Induced Seismicity Potential in Energy Technologies

Conducted by the National Research Council's Committee on Induced Seismicity Potential in Energy Technologies

Sponsor
Department of Energy

Overseen by the Board on Earth Sciences and Resources and its standing Committees on Earth Resources; Geological and Geotechnical Engineering; & Seismology and Geodynamics

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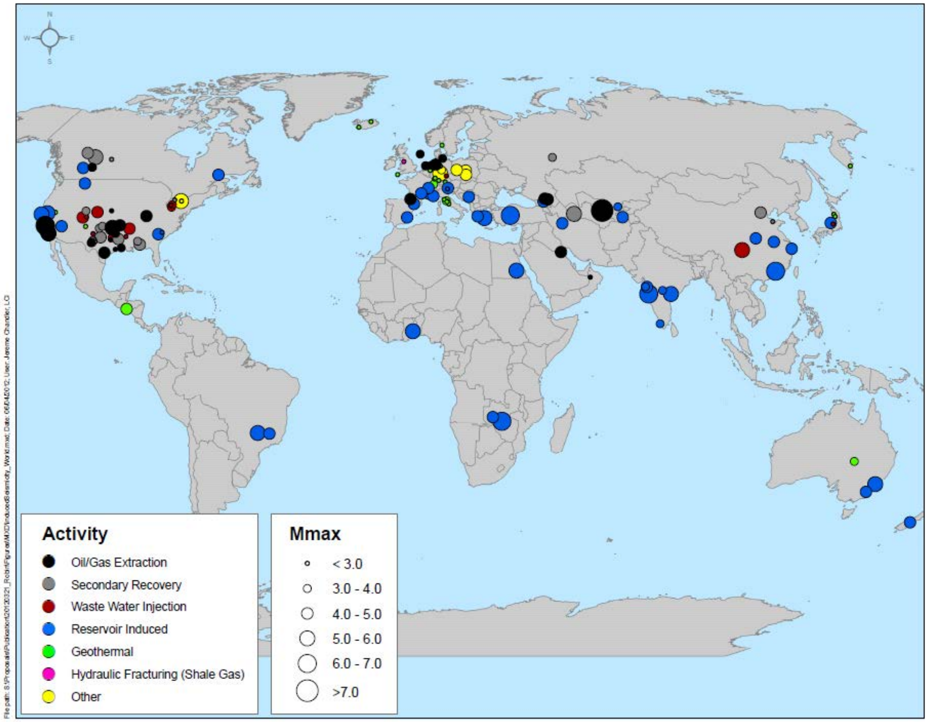
Background



- A number of seismic events apparently related to fluid injection for energy development occurred during the past 6 years, for example:

  - Basel, Switzerland, 2006, Enhanced geothermal system (M 3.4)

  - Dallas-Ft. Worth airport area, 2008-09, Waste water disposal from shale gas development (M 3.3)

  - Blackpool, England, 2011, Hydraulic fracturing (shale gas) (M 2.3)

- Public concern about these kinds of events prompted Senator Bingaman to ask Secretary Chu to request a study by the National Research Council on “Induced Seismicity in Energy Technologies”

Statement of Task

This study will address the potential for felt induced seismicity of geothermal systems, oil and gas production including enhanced oil recovery and hydraulic fracturing for shale gas production, and carbon capture and storage (CCS) and specifically will:

- summarize the current state-of-the-art knowledge on the possible scale, scope and consequences of seismicity induced during the injection of fluids related to energy production;

- identify gaps in knowledge and the research needed to advance the understanding of induced seismicity, its causes, effects, and associated risks;

