# Impact of Hydrogen Production on U.S. Energy Markets

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This presentation does not contain any proprietary or confidential information

Project ID #
**AN2**

# Overview

## Timeline

- Project start May 2005
- Project end date is September 2008

## Budget

- Total project funding is $1.3 million
- EEA funding for FY06 $280K
- EEA funding for FY07 $330K
- BNL funding for FY06 $150K
- BNL funding for FY07 $290K

## Barriers

- Lack of Consistent Data, Assumptions, and Guidelines
- Lack of Macro-Systems Model
- Lack of Understanding of Transition of a Hydrocarbon-Based Economy to a Hydrogen-Based Economy

## Partners

- EEA Inc.
- Brookhaven National Laboratory
- Power & Energy Analytic Resources



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# Objectives

## Overall

- Develop a consistent, integrated framework for evaluation of impacts of hydrogen production within U.S. energy markets.
- Evaluate costs and timeliness of various scenarios of a developing hydrogen supply infrastructure.
- Evaluate impacts on U.S. energy markets including price and consumption changes for coal, natural gas, renewables and electricity.
- Identify most economic routes and financial risks of hydrogen production.

## Last Year

- Complete regional supply and cost analyses of coal and carbon sequestration
- Develop regional biomass supply curves
- Develop fuel and feedstock transportation capacity and cost
- Perform study of natural gas infrastructure constraints and costs
- Produce and test initial multi-regional version of MARKAL

# Approach

- Primary modeling framework will be the MARKAL model, modified to incorporate latest and most consistent cost and performance data from DOE hydrogen program and AEO.
- Initial work done using existing version of MARKAL and current work based on a new regionalized version of the model.
- Additional analyses on natural gas markets will be performed using databases and models from EEA.
- Extensive scenario analyses and sensitivity analyses to be performed.
- Results to be presented in series of briefings and reports.



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# Accomplishments

- Researched **coal resource base** descriptions, size estimates and cost distributions.  Developed initial MARKAL regional inputs.
- Researched historical **coal transportation costs** and developed modeling algorithms.
- Created more consistent performance and cost inputs for coal-to-hydrogen and other **coal conversion technologies** in MARKAL. Developed cost algorithms for underground coal gasification for MARKAL
- Researched **geologic sequestration** cost and maximum storage capacities by region. Developed cost model and cost curves for MARKAL.

# Accomplishments (continued)

- Researched **biomass resource base** descriptions, regional availability estimates and cost distributions.
- Created initial **infrastructure design scenarios** for metropolitan market area hydrogen demand through 2060.
- Developed suite of **distance-based costing algorithms** to allow specification of cost tradeoffs of infrastructure location and size.
- Performed an analysis of **natural gas infrastructure adequacy** for transition period by major metropolitan area.
- Completed regionalized version of MARKAL model and began to investigate **integrated hydrogen scenarios**.

