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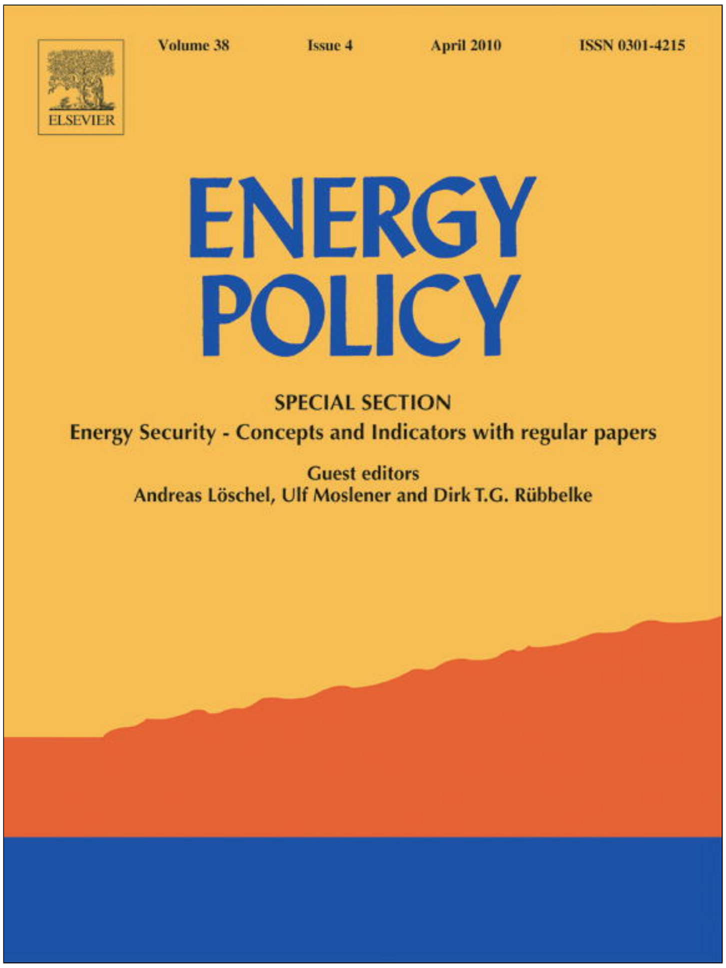

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Assessing innovation in emerging energy technologies: Socio-technical dynamics of carbon capture and storage (CCS) and enhanced geothermal systems (EGS) in the USA

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ABSTRACT

This study applies a socio-technical systems perspective to explore innovation dynamics of two emerging energy technologies with potential to reduce greenhouse gas emissions from electrical power generation in the United States: carbon capture and storage (CCS) and enhanced geothermal systems (EGS). The goal of the study is to inform sustainability science theory and energy policy deliberations by examining how social and political dynamics are shaping the struggle for resources by these two emerging, not-yet-widely commercializable socio-technical systems. This characterization of socio-technical dynamics of CCS and EGS innovation includes examining the perceived technical, environmental, and financial risks and benefits of each system, as well as the discourses and actor networks through which the competition for resources – particularly public resources – is being waged. CCS and EGS were selected for the study because they vary considerably with respect to their social, technical, and environmental implications and risks, are unproven at scale and uncertain with respect to cost, feasibility, and life-cycle environmental impacts. By assessing the two technologies in parallel, the study highlights important social and political dimensions of energy technology innovation in order to inform theory and suggest new approaches to policy analysis.

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1. Introduction

The portfolio of energy technologies with potential to contribute to a transition to a low-carbon-emitting energy infrastructure includes a diverse set of options each with distinctly different attributes, uncertainties, and current and projected opportunities and limitations (Pacala and Socolow, 2004; Tester et al., 2005; IPCC, 2007). While it is widely acknowledged that no "silver bullet solution" to society's energy challenges exists (Holdren, 2006), there is little agreement on how to prioritize and distribute scarce resources among various promising emerging technologies. While analysts regularly assess technical and economic dimensions of potential energy options (Isoard and Soria, 2001; Grubler et al., 2002; NCEP, 2004), far fewer consider how perceptions and interpretations about a nascent technology's potential form and, along with related strategies of social mobilization, influence the technology's actual development (Hekkert et al., 2007; Wustenhagen et al., 2007). With public policy decisions playing a critical role in influencing the prospects for alternative low-carbon energy options, socio-technical systems approaches that place technical and economic considerations within wider social and political processes are needed to more fully assess energy portfolio options (Rogers, 2003; Stephens et al., 2008; Jiusto, 2009).

