j - [H_2CO_3^*]_i) + D_{HCO_3^-}([HCO_3^-]_j - [HCO_3^-]_i) + D_{CO_3^{2-}}([CO_3^{2-}]_j - [CO_3^{2-}]_i)}{([H_2CO_3^*]_j - [H_2CO_3^*]_i) + ([HCO_3^-]_j - [HCO_3^-]_i) + ([CO_3^{2-}]_j - [CO_3^{2-}]_i)}$$

Leakage probabilities & risk profiles will show spatial variation and change with time





Semi-analytical solution for injection plumes and leakage plumes, and flow through leaky wells.

Inputs: Well distribution, formation characteristics, brine composition, injection conditions,…

Model outputs probability distributions of CO_2 leakage to:

- Atmosphere
- Subsurface compartments

Thrust II: Basin-scale 3D GIS map of leakage and liability

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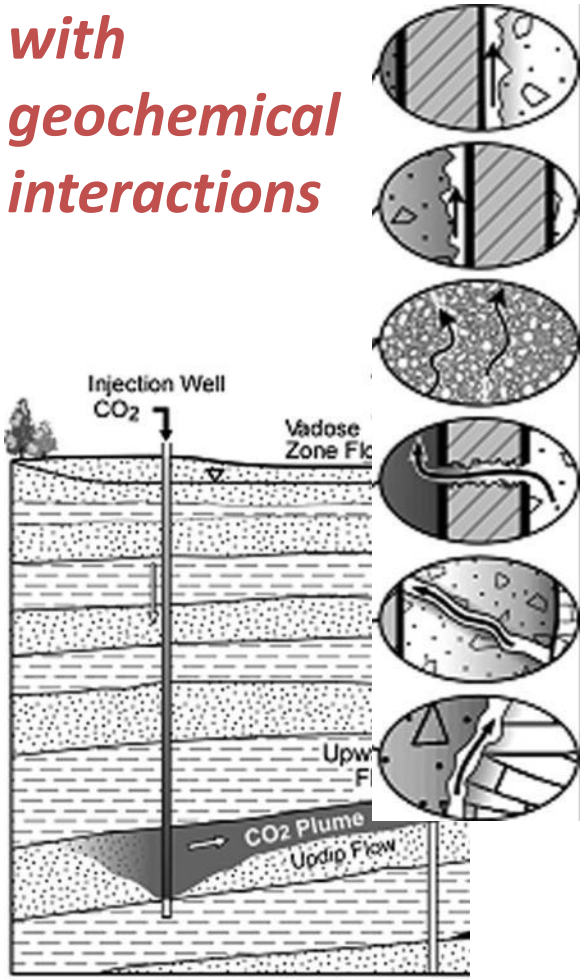

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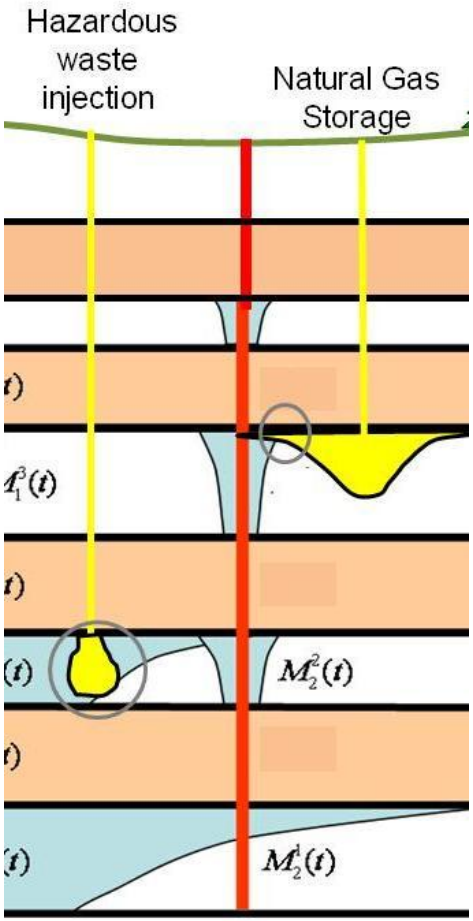