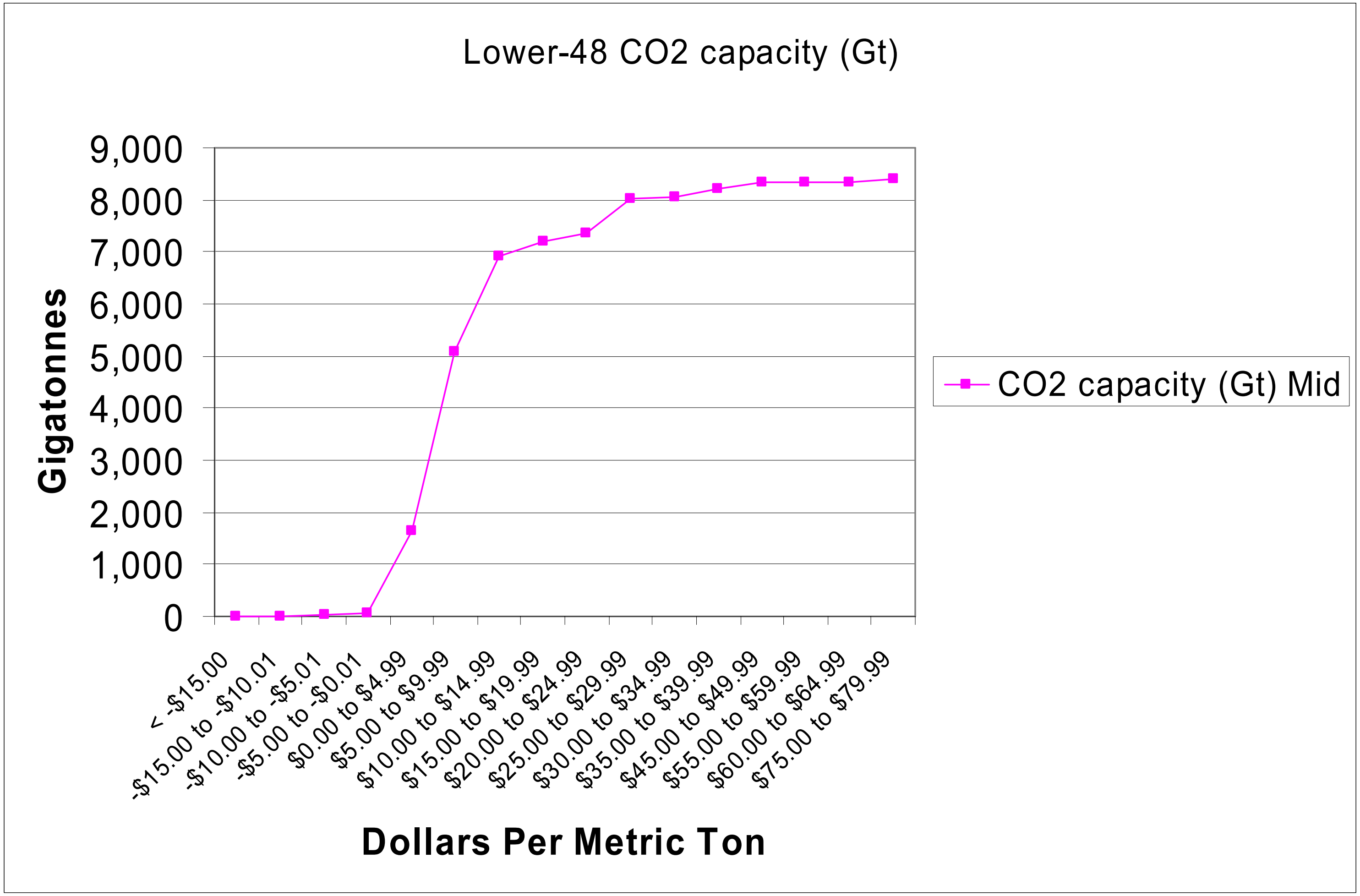
# Future Work

- Finalize data inputs for MARKAL and scenario design.
- Examine alternative integrated scenarios and sensitivities with MARKAL.
- Produce report on methodology, data, assumptions and conclusions.

# Work Area Focus #1: CO2 Sequestration Assessment and Economics

- An important, low-cost source of hydrogen production is expected to be coal gasification and coal/biomass gasification.
- These processes generate large quantities of CO2 that will need to be sequestered.
- Thus the economics of hydrogen supply are dependent upon the costs of CO2 capture, transportation, and sequestration.
- The EEA analysis encompasses hydrogen production, power generation, synfuel manufacturing, and related carbon capture, transporation, and sequestration.

# Summary Chart of EEA Analysis of Sequestration Economics for U.S. Storage Capacity Estimate (Middle Estimate)



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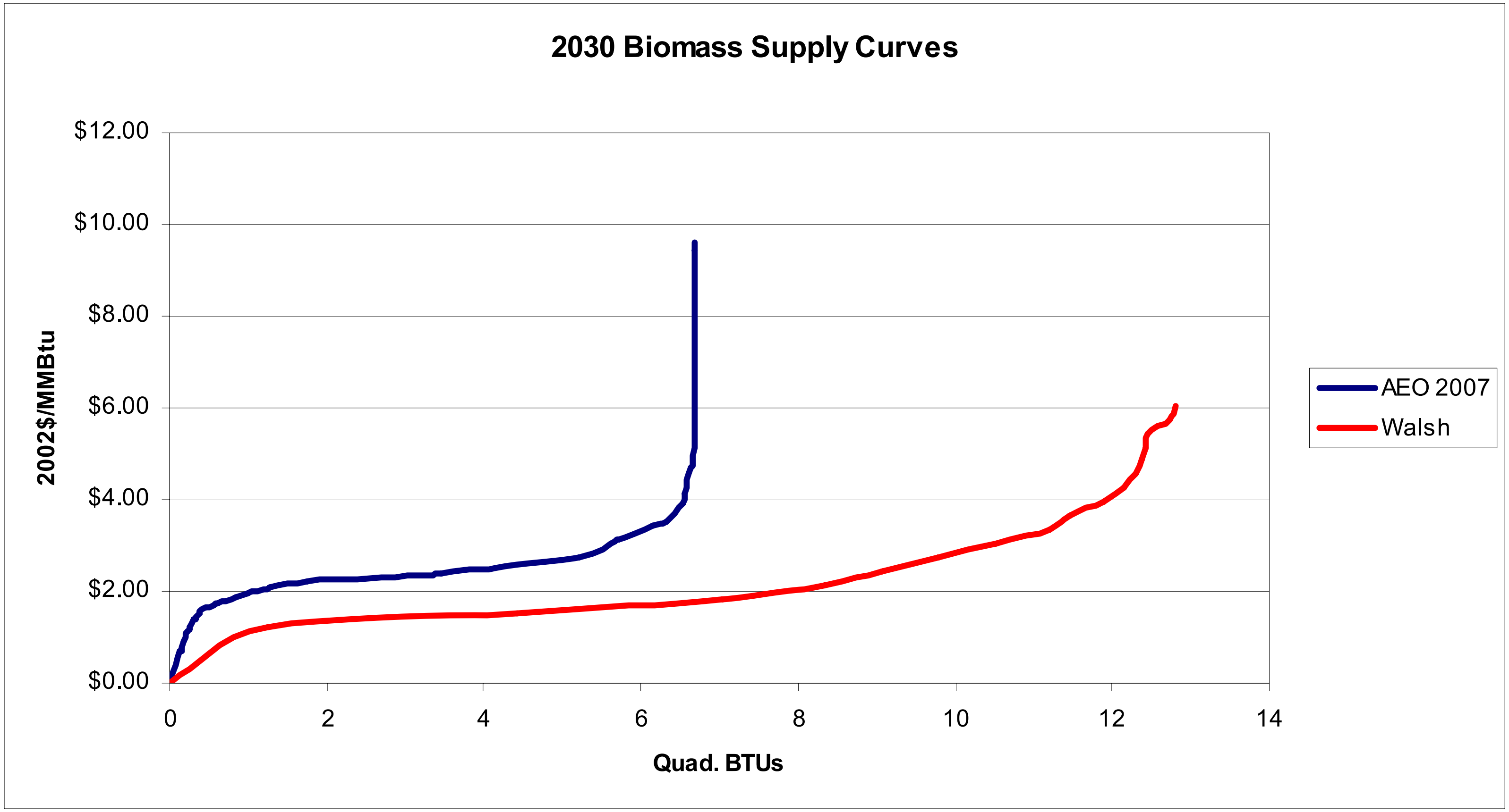
# Work Area Focus #2: Biomass Supply Assumptions