A growing body of research on socio-technical system transitions provides a framework for understanding the role these contextual factors play in shaping the course of technological evolution (Rip and Kemp 1998; Geels, 2005). Socio-technical systems analysis has roots in sociological (Bijker et al., 1987) and historical (Hughes, 1983) accounts of technological change, as well as in evolutionary economics and other influences. Central to this framework is the notion that large technical systems co-evolve with associated social, cultural, and political institutions. Technologies that achieve market dominance and widespread application engender social formations with strong incentives to protect and promote the entrenched regime. In this framework, socio-technical transition occurs when a niche technology gains enough traction to compete with, and then to a significant degree replace, the entrenched socio-technical regime. Often this occurs as developments in the broader "landscape level" are also undermining the entrenched regime, creating opportunities for destabilizing the mainstream (Smith et al., 2005; Loorbach, 2007).

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In the field of sustainability science, much of the interest in technological innovation takes on a normative dimension, driven by an interest in understanding the socio-technical processes that might lead toward "sustainability transitions" (Geels, 2005; Loorbach, 2007; Meadowcroft, 2007).

This study seeks to contribute to the overlapping literatures on energy policy, sustainability science, and socio-technical systems innovation. We take as our case studies two technologies in early development with potential to provide low-carbon electricity generation, carbon capture and storage (CCS) for application with coal-fired power production,[1] and enhanced geothermal systems (EGS). We bound the study geographically by considering these systems' development principally in the United States, where electricity generation accounts for about 40% of all carbon dioxide emissions. Coal power currently accounts for half the nation's electricity supply and four-fifths of the electrical sector's carbon emissions. The pressing need for low-carbon energy options has spawned significant interest in energy technology innovation in both political circles and in the research community (Holdren, 2006; Office of Management and Budget, 2009). Multiple approaches to understanding factors influencing energy technology innovation processes have attempted to assess specific deterministic factors (Toke et al., 2008; Bohn and Lant, 2009) and have frequently focused on the influence of specific policies on deployment (Menz and Vachon, 2006; Rabe, 2006). To complement these studies, this research embraces a broader socio-technical perspective and uses it to examine social and political factors, including discursive strategies and mobilizing of actor networks, that influence perceptions of each systems' technical, economic, and environmental risks and benefits and their success in acquiring financial resources for research, development, and deployment (RD&D).

This research is based on secondary analysis of research reports, position papers, and other archival data as well as interviews with key stakeholders involved in the innovation of each technology. Section 2 reviews recent shifts in energy systems research to provide some additional background and justification for our approach and Section 3 reviews the technological status of both CCS and EGS highlighting the potential and current technical limitations of each. Section 4 discusses the environmental risks and benefits of both technologies and Section 5 reviews the competing societal discourse associated with each technology. Then the strength and composition of the actor-network of both CCS and EGS are explored in Section 6, followed by a review of the financial investment, both public and private, in research, development, and demonstration (RD&D) for both CCS and EGS in Section 7. Finally Section 8 highlights both theoretical and policy implications of our analysis.

2. Shifts in energy systems and energy systems research

The current energy system landscape is changing as concerns over climate change, energy price volatility, and energy security have stimulated government, entrepreneurs, and civil society to search for energy system alternatives. As the macro level energy landscape changes, new opportunities are emerging for novel technologies that have varying potential for contributing to an energy system transformation (Verbong and Geels, 2007). This study juxtaposes analysis of the innovation dynamics of CCS – a set of technologies that is directly connected to the entrenched, mainstream, coal-dominated energy regime – with assessment of the innovation dynamics of EGS—a novel, niche technology with minimal connections to the existing electricity generating infrastructure. CCS is increasingly considered a technological prerequisite for continued coal-fired electrical power production in a carbon constrained world and has a strong, supportive actor-network associated with substantial financial investment. The EGS actor-network is weaker and less able to secure public and private investment, though recent developments have strengthened its position.

For over a century, the coal industry has remained central to US energy systems by responding with incremental changes to numerous societal and environmental pressures (Freese, 2003; Goodell, 2006). Coal is a domestically abundant and historically inexpensive fuel, and CCS has emerged as a critical, "end-of-pipe" component of the coal industry's response to growing societal concerns about climate change. CCS thus can be viewed as being supported by and contributing to the stabilization of the "entrenched regime" of the current coal-based energy system, while EGS represents a niche technology that might ultimately be disruptive to the mainstream regime. We show below, however, that CCS shares with EGS some classic attributes of niche technology (Hegger et al., 2007; Schot and Geels, 2008). Both technologies are responding to new opportunities and constraints in the changing environmental landscape, both require some protection from competition while the process of research and development unfolds, both need to extend socio-technical networks to include new and powerful actors, and both need to attract funding from government and other investors to advance. Each of these needs and strategies are dependent on the success with which early-stage technology developers can create a compelling discourse that explains the technology as an effective response to vital societal needs or desires and that its developmental costs are prudent in light of its future market potential (Lounsbury and Glynn, 2001).