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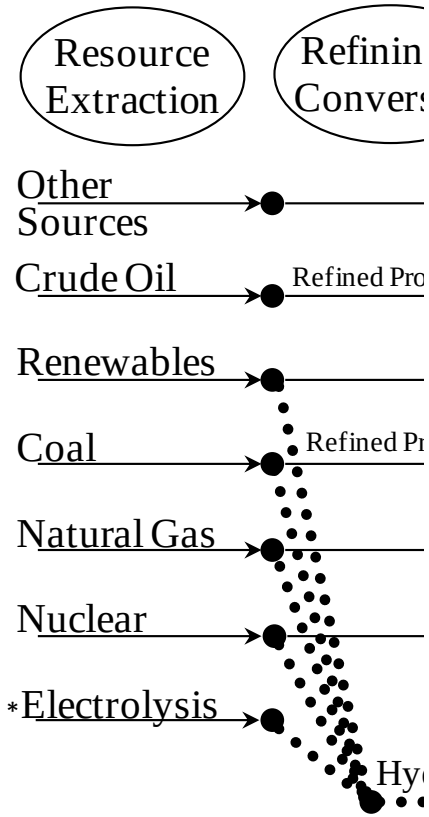


THRUST II: Linking leakage risk to subsurface liabilities

OUR GOALS:

1. Identify risks from CCS to other subsurface activities
2. Explore the implications of those risks
3. Analyze how best to manage them.

Current subsurface activities

- Oil and gas extraction
- Waste disposal
- Natural gas storage
- Groundwater supply
- Shale Gas

Emerging subsurface activities

- Geothermal energy
- In-situ coal gasification
- Compressed air storage

Current Subsurface Activities in the Michigan Basin

Activity	Extent in Michigan	Context
Oil extraction	6 million barrels	17th in U.S.
Natural Gas extraction	5.5 billion m^3	12th in U.S.
Natural Gas Storage	24 billion m^3	1st in U.S.
Groundwater extraction	~200 billion gallons	Drinking water source for 50% of MI pop.
Deep Hazardous and Non-hazardous Waste Injection (UIC Class I)	27 wells	6th in U.S.
Oil and gas waste disposal (UIC Class II)	~1,500 wells	13th in U.S.
Solution mining (UIC Class III)	~50 wells	9th in U.S.