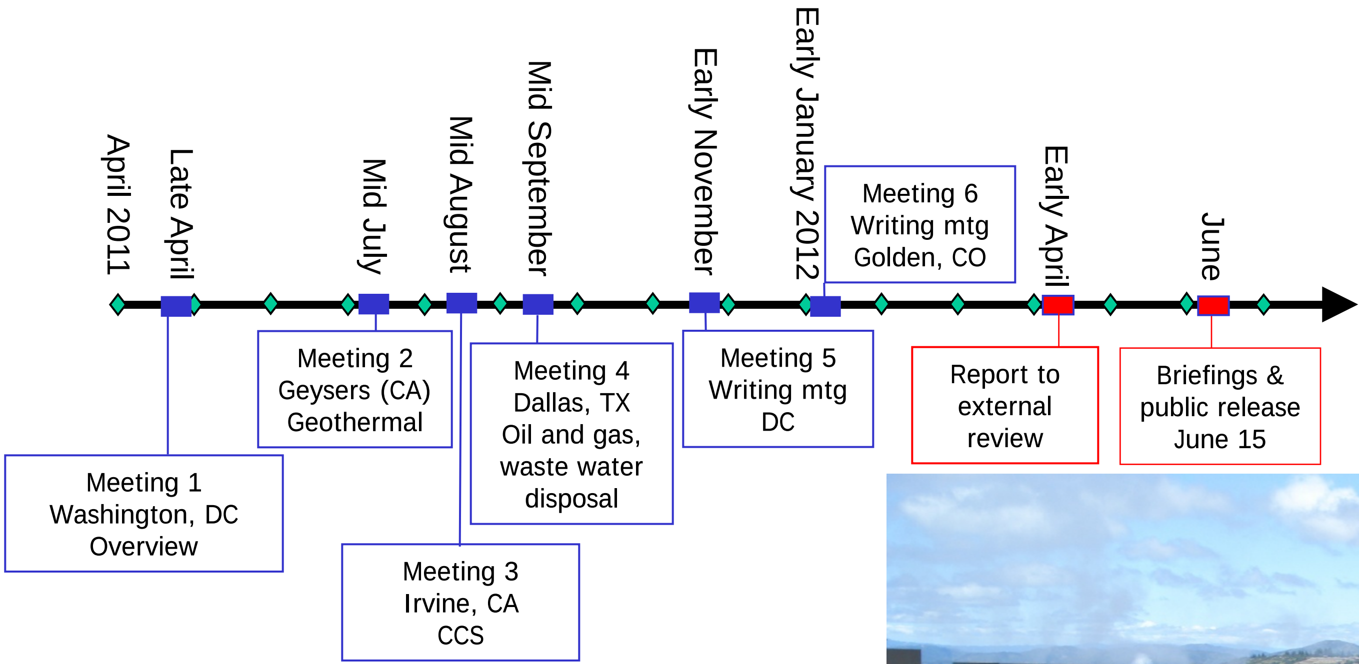
- identify gaps and deficiencies in current hazard assessment methodologies for induced seismicity and research needed to close those gaps;

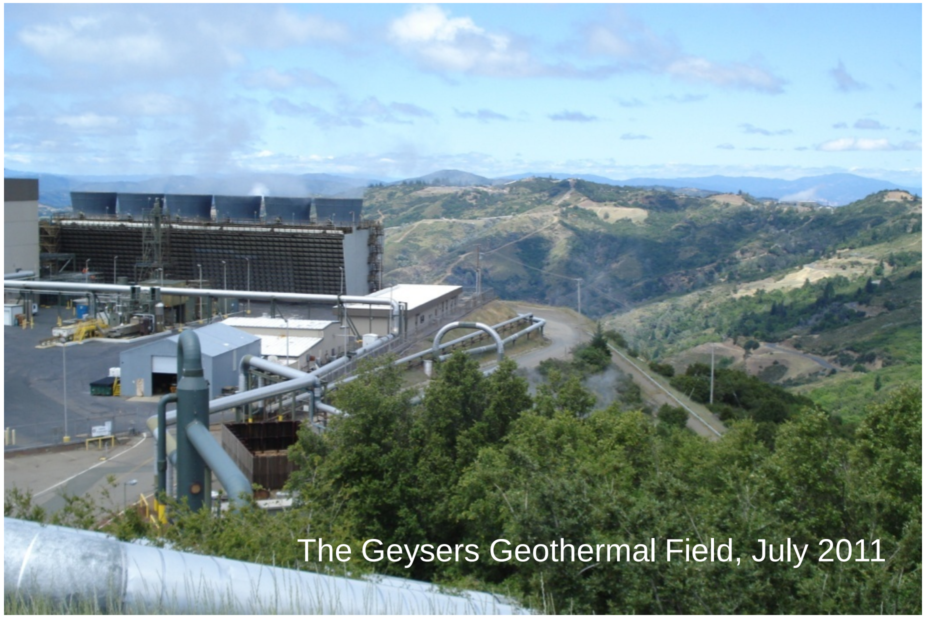
- identify and assess options for interim steps toward best practices, pending resolution of key outstanding research questions.