As researchers and theorists have moved to embrace a wider, often interdisciplinary range of explanatory factors in the evolution of technological systems, they have been challenged to balance comprehensiveness with parsimony and theoretical insight with empirical richness. Given, too, that the categories of analysis used in innovation studies are widely acknowledged to be heuristic rather than actual, there has been considerable conceptual heterogeneity in socio-technical systems analysis, and theorists have struggled to provide accounts that are practical for policymakers and analysts to use (Bergek et al., 2008).

Recently, a number of theorists have coalesced around a model of technological innovation systems (TIS) evolution defined by seven functions; entrepreneurial activities, knowledge development, knowledge diffusion through networks, guidance of the search (for innovation potential), market formation, resources mobilization, and creation of legitimacy (Hekkert et al., 2007). This TIS framework with its discrete functions has been applied to multiple technologies in various contexts with a goal of identifying leverage points for enhancing or accelerating the innovation process, including one particularly relevant empirical analysis of CCS development in Norway (Alphen et al., 2009). While our approach does not apply these same categories of functional analysis, we focus on core elements that cross-cut the seven functions.

While addressing many elements of the TIS framework, we also intend the parallel case study approach to highlight aspects of both technologies that are often not fully considered in policy analysis or the transition management and innovation studies literature. These considerations include the role of discourse in shaping policy deliberations, something that is touched on

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[1] While CCS has potential application in a variety of carbon-emitting industries, we confine our discussion here to CCS systems linked to coal-fired power generation, the largest source of CO_2 that CCS might address and the one in the US currently attracting most policy debate and public investment.

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implicitly by Hekkert and colleagues (2007), but that we see as central to a number of functional areas (e.g., knowledge development, guidance, and legitimacy). Another important point is that while the TIS model provides a useful way to explore innovation dynamics, as with many other social science theorizations of innovation and economic development, issues of sustainability fall outside the model's conceptual framework. Thus, while Alphen and colleagues (2009) use the TIS framework normatively to advance ‘‘policy instruments that would foster the deployment of CCS’’ in Norway (p. 43), they offer little evidence of having analyzed the environmental or social sustainability of CCS. In this study, we do not take a position on either CCS or EGS *per se*, but instead contrast important environmental risks and benefits of the two systems that we believe could contribute to a fuller policy assessment.

Of course, the choice ‘‘between’’ CCS and EGS that the case study hints at is rather artificial—we know of no policy deliberation explicitly considering resource allocations between these two technologies. In the broader picture, however, these technologies do compete with each other and with other low carbon energy system options for finite public and private RD&D resources. While public investment in low carbon energy options is growing, the US has historically invested very little in energy sector RD&D relative to other industries and given the major problems associated with conventional energy systems (Nemet and Kammen, 2007). With limited resources, difficult decisions are being made about how much to invest in various potential options, especially when there are fundamental tensions between certain options, notably those like coal CCS and nuclear power that reinforce the existing ‘‘hub and spoke’’ grid architecture and governance structures, and others, potentially including EGS, that might encourage a more distributed grid and potentially new governance institutions (Lovins and Sheikh, 2008). While important energy policy research has attempted to compare technical, economic, and environmental potential of different energy options (NCEP, 2004; Pacala and Socolow, 2004; UNDP, 2004), emerging technologies by their very nature present large unknowns. Policy analysts, investors, and others must necessarily base their thinking on incomplete and often somewhat self-interested research by scientists in corporate, academic, and government research centers. For this reason, we consider the role of science as both a source of knowledge creation and innovation, and as an actor group whose vested interests and commitments can advantage certain technologies over others in ways that may or may not be consistent with optimal policy development.

3. Technological status

In assessing the current state of any technology, three discrete but clearly intertwined phases of technological innovation, each embedded within a larger socio-technical system, are useful to consider: (1) basic research and development (R&D) where technological details of new ideas are explored and advanced, (2) demonstration where new technologies are piloted and tested, and (3) deployment where new technologies are adopted at scale, implemented, and commercialized (Sagar and van der Zwaan, 2006). Interactions and feedback among these three phases of technological innovation are frequent, and both social and technical learning occur during each phase. Innovative activities associated with both CCS and EGS are currently focused primarily in the R&D phase, a need for large-scale demonstration is widely acknowledged for both technologies, and wide variation in perceptions of a likely timeframe for deployment or commercialization for both technologies is apparent.