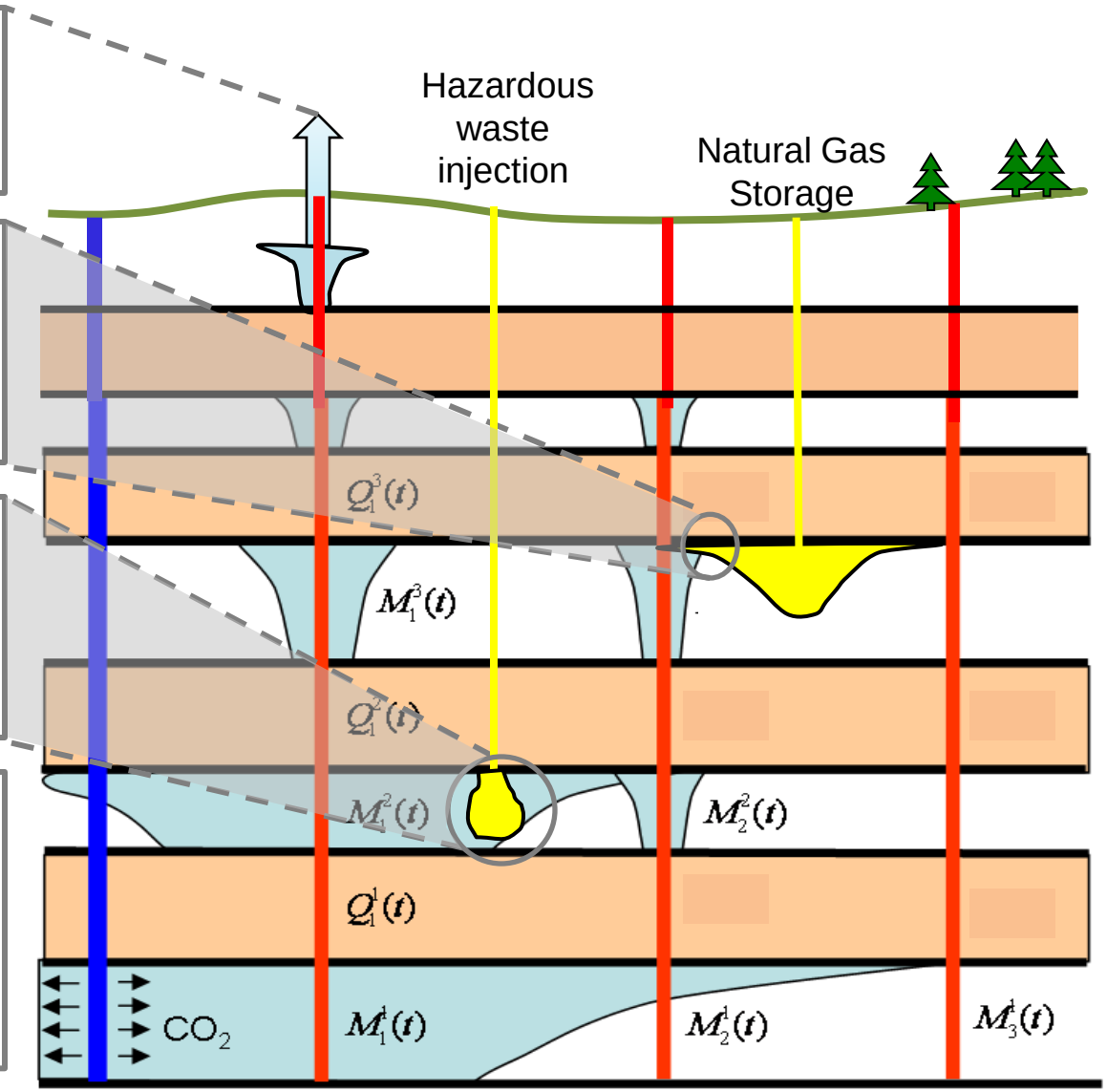
Examples of scenarios where leakage could create liabilities

1. Climate Liability:
Release to atmosphere

2. Subsurface Liability:
Impacts to natural gas storage

3. Subsurface Liability:
Impacts to haz. waste disposal

4. Other Subsurface Liabilities:
Impacts to oil and gas, groundwater, others….?

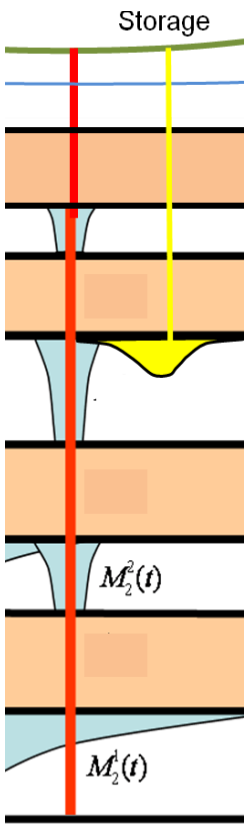


Injection well

Abandoned wells

Create a theoretical framework integrating leakage risk with legal and regulatory risk

Scenario: Impacts to natural gas storage



Laws, regulations, and stakeholders related to natural gas storage

Civil and administrative damages for harm to natural gas storage

Geochemical and hydrodynamic modeling: likelihood of leakage harming natural gas storage

Potential Costs ($)