Report Overview

- Introduction to induced seismicity and its history
- Types and causes of induced seismicity
- Induced seismicity of energy technologies
  - Geothermal
  - Oil and gas (including EOR and shale gas recovery)
  - Waste water injection
  - Carbon capture and sequestration (CCS)
- Government roles and responsibilities
- Understanding hazard and risk assessment to manage induced seismicity
- Steps toward best practices
- Findings, gaps, proposed actions, and research recommendations

Study Process




The Geysers Geothermal Field, July 2011

Types and Causes of Induced Seismicity

- Induced seismic activity has been attributed to a range of human activities including:
  - Impoundment of large reservoirs behind dams
  - Controlled explosions related to mining or construction
  - Underground nuclear tests
  - *Energy technologies that involve injection or withdrawal of fluids from the subsurface*

Types and Causes of Induced Seismicity in Fluid Injection/Withdrawal for Energy Development

- The general mechanisms that create induced seismic events are well understood.

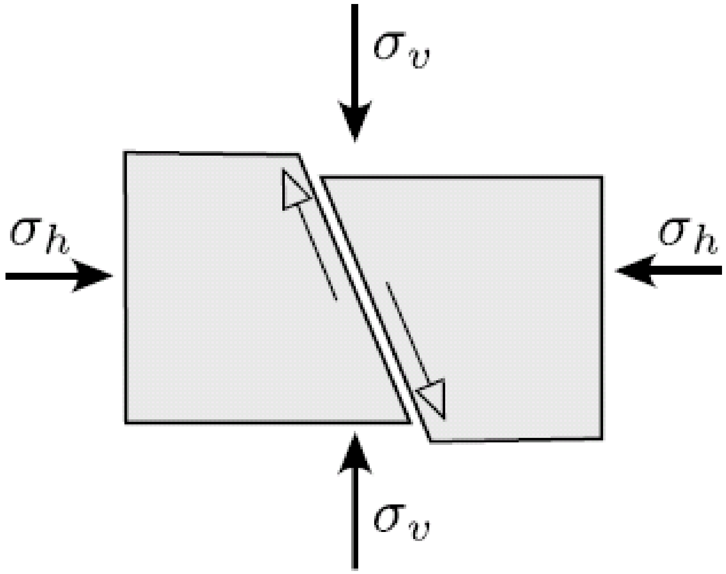
- However, we are currently unable to accurately predict the occurrence or magnitude of such events due to the lack of comprehensive data on complex natural rock systems and the lack of validated predictive models.

Types and Causes of Induced Seismicity in Fluid Injection/Withdrawal for Energy Development

- Induced seismicity is caused in most cases by change in pore fluid pressure and/or change in stress in the subsurface in the presence of:
  - faults with specific properties and orientations;
  - a critical state of stress in the crust.

- The factor that appears to have the most direct correlation in regard to induced seismicity is the net fluid balance — *the total balance of fluid introduced into or removed from the subsurface*.

- Additional factors may also influence the way fluids affect the subsurface.