3.1. CCS: current state of the technology

CCS is not a single technology but rather a set of technological components for capturing, transporting and storing CO_2 which is then integrated with a source of CO_2, the most important of which for climate change mitigation are coal-fired power plants. A fully functional CCS system does not yet exist, but most CCS components have been used in industrial manufacturing processes or oil and gas development, and several different full CCS system configurations can be envisioned.

CCS begins with carbon ‘‘capture’’ using post-combustion, pre-combustion, or oxyfuel technologies to separate and compress CO_2 for transportation. CO_2 capture is energy intensive and increases coal requirements, and hence pre-storage CO_2 levels, by 14–40% (IPCC, 2005a, b). The type and design of the coal plant influences the technological options for capture; post-combustion capture for conventional coal combustion plants separates the CO_2 from the emissions in the smoke stack, while pre-combustion capture for integrated gasification combined cycle (IGCC) coal power plants captures the CO_2 from the gasified coal before the fuel is burned. Capture is the most expensive component of CCS development and operation. Transportation of CO_2 is technically straight-forward, but the high volumes of CO_2 gas that would need to be transported were CCS to become fully commercialized could require a pipeline system of similar scale to the current system of natural gas pipelines (IPCC, 2005a, b; Bielicki, 2008). Infrastructure development of this potential magnitude often faces significant hurdles with respect to cost, siting, and public controversy.

Carbon storage involves pumping CO_2 into deep geological formations, primarily in sedimentary basins, that can contain the CO_2 gas with an impermeable rock layer. CO_2 has been used in enhanced oil recovery (EOR) for some time and thus the oil industry has experience injecting CO_2 underground, so EOR provides an early opportunity for gaining experience with CO_2 storage in existing economically motivated activities. Experience gained by EOR is limited, however, because of the limited scale and context of EOR sites; EOR occurs in geological strata unlike the saline formations that constitute the overwhelming majority of potential geologic CO_2 storage capacity (MIT, 2007). Uncertainties regarding leakage, groundwater contamination, and acidification under varying geological conditions remain; to reduce those uncertainties experience and demonstration with extensive monitoring and verification in a wide variety of geologic conditions are deemed necessary (IPCC, 2005a, b). Geologic storage of CO_2 at small scale has been occurring in several locations throughout the world, most notably at Sleipner in the North Sea where 1 million ton of CO_2 per year has been injected underground since 1995 and where a long-term storage monitoring and verification program has been developed.

Top research priorities for CCS include reducing the energy intensity and cost of carbon capture, demonstrating underground CO_2 storage in geologically diverse formations, and building integrated, scaled-up CCS systems that allow for ‘‘learning-by-doing’’ in all phases of CO_2 capture, transport, and storage (IPCC, 2005a, b; Stephens and Zwaan, 2005; MIT, 2007; IEA, 2008). The centerpiece of the US effort to create a commercial-scale project to demonstrate a fully integrated, complete coal-CCS system has been the FutureGen project, a partnership between the Department of Energy (DOE) and an alliance of private sector energy companies. Initiated in 2002 as the flagship program of the Bush Administration's clean coal technology and climate change mitigation strategy, FutureGen was to be the first large scale, near-zero-emission, state of the art coal-fired power plant, simultaneously demonstrating CCS, hydrogen production, coal gasification, and other advanced coal technologies. Just after site

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selection was completed, however, the Bush Administration, citing cost escalation, "restructured" the FutureGen program, dramatically reducing its financial commitment, and committing to support multiple smaller demonstration projects rather than the one large-scale project. The Obama Administration has demonstrated a commitment to revitalizing FutureGen, and in the summer of 2009 the industry consortium, the FutureGen Alliance, purchased the site in Illinois so this project is advancing.

The IPCC (2005a, b) projects by 2050 "20–40% of global fossil fuel CO_2 emissions [and 30–60% of power plant emissions] could be technically suitable for capture." While research in the past decade has increased optimism about CCS's potential, the slow pace and high cost of demonstration and deployment and an emerging opposition movement suggests that any projections for large-scale development remain highly uncertain.