- Developed by Marie Walsh using POLYSYS model.
- POLYSIS is a dynamic model of the U.S. agricultural sector
  - represents 305 supply region models for the land allocation decision with relatively homogeneous production characteristics (Agricultural Statistical Districts)
  - simulates impact of changes in policy, economic, or resource conditions to the U.S. agricultural sector
  - analyzes many variables including; planted and harvested acres, yields, production, exports, variable costs, market demand by use, farm price, cash receipts, government payments, and net realized income
- Additional scenarios can be developed to reflect more aggressive biomass supply scenarios.

# Key MARKAL Model Assumptions




- The Walsh supply curves contain roughly twice the amount of resource as the 2007 AEO supply curves, but less than the ultimate resources shown in DOE's Billion Ton Study.

# Work Area Focus #3: MARKAL Model Modifications and Testing

- A 10 region U.S. MARKAL model was developed to capture the differences in availability of energy resources and technologies, as well as the impacts of energy policies, between different parts of the U.S. For each region the Multi Region U.S. model has:
  - Individual supply curves for each fuel (resource availability and cost)
  - Individual energy transmission/distribution/transport options and costs
  - Individual demand levels and characterizations
- Model calibrated to 2007 Annual Energy Outlook, with non-hydrogen technology assumptions derived from NEMS database.
  - Hydrogen transmission and distribution costs are drawn from ANL H2 Delivery Model analysis.
  - Hydrogen production technology assumptions adapted from H2A results and HFCIT Program goals.

# Key MARKAL Model Assumptions

| | | |
|---|---|---|
| Economic activity | | AEO 2007 Reference Case |
| Energy service demands by sector | | AEO 2007 Reference Case |
| Fuel prices | | AEO 2007 Reference Case |
| Electricity demand | | AEO 2007 Reference Case |
| Power gen. technologies costs and characteristics | | AEO 2007 Reference Case |
| GHG policy | | based on scenarios |
| Carbon sequestration capacity and costs | | as developed for this project by EEA |
| Crop/biomass capacity and costs | | as developed for this project by Marie Walsh using POLYSYS model |
| Hydrogen production costs | | H2A & Program Goals |
| Hydrogen distribution costs | | H2A data in reduced form from ORNL work & Program Goals |
| Vehicle characteristics and costs | | set by scenario |
| Fuel cell costs | | set by scenario |