MARKAL modeling

Thrust III: Evaluate CCS Energy Market Competitiveness

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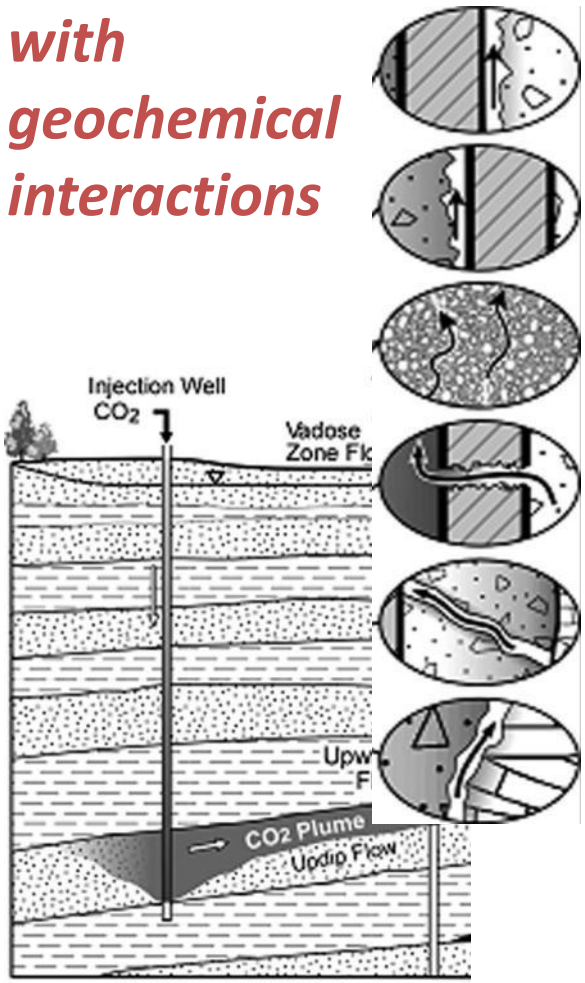

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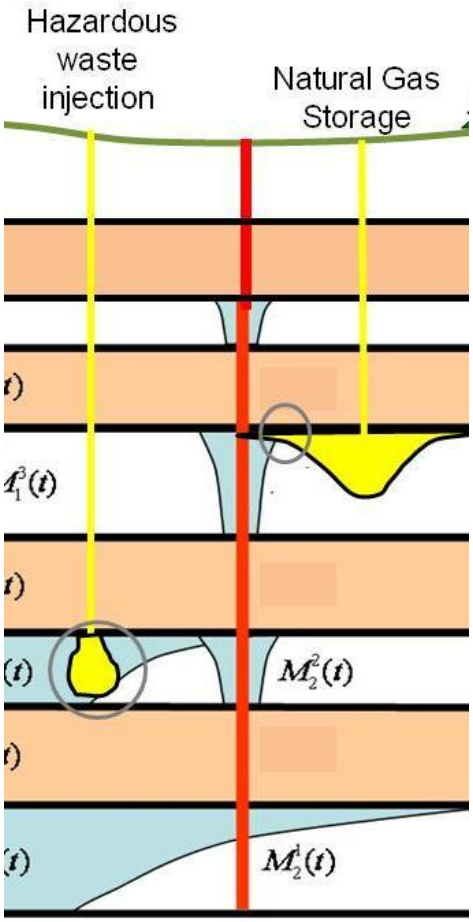