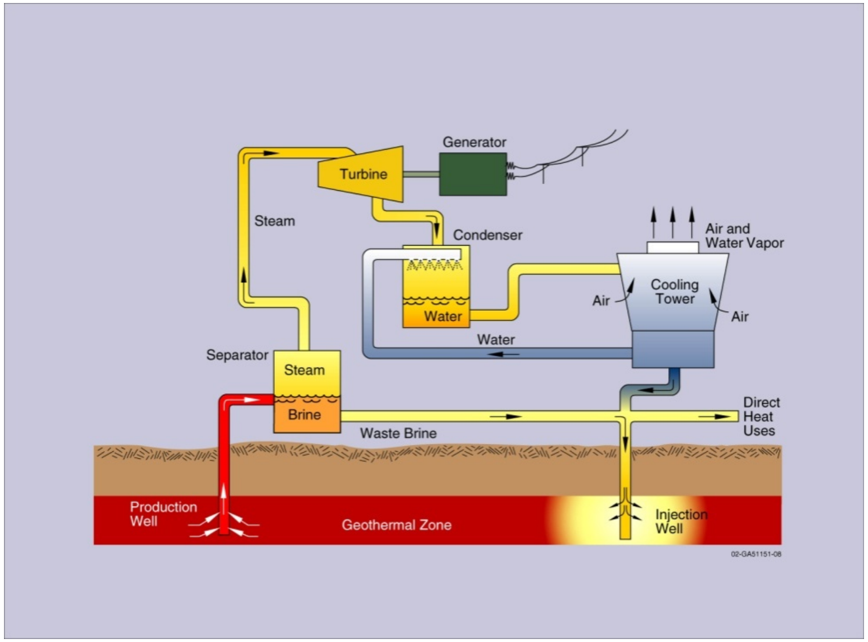
Normal fault

$\sigma_v > \sigma_H > \sigma_h$

Energy Technologies

- Geothermal energy development
  - *Vapor-dominated*
  - *Liquid-dominated*
  - *Enhanced geothermal systems (EGS)*
- Oil and gas development
  - *Oil and gas extraction (fluid withdrawal)*
  - *Secondary recovery (waterflooding)*
  - *Tertiary recovery (CO_2 flooding)*
  - *Hydraulic fracturing for shale gas*
- Waste water disposal wells
- Carbon capture and storage (CCS)

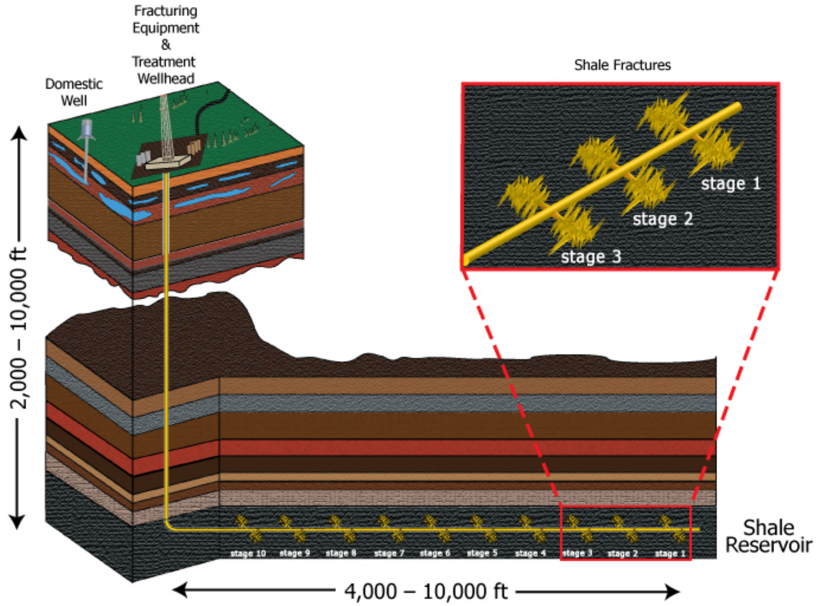
Energy Technologies—Geothermal Energy



Flash Steam Power Cycle for liquid-dominated systems

- Vapor-dominated—primarily steam in pores and fractures of the rock
- Liquid-dominated—primarily hot water in the pores and fractures of the rock
- Enhanced geothermal systems (EGS)—"hot dry rock" requires fracturing to promote hot water circulation
- Operators attempt to keep balance between fluid volumes produced and fluids replaced by injection to maintain reservoir pressure
- *Different from other energy technologies in temperature of reservoir*