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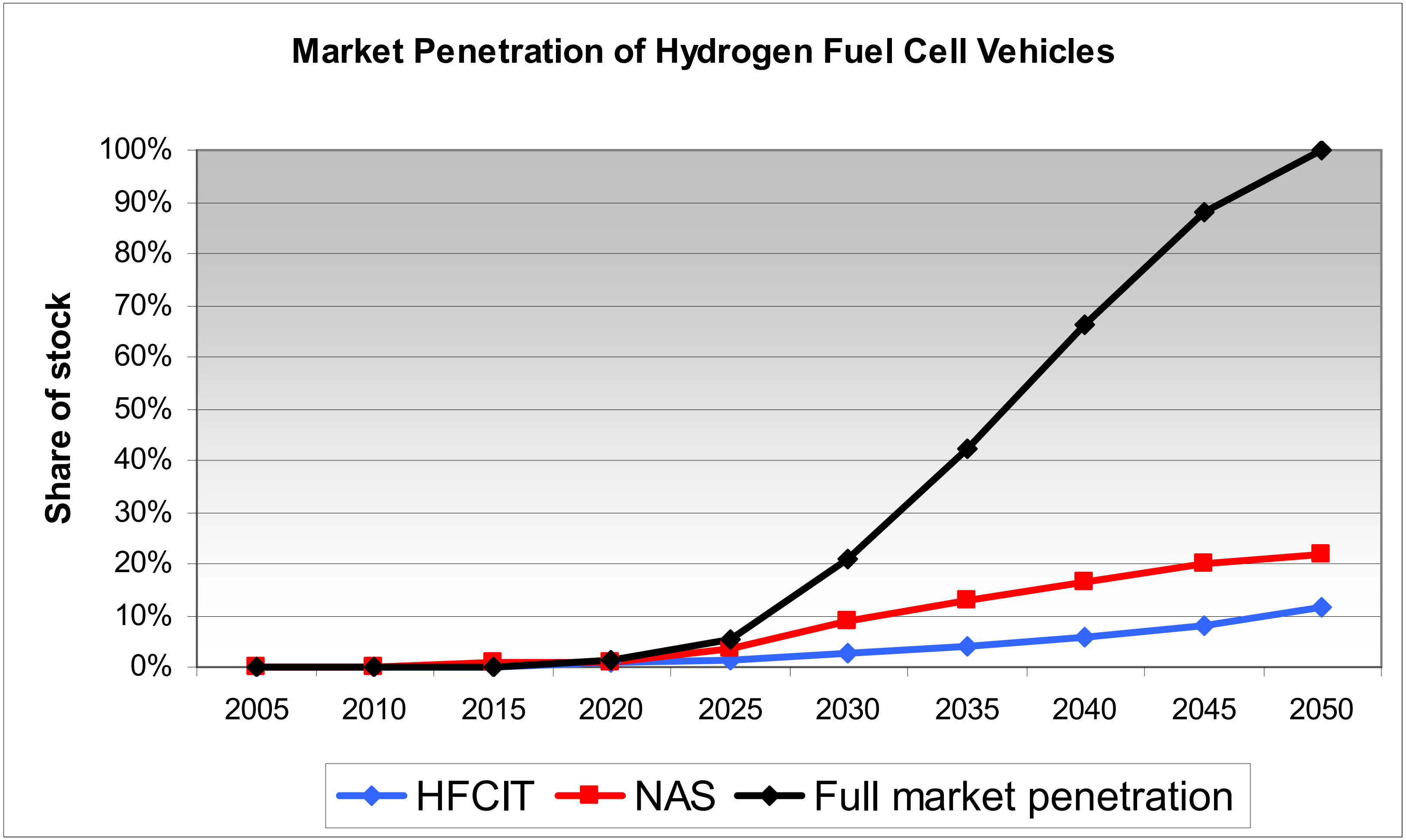
# Progress Report

- Sample analysis includes the following scenarios
  - Base case
  - HFCIT technology goals model optimizes path
  - NAS recommended penetration rate (10 million vehicles by 2025), model optimizes path after 2025
  - Fixed penetration path with 100% market share by 2050
- Full analysis will test alternative:
  - Technology assumptions
  - Direct and indirect subsidies
  - Fixed vehicle penetration rates

# MARKAL Model Preliminary Results



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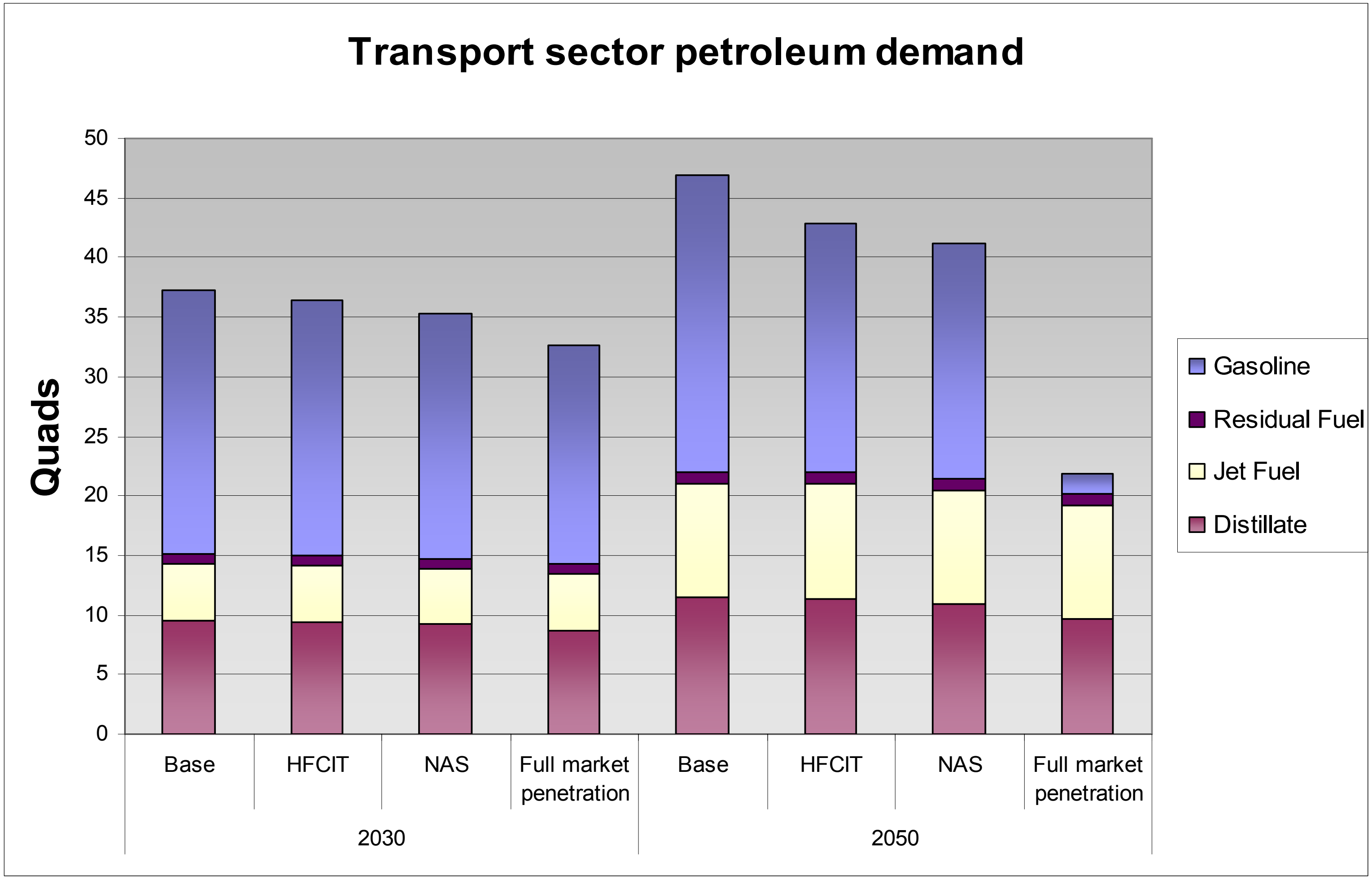
# MARKAL Model Preliminary Results