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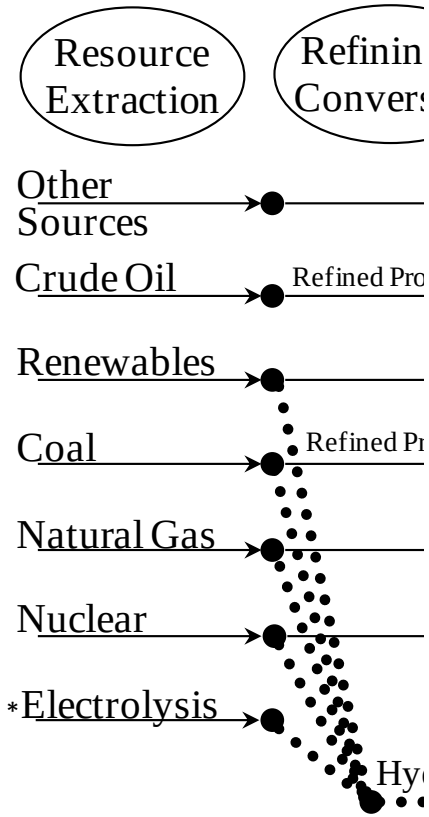
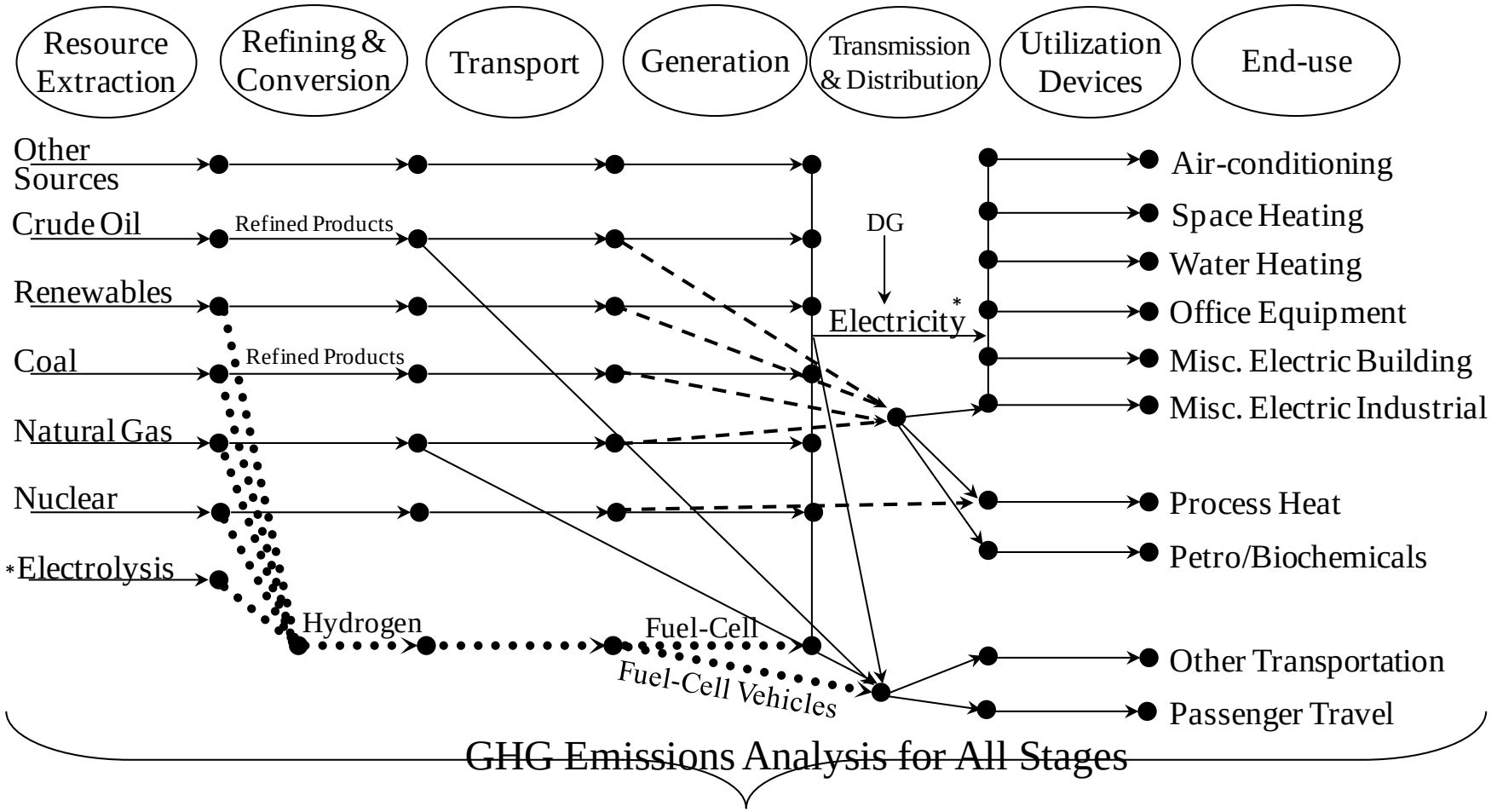