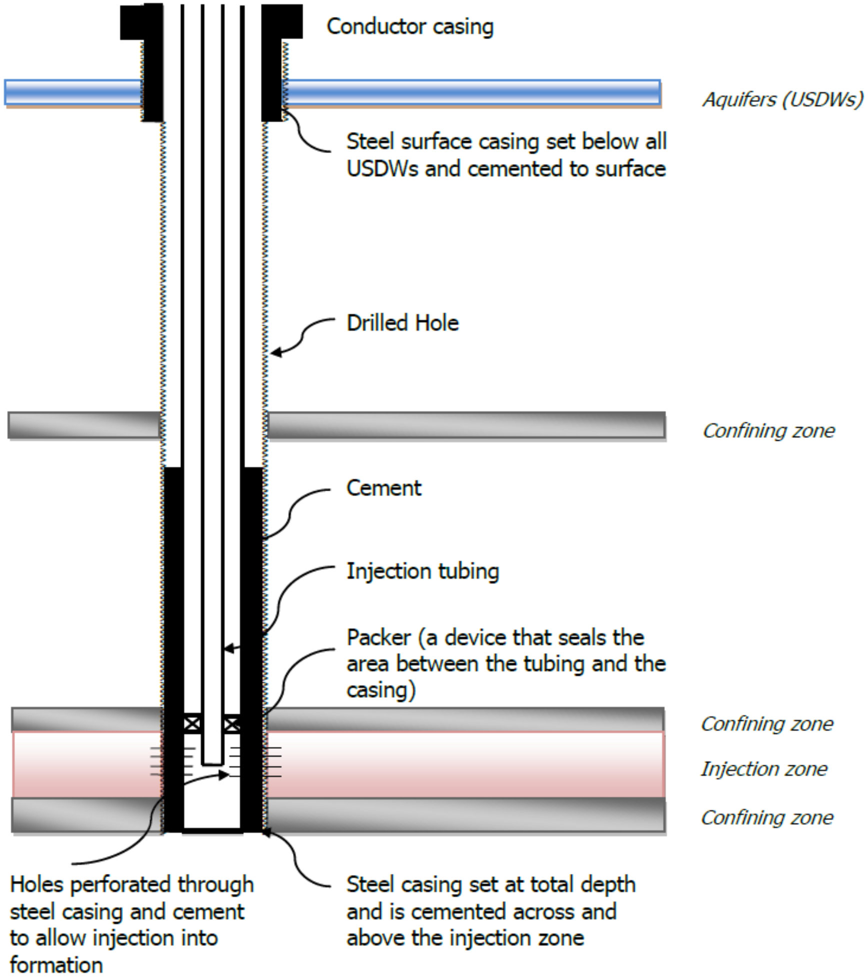
Energy Technologies — Oil and Gas



Shale gas development

- Oil and gas withdrawal—removes large volumes of fluids over decades, usually with accompanying fluid injection
- Enhanced recovery—inject fluids (water, steam, CO_2, etc.) to extract remaining oil and gas
    - secondary recovery (often 'waterflooding')
    - tertiary recovery (enhanced oil recovery)
- Hydraulic fracturing a well for shale gas development—use horizontal drilling and hydraulic fracturing to create fractures for gas to migrate to a well
- Oil and gas operators attempt to balance the fluid volumes produced with fluid injection to maintain reservoir pressure

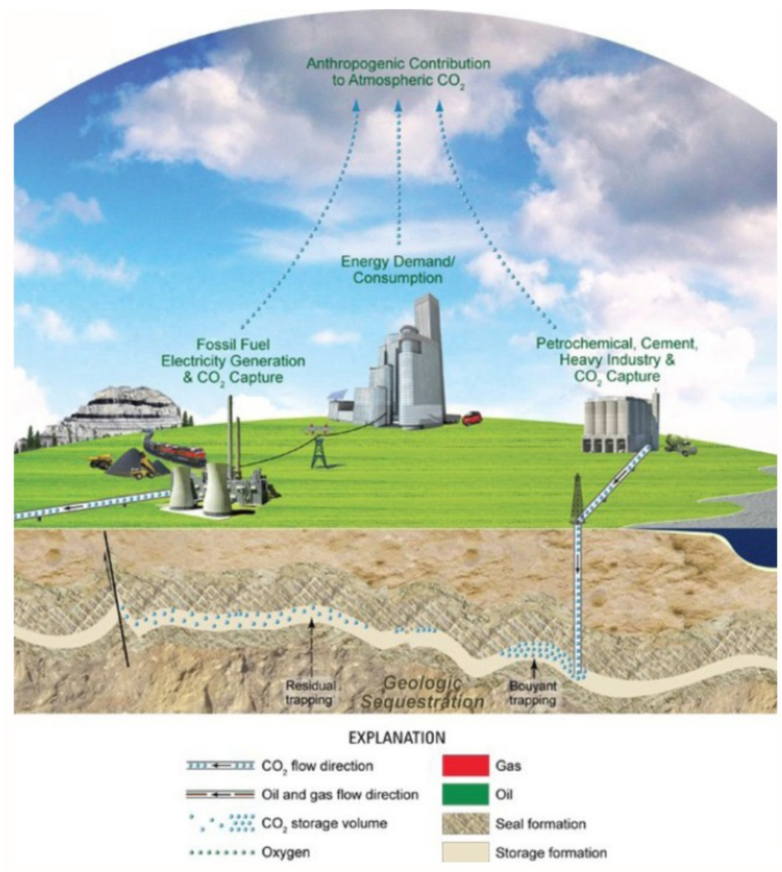
Energy Technologies — Waste Water Disposal Wells



- Fluid from flow back after hydraulic fracturing and waste fluid produced from conventional oil and gas production in the United States = over 800 billion gallons a year