# MARKAL Model preliminary findings

- Significant impact on liquid fuel markets
  - Petroleum refiners need to adapt to changes in fuel demand (much higher distillate to gasoline ratio).
  - Limited ability to fuel switch away from other liquid fuels (or to gasoline) in the rest of the economy. If hydrogen transitions are taking place in the rest of the world there is also a limit to the amount/price that can be exported.
- Significant reduction in fuel tax revenue
- Little overall impact on natural gas prices
  - Overall demand increase is modest
- High pressure on biomass resources
  - In combination with the demand for biofuels under the RFS, hydrogen production from biomass will require that a large share of the available biomass will be required for energy production.

# Summary

- This project integrates supply/demand dynamics in all US energy markets
- Employs an inter-temporal approach that looks at technology evolution and stranded investments over the long-term (to 2050)
- Examines alternative scenarios for energy prices and GHG controls
- Considers hydrogen demand levels, technology costs, and feedstock prices on a regional basis
- Estimates impact of hydrogen production on hydrogen feedstock prices and consumption changes in other energy markets
- Leverage use of an existing model with wide use within DOE
- Project maximizes use of existing H2A and other DOE data while expanding other important databases; biomass cost curves, carbon sequestration cost curves, natural gas infrastructure constraints and costs, etc.

# Objectives and Data Sources – Sequestration Assessment

- The goal of this analysis was to develop a database of CO2 storage capacity by state and geologic category for use in economic analysis in the MARKAL model.
- The study represents a compilation of sequestration assessments from other groups and the development of an assessment framework amenable to regional and national economic modeling.
- The primary sources of information for the assessment are:
  - Regional DOE NATCARB studies; assessed volumes by type; geologic parameters
  - DOE report on coalbed sequestration potential
  - The 2005 DOE regional EOR assessment potential reports
  - A Battelle national assessment (Global Energy Technology Strategy Program)
  - DOE GASIS reservoir data (reservoir properties, depths for economics)
  - EEA resource assessments and engineering data

## Summary of EEA Assessment of U.S. CO2 Storage Potential In Underground Reservoirs

EEA July 14, 2006

Gigatonnes of CO2 Storage

| Region (Markal Region Name) | EOR | Depleted Oil Fields | Depleted Gas Fields | Coals | Shale | Aquifers | Basalt | Total |
|---|---|---|---|---|---|---|---|---|
| California (California) | 3.50 | 8.03 | 1.80 | 0.00 | 0.00 | 500.00 | 0.00 | 513.33 |
| Eastern Gulf Coast (East South Central) | 0.25 | 1.12 | 1.27 | 1.89 | 28.00 | 146.90 | 0.00 | 179.43 |
| Gulf of Mexico | 2.75 | 5.48 | 8.38 | 0.00 | 0.00 | 800.00 | 0.00 | 816.62 |
| Midwest (East North Central) | 0.40 | 1.32 | 0.23 | 3.28 | 12.70 | 372.60 | 0.00 | 390.53 |
| Northern Midcontinent (West North Central) | 0.23 | 5.90 | 2.09 | 0.17 | 0.00 | 46.00 | 0.00 | 54.39 |
| Northern Rockies (Mountain 1) | 0.95 | 4.60 | 2.50 | 17.71 | 0.00 | 46.00 | 33.30 | 105.07 |
| New England (New England) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Northeast (Middle Atlantic) | 0.00 | 0.35 | 0.59 | 0.08 | 12.00 | 75.60 | 0.00 | 88.62 |
| Pacific NW (Pacific; Lower 48 Onshore Part) | 0.00 | 0.00 | 0.00 | 2.30 | 0.00 | 0.00 | 66.60 | 68.90 |
| Pacific Offshore (Pacific; L48 Offshore) | 0.00 | 1.25 | 0.04 | 0.00 | 0.00 | 100.00 | 0.00 | 101.29 |
| Southern Rockies (Mountain 2) | 0.84 | 3.30 | 5.99 | 19.62 | 0.00 | 4,515.00 | 0.00 | 4,544.75 |
| Southeast (South Atlantic) | 0.00 | 0.23 | 0.71 | 0.31 | 19.01 | 181.60 | 0.00 | 201.85 |
| Texas and S. Midcontinent (West S. Central) | 8.87 | 27.95 | 26.05 | 5.70 | 35.00 | 1,237.40 | 0.00 | 1,340.98 |
| Total | 17.79 | 59.54 | 49.65 | 51.06 | 106.71 | 8,021.10 | 99.90 | 8,405.75 |
| Offshore | 2.75 | 6.73 | 8.42 | 0.00 | 0.00 | 900.00 | 0.00 | 917.90 |
| Onshore | 15.04 | 52.81 | 41.23 | 51.06 | 106.71 | 7,121.10 | 99.90 | 7,487.85 |