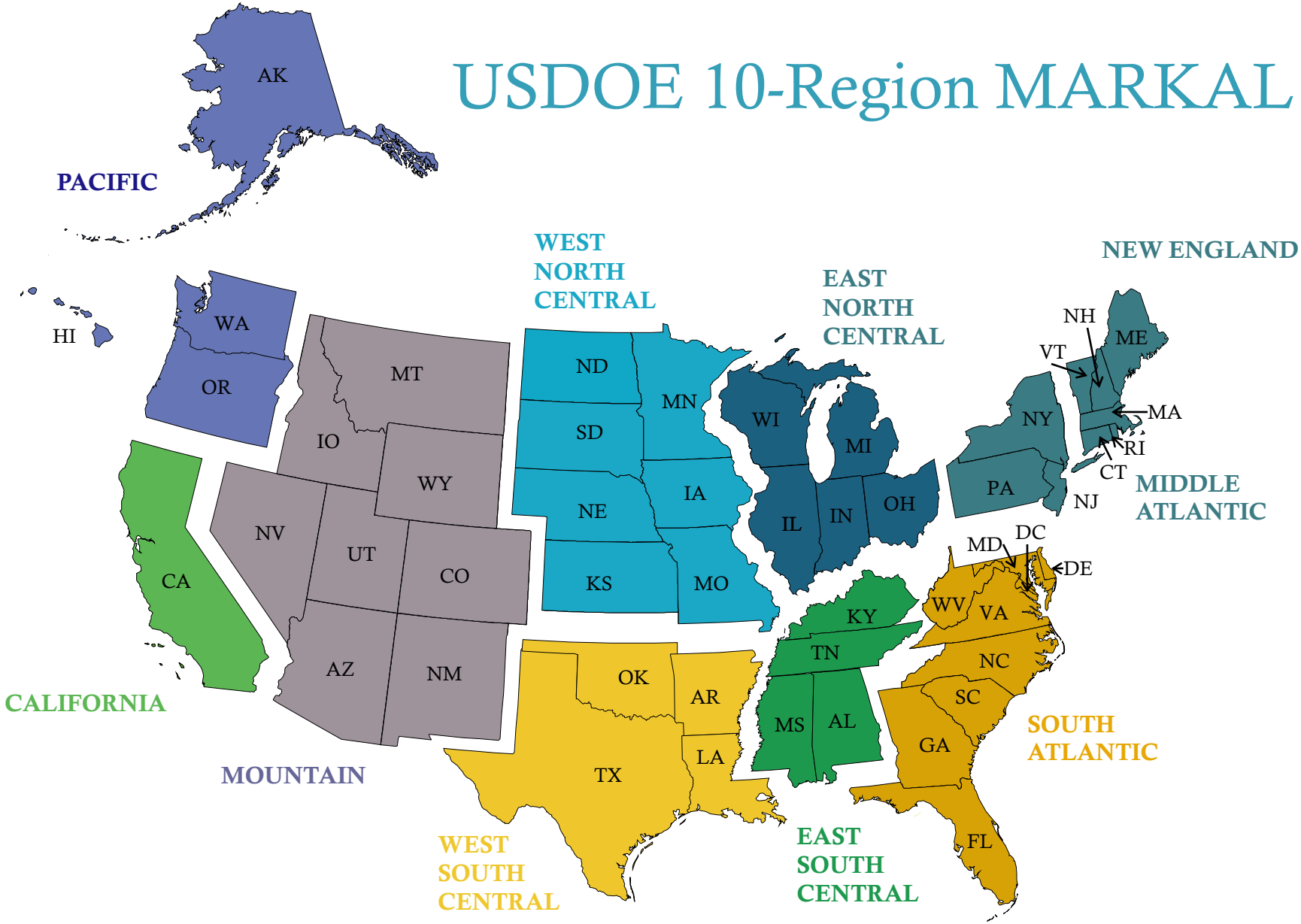
How will CO_2 leakage risk potential impact market competitiveness of CCS?