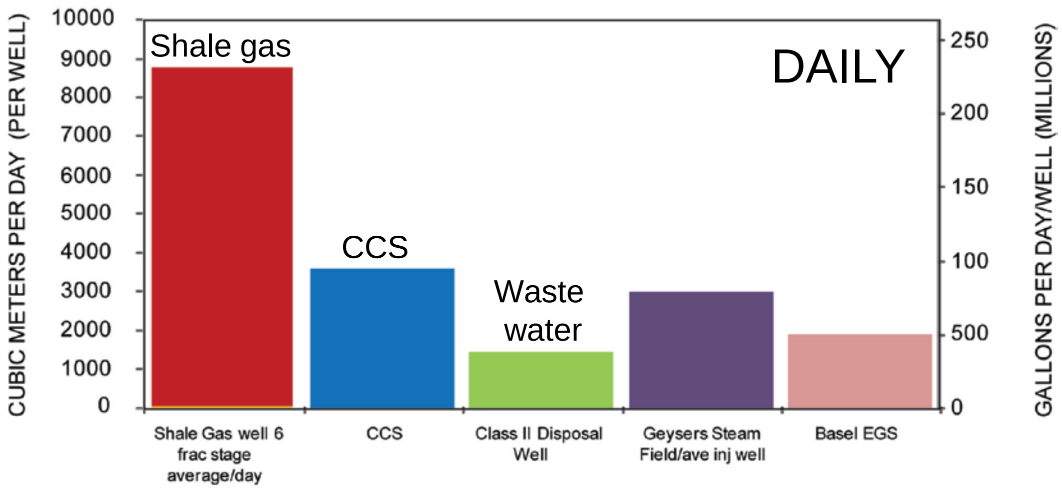
- More than one third of the volume is managed through underground injection for permanent disposal in “Class II” wells, permitted by EPA and states with delegated authority

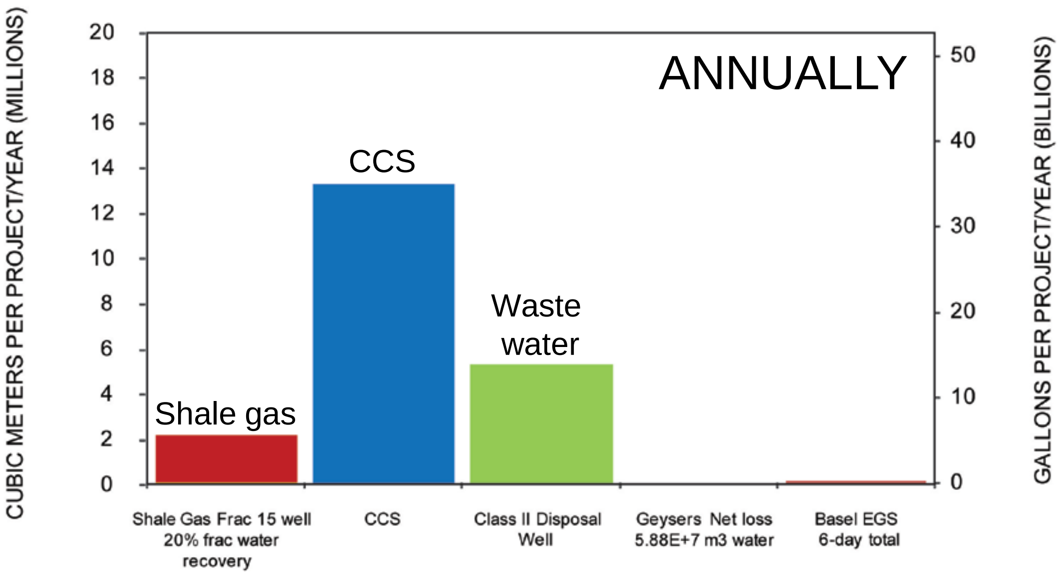
Energy Technologies—CCS



- CO_2 can be captured, liquefied, and injected into various kinds of geological formations for permanent storage
- CO_2 remains a liquid (in "supercritical" phase) underground
- Small-scale commercial projects in operation (offshore Norway, onshore Algeria) inject about 1 million metric tonnes of CO_2 per year
- Regional partnerships in U.S. to test technologies and small-scale injection (Illinois)—plan to inject ~1 million metric tonnes of CO_2 per year
- Future projects expect to inject much greater than 1 million metric tonnes

Comparative Estimated Fluid Volumes for Energy Technologies





- ❑ Daily fluid volumes injected are highest for hydraulic fracturing — 8,500 m^3
- ❑ Annual fluid volumes injected are highest for proposed CCS projects (13,000,000 m^3) and then Class II waste water disposal wells (4,000,000 m^3)
- ❑ Geysers geothermal field records net fluid loss annually

Historical Felt Seismic Events Caused by or Likely Related to Energy Technologies in U.S.