# Sequestration Cost Model

- EEA has developed a spreadsheet model to evaluate the cost of underground geologic sequestration of CO2 in the U.S.
- The model incorporates an EEA/NATCARB assessment of CO2 storage volumes by state and reservoir type.
- A depth distribution is also applied to each state and reservoir type.
- The sequestration cost is determined by the depth and type of reservoir, capital and operating costs, improved economics resulting from enhanced oil or gas production (with some categories), and other factors.
- Model inputs include cost assumptions by state and reservoir type and the EEA volumetric assessments, which are applied to the unit resource costs to develop cumulative curves relating costs to potential storage volumes.

# CO2 Sequestration Cost Example

**State:** **MICHIGAN**
**Type:** **Saline Aquifers - Non Basalt**

| | metric tons | barrels | Million standard cubic feet |
|---|---|---|---|
| Daily Injection Volume per Well | 405 | 3,000 | 7.6 |
| Annual Injection Volume per Well | 147,973 | 1,095,000 | 2,791 |
| Life-time Injection Volume per Well (20 years) | 2,959,459 | 21,900,000 | 55,815 |

| | | | |
|---|---|---|---|
| Well Depth (feet) | 6,000 | database: | 6,000 |
| Well Cost per Foot | $93 | | |
| Lease Equipment Costs ($/injector, excluding pump) | $100,000 | | |
| Additional Capital Cost per Injector (land rights, G&G, permits) | $250,000 | | |
| Annual (nonelectric) O&M Cost per Injector | $100,000 | | |
| Variable Injection Costs $/barrel CO2 | $0.10 | | |
| Pipeline Pressure (psi) | 1,900 | | |
| Pump Outlet Pressure (psi) | 2,559 | | |
| Pump Operating Load Factor | 0.90 | | |
| Pump Capacity (HP) | 51 | | |
| Pump Capital Cost $/HP | 1,459 | | |
| Number of Monitoring Wells per Injector Well | 4 | | |
| Monitoring Well Depth | 4,500 | | |
| Monitoring Well Cost per Foot (slim hole) | $80 | | |
| Lease Equipment Costs ($/monitor well) | $50,000 | | |
| Annual (nonelectric) O&M Cost per Monitoring Well | $50,000 | | |
| Number of Dewatering Wells per Injector Well | 0.25 | | |
| Lease Equipment Costs ($/dewatering well) | $50,000 | | |
| Annual O&M Cost per Dewatering Well (ex water disposal) | $40,000 | | |
| Produced Water Volume bbl water/bbl CO2 | 0.0 | | |
| Produced Water Disposal Cost $/bbl water | $1.00 | | |
| Volume of Crude Oil Produced bbl crude / Mcf CO2 | 0.000 | | |
| Value of Crude After Royalty/Sev Tax $/bbl | $0.00 | | |
| Incremental Crude Production Costs $/bbl | $0.00 | | |
| Volume of Natural Gas Produced Mcf NG / Mcf CO2 | 0.00 | | |
| Value of NG After Royalty/Sev Tax $/Mcf | $0.00 | | |
| Incremental NG Production Costs $/Mcf | $0.00 | | |
| G&A Factor | 20% | | |
| Annual Annual Capital Recovery Factor | 0.137 | | |
| O&M as % of Initial Capital Cost | 0.042 | | |
| Electricity $/kWh | $0.056 | | |

| **Capital Costs (for each injection well)** | |
|---|---|
| Injector, Monitoring, Dewatering Wells | $2,143,701 |
| Lease Equipment | $312,500 |
| Pump | $73,815 |
| Other Capital Costs | $250,000 |
| G&A | $556,003 |
| Total | $3,336,020 |

| **Annual Costs (for each injection well)** | **Annual** | $ per metric ton CO2 | $ per barrel CO2 | $ per Mcf CO2 |
|---|---|---|---|---|
| Capital costs | $457,035 | $3.09 | $0.42 | $0.16 |
| Fixed O&M Costs + G&A | $408,000 | $2.76 | $0.37 | $0.15 |
| Variable Operating Costs | $109,500 | $0.74 | $0.10 | $0.04 |
| Electricity Costs | $12,156 | $0.08 | $0.01 | $0.00 |
| Total Costs | $986,691 | $6.67 | $0.90 | $0.35 |
| Byproduct o/g Credit | $0 | $0.00 | $0.00 | $0.00 |
| Net Cost | $986,691 | $6.67 | $0.90 | $0.35 |

| **Electricity Use** | **Annual kWh** | kWh per metric ton CO2 | kWh per barrel CO2 | kWh per Mcf CO2 |
|---|---|---|---|---|
| Pumping | 219,036 | 1.48 | 0.20 | 0.08 |