- Develop framework to examine CCS competitiveness in light of uncertainty in CO_2 leakage risks
  - Account for site-specific costs and liabilities resulting from subsurface leakage potential
  - Customize MARKAL regional/national energy systems analysis methodology to include CCS
  - Study project viability under different carbon mitigation prices/limits

MARKAL Reference Energy System



USDOE 10-Region MARKAL

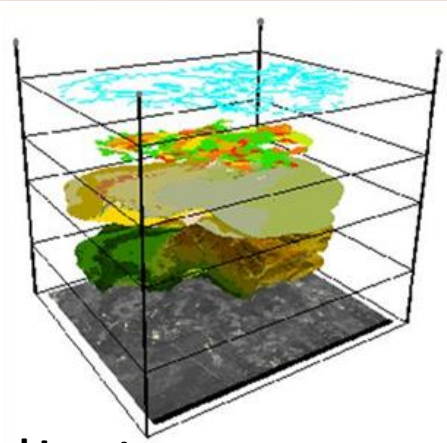


Extend MARKAL to include CCS

CCS Economic & Policy Drivers Module

Unique Inputs from this project

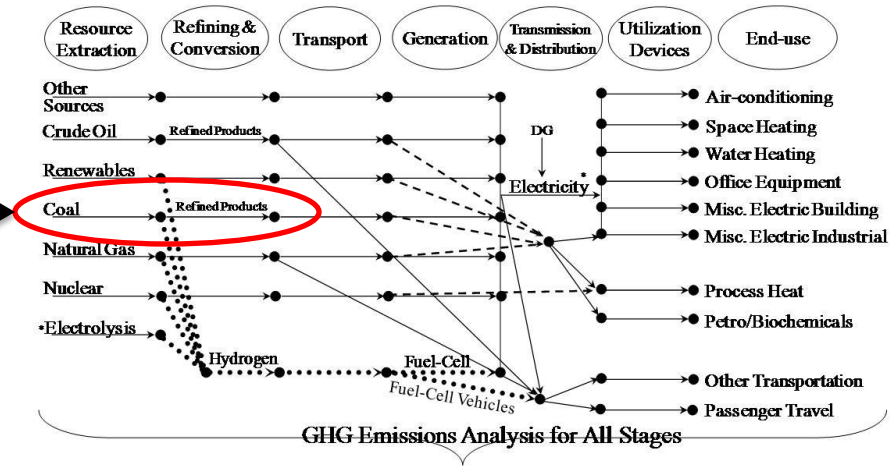
- Costs and liabilities from subsurface leakage
- Leakage rates to the atmosphere



Additional Inputs:

- Investment cost
- Fixed & variable operation/maintenance costs
- Storage capacity
- Lifetime costs of MVA

MARKAL Sensitivity Analysis



Feedback to Science & Subsurface Frameworks Thrust I & II

Unique characteristics of this project

- Devising novel methods to incorporate geochemical processes into leakage risk models.
- Accounting for site-specific & basin-scale leakage risks and quantifying a broad range of costs and liabilities.
- Bridging the gap between the science, economics, and policy.