Energy Technology	Number of **Current** Projects	Number of **Historical** Felt Events	**Historical** Number of Events M≥4.0	Locations of Events M≥2.0
Geothermal				
Vapor-dominated (The Geysers)	1	300-400 per year since 2005	1 to 3	CA
Liquid-dominated	23	10-40 per year	Possibly one	CA
EGS	~8 pilot	2-10 per year	0	CA
Oil and gas				
Withdrawal	~6,000 fields	20 sites	5	CA, IL, NB, OK, TX
Secondary recovery (water flooding)	~108,000 wells today	18 sites	3	AL, CA, CO, MS, OK, TX
EOR	~13,000 wells today	None known	None known	None known
Hydraulic fracturing for shale gas recovery	~35,000 wells today	1	0	OK
Waste water disposal wells (Class II)	~30,000 wells today	8	7	AR, CO, OH,TX
Carbon capture and storage (small scale)	1	None known	None known	None known

Energy Technology Potential for Induced Seismicity — Summary Points

The factors important for understanding the potential to generate felt seismic events are complex and interrelated and include:

- the rate of injection or extraction
- volume and temperature of injected or extracted fluids
- pore pressure
- permeability of the relevant geologic layers
- faults, fault properties, fault location
- crustal stress conditions
- the distance from the injection point
- the length of time over which injection and/or withdrawal takes place

Energy Technology Potential for Induced Seismicity — Summary Points

- The net fluid balance (*total balance of fluid introduced and removed*) appears to have the most direct consequence on changing pore pressure in the subsurface over time.

- Energy technology projects designed to maintain a balance between the amount of fluid being injected and the amount of fluid being withdrawn, such as geothermal and most oil and gas development, may produce fewer induced seismic events than technologies that do not maintain fluid balance.

Study Findings on Induced Seismicity Potential of Different Energy Technologies

- Geothermal
- Conventional oil & gas production
- Unconventional oil & gas production (shale gas)
- Energy waste water disposal
- Carbon capture and sequestration

Induced Seismicity Potential — Geothermal

- Induced seismicity appears related to both net fluid balance considerations and temperature changes produced in the subsurface

- Different forms of geothermal resource development appear to have differing potential for producing felt seismic events:

    - High-pressure hydraulic fracturing undertaken in some geothermal projects (EGS) has caused seismic events that are large enough to be felt

    - Temperature changes associated with geothermal development of hydrothermal resources has also induced felt seismicity (The Geysers)

Induced Seismicity Potential — Conventional Oil & Gas Production

- Generally, withdrawal associated with conventional oil and gas recovery has not caused significant seismic events, however several major earthquakes have been associated with conventional oil and gas withdrawal.

- Relative to the large number of waterflood projects for secondary recovery, the small number of documented instances of felt induced seismicity suggests such projects pose small risk for events that would be of concern to the public.

- The committee did not identify any documented, felt induced seismic events associated with EOR (tertiary recovery); the potential for induced seismicity is low.

Induced Seismicity Potential — Unconventional Oil & Gas Production (Shale Gas)

- The process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events.

- ~35,000 wells have been hydraulically fractured for shale gas development to date in the United States.

- Only one case of demonstrated induced seismicity from hydraulic fracturing for shale gas has been documented worldwide (Blackpool, England – 2011).

Induced Seismicity Potential — Energy Waste Water Disposal

- The US currently has approximately 30,000 Class II waste water disposal wells (water from energy production). Very few felt induced seismic events reported as either caused by or likely related to these wells. Rare cases of waste water injection have produced seismic events, typically less than **M** 5.0.

- High injection volumes may increase pore pressure and in proximity to existing faults could lead to an induced seismic event.

- The area of potential influence from injection wells may extend over several square miles.

- Induced seismicity may continue for months to years after injection ceases.

- Evaluating the potential for induced seismicity in the location and design of injection wells is difficult because there are no cost-effective ways to locate faults and measure in situ stress.

Induced Seismicity Potential —
Carbon Capture and Sequestration (CCS)

- The only long-term (~14 years) commercial CO_2 sequestration project in the world at the Sleipner field offshore Norway is small scale relative to commercial projects proposed in the US. Extensive seismic monitoring has not indicated any significant induced seismicity.