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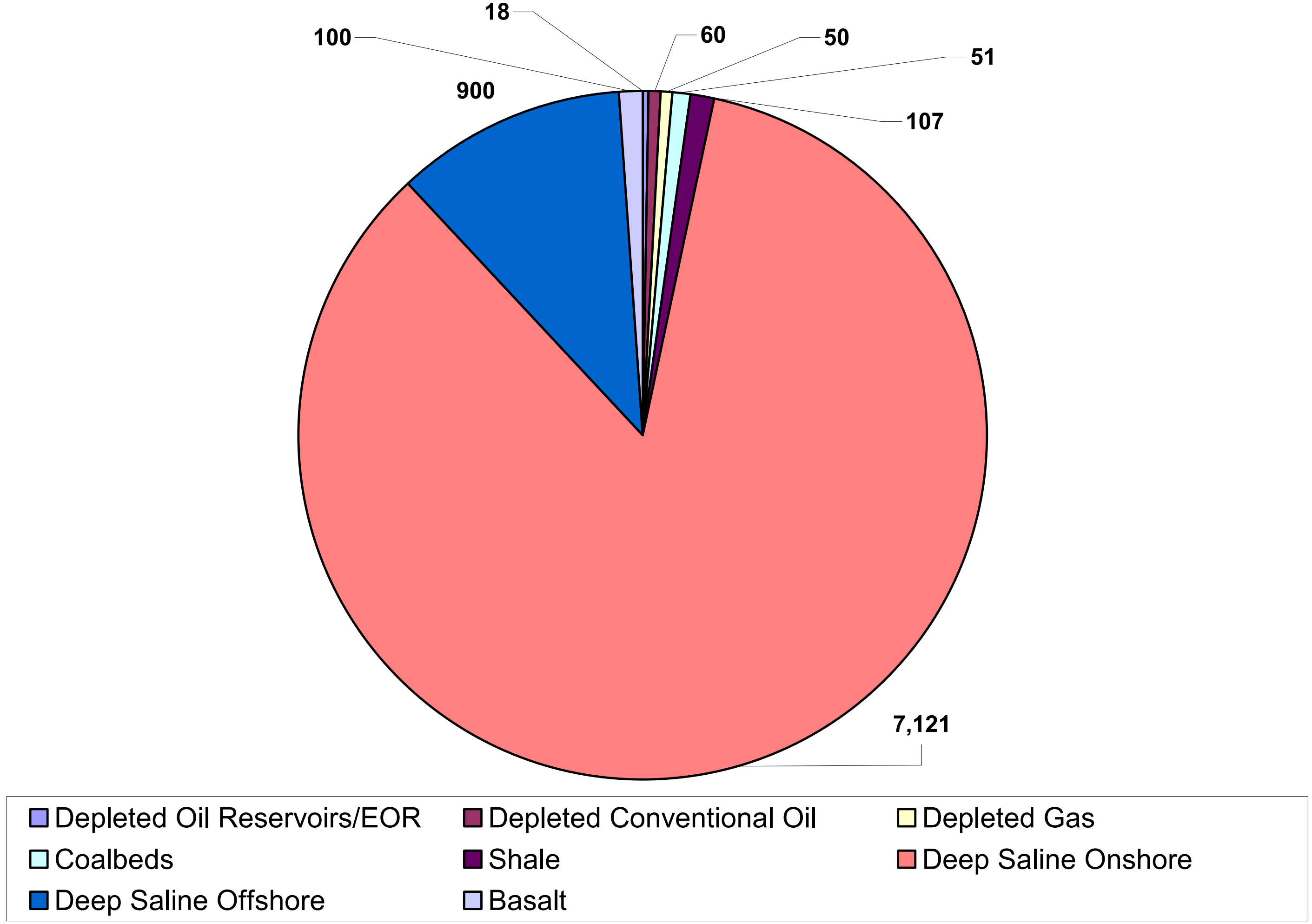
# Sequestration Economics in Context