- There is no experience with the proposed injection volumes of liquid CO_2 in large-scale sequestration projects (> 1 million metric tonnes per year). If the reservoirs behave in a similar manner to oil and gas fields, these large volumes have the potential to increase the pore pressure over large areas and may have the potential to cause significant seismic events.

- CO_2 has the potential to react with the host/adjacent rock and cause mineral precipitation or dissolution. The effects of these reactions on potential seismic events are not understood.

Government Roles and Responsibilities (Findings)

1. Responsibility for oversight of activities that can cause induced seismicity is dispersed among a number of federal and state agencies.

2. Recent, potentially induced seismic events in the US have been addressed in a variety of manners involving local, state, and federal agencies, and research institutions. These agencies and research institutions may not have resources to address unexpected events; more events could stress this ad hoc system.

3. Currently the EPA has primary regulatory responsibility for fluid injection under the Safe Drinking Water Act; ***this act does not address induced seismicity***.

4. The USGS has the capability and expertise to address monitoring and research associated with induced seismic events. However, their mission does not focus on induced events. Significant new resources would be required if their mission is expanded to include comprehensive monitoring and research on induced seismicity.

Government Roles and Responsibilities (Gap & Proposed Actions)

Gap

Mechanisms are lacking for efficient coordination of governmental agency response to induced seismic events.

Proposed Actions

1. In order to move beyond the current ad hoc approach for responding to induced seismicity, relevant agencies including EPA, USGS, land management agencies, and possibly the Department of Energy, as well as state agencies with authority and relevant expertise, should consider developing coordination mechanisms to address induced seismic events that correlate to established best practices.

2. Appropriating authorities and agencies with potential responsibility for induced seismicity should consider resource allocations for responding to future induced seismic events.

Understanding Hazard and Risk to Manage Induced Seismicity (Finding)

Currently, methods do not exist to implement assessments of hazards upon which risk assessments depend. The types of information and data required to provide a robust hazard assessment include:

- Net pore pressures, in situ stresses, information on faults
- Background seismicity
- Gross statistics of induced seismicity and fluid injection for the proposed site activity

Understanding Hazard and Risk to Manage Induced Seismicity — Proposed Actions

1. A detailed methodology should be developed for quantitative, probabilistic hazard assessments of induced seismicity risk. The goals in developing the methodology would be to:
   - make assessments before operations begin in areas with a known history of felt seismicity
   - update assessments in response to observed induced seismicity

2. Data related to fluid injection (well locations coordinates, injection depths, injection volumes and pressures, time frames) should be collected by state and federal regulatory authorities in a common format and made accessible to the public (through a coordinating body such as the USGS).

3. In areas of high-density of structures and population, regulatory agencies should consider requiring that data to facilitate fault identification for hazard and risk analysis be collected and analyzed before energy operations are initiated.

Steps Toward Best Practices (Findings & Gap)

Findings

1. The DOE Protocol for EGS provides a reasonable initial model for dealing with induced seismicity that can serve as a template for other energy technologies.

2. Based on this model, two matrix-style protocols illustrate the manner in which activities can ideally be undertaken concurrently (rather than only sequentially), while also illustrating how these activities should be adjusted as a project progresses from early planning through operations to completion.

Gap

No best practices protocol for addressing induced seismicity is in place for each of these technologies, with the exception of the EGS protocol. The committee suggests that best practices protocols be adapted and tailored to each technology.

Study Research Recommendations

1. **Collecting field and laboratory data** on active seismic events possibly caused by energy development and on specific aspects of the rock system at energy development sites (for example, on fault and fracture properties and orientations, crustal stress, injection rates, fluid volumes and pressures).

2. **Developing instrumentation** to measure rock and fluid properties before and during energy development projects.

3. **Hazard and risk assessment** for individual energy projects.

4. **Developing models,** including codes that link geomechanical models with models for reservoir fluid flow and earthquake simulation.

5. **Conducting research on carbon capture and storage,** incorporating data from existing sites where carbon dioxide is injected for enhanced oil recovery, and developing models to estimate the potential magnitude of seismic events induced by the large-scale injection of carbon dioxide for storage.

Conclusion

Although induced seismic events have not resulted in loss of life or major damage in the United States, their effects have been felt locally, and they raise some concern about additional seismic activity and its consequences in areas where energy development is ongoing or planned.

Further research is required to better understand and address the potential risks associated with induced seismicity.

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