**Summary of $CO_2$ Capture, Transport and Sequestration Costs ($/metric ton)**

| | Capture Phase (select one) | | | Tranport Phase (multiple by miles/75) | Underground Sequestration Phase (select one) | | Typical PC Powerplant Example |
|---|---|---|---|---|---|---|---|
| | High Quality Industrial CO2 Stream | Pulverized Coal Power Plant | IGCC Power Plant | CO2 Pipeline Transportation for 75 miles | Aquifer Injection (Low Cost) | Aquifer Injection (High Cost) | PC Capture + Transport for 75 miles + Low Cost Injection |
| Capital Costs | $2.15 | $16.55 | $7.38 | $1.13 | $1.56 | $7.12 | $19.24 |
| Fixed O&M Costs | $0.66 | $6.23 | $2.77 | $0.35 | $1.22 | $3.65 | $7.79 |
| Variable Operating Costs | $0.50 | $4.60 | $4.60 | $0.00 | $0.74 | $0.74 | $5.34 |
| Electricity Costs | $5.11 | $16.23 | $10.80 | $0.13 | $0.08 | $0.25 | $16.44 |
| **Total Cost** | **$8.42** | **$43.61** | **$25.56** | **$1.61** | **$3.60** | **$11.76** | **$48.81** |
| Electricity use (kWh/metric ton CO2) | 92.1 | 292.5 | 194.6 | 2.3 | 1.5 | 4.4 | 296.2 |

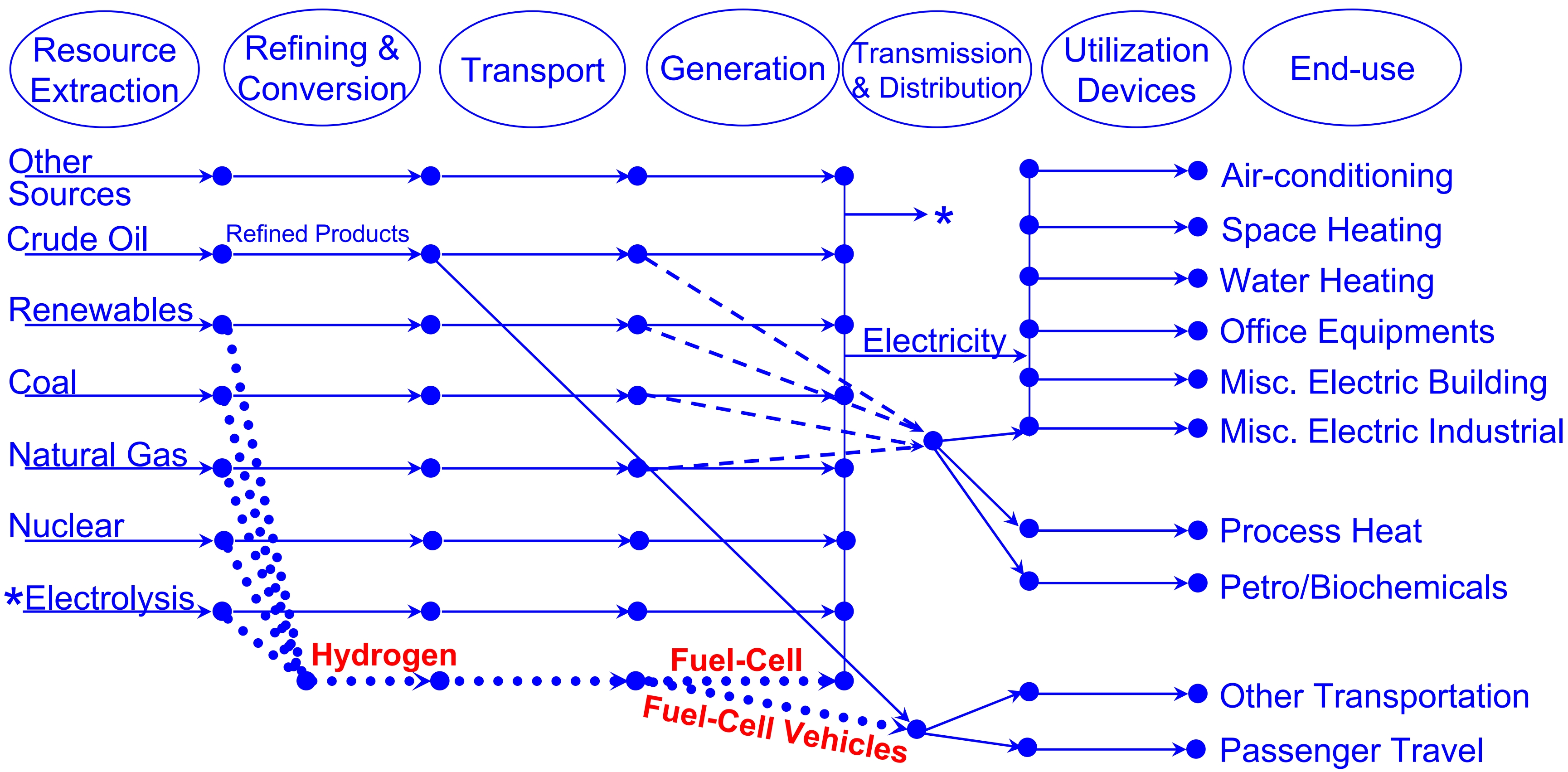
## 2006 EEA Assessment of Lower-48 CO2 Sequestration Potential - Total 8405 Gt



# Key Uncertainties for Geologic Sequestration

- Geologic assessments are still in an early stage
- Key parameters affecting costs (injectivity and well capacities) have not been measured widely
- Possible need to dispose of some displaced water
- Environmental and safety regulatory regime is not known
- Liability and risk allocation yet to be determined
- How will NIMBY concerns evolve?

# MARKAL for Integrated Market Analysis



# New U.S. MARKAL Regions