3.2. *EGS: current state of the technology*

Enhanced geothermal systems, like CCS, are today an immature set of technologies with significant engineering and economic uncertainties. Also like CCS, EGS is not an entirely new technology, but rather an extension of conventional geothermal systems that for decades have provided small-scale power, 0.35% of net US generation in 2007. Most of this geothermal power is located in California where high-grade hydrothermal reservoirs exist within highly permeable, saturated rock formations that recharge quickly and are easily reachable (EIA, 2009a, b). In conventional geothermal systems, hot water from geothermal reservoirs is passed through a heat exchanger to create steam in a low-boiling-point fluid that is then used to drive a standard steam turbine generator. EGS is intended to expand dramatically the limited geographic range and power production capacity of conventional geothermal by taking advantage of the hot, but usually dry and non-porous, rock layers that lie within 10 km of the Earth's surface almost everywhere (MIT, 2006). This EGS or "hot, dry rock" (HDR) technique involves drilling wells and introducing water first to fracture the targeted rock layer, and then to circulate and collect heat through production wells that can drive turbines located on the surface.

The EGS resource base is huge, estimated to total 13 million exajoules (EJ). Considering current economic and technological constraints, 200,000 EJ of this resource is estimated to be extractable, which is about 2000 times the current annual US energy consumption (MIT, 2006). EGS is also attractive because, unlike other renewables, the resource is constantly available and thus can be used to generate baseload power with no need for storage and with virtually no emissions. The systems are also expected to offer high flexibility in siting, on small land areas, with comparatively little negative aesthetic impacts or public controversy. By 2050, EGS could provide 100+ GWe or 10% of current generating capacity (MIT, 2006). A critical question is whether development can be accelerated and expanded through an aggressive RD&D effort.

EGS was first aggressively investigated in the 1970s, then largely absent from energy planning exercises until two major recent studies, one by scientists and engineers at MIT (2006) and another by the US Department of Energy (DOE, 2008) that critically evaluated findings of the MIT study. The MIT study found that several geological challenges surrounding EGS in 1970 s – flow short-circuiting, high injection pressure requirements, water losses, geochemical impacts, and induced seismicity – are now manageable or fully resolved (MIT, 2006). The study concluded that "Most of the key technical requirements to make EGS work economically over a wide area of the country are in effect, with remaining goals easily within reach" and that the essential questions about EGS therefore revolve around geological sciences and understanding the nature of deep rock fracturing and rock-fluid interactions (MIT, 2006). The DOE study confirmed most of the core MIT findings, but reached a higher estimate of the research and investment needed to bring EGS to commercial competitiveness.

The primary remaining technical challenges for EGS relate to how best to fracture deep rock to create sufficient connectivity within injection wells and production wells in such a way as to generate adequate power without cooling the reservoir and reducing its lifetime and increasing the time for investment cost recovery. Improvements are particularly needed in the areas of lower cost drilling techniques, high-temperature electronics, deep fracture and flow monitoring and detection systems, and computer modeling to optimize heat-extraction strategies and increased power plant energy conversion efficiencies (Tester et al., 2005; MIT, 2006). Commercial viability of EGS depends upon the successful demonstration in early projects that large commercial-scale EGS reservoirs can be developed, sustained, and replicated under varying geological conditions (MIT, 2006; DOE, 2008); these areas of R&D priority are reflected in the most recent DOE's EGS grants.

Like CCS, innovation of EGS has relied upon techniques and insights from subsurface oil and gas exploration. Abandoned or depleted oil and gas fields may provide low-cost early opportunities for early EGS development due to reduced requirements for subsurface investigation and drilling (McKenna et al., 2005). In addition, much of the R&D focused on conventional geothermal systems complements and informs EGS innovation. For example, one early pathway to EGS development is occurring on the fringes of existing hydrothermal reservoirs, where the costs of EGS wells, rock fracturing, flow monitoring and power production are comparatively inexpensive. For example, with support from DOE, Ormat Technologies is using EGS to produce resources from underperforming wells on the fringe of the existing Brady hydrothermal field in Nevada and will be the first US commercial application of EGS. is doing such work in Nevada with support from the DoE. A growing number of EGS projects in the US, France, Germany and elsewhere are currently operating or in development, serving research needs and in some cases producing commercially competitive power. The world's largest EGS project in Australia's Cooper Basin recently completed a successful 6-year "proof of concept" phase, during which commercial-scale reservoirs and wells were successfully fractured and drilled, achieving desired production flows. The project is now shifting to Stage 2 which includes replication totaling 9 wells, plant design and construction and transmission line construction. The final Stage 3 will involve commercial-scale demonstration of ten 50-MW modules.

Engineers in several countries throughout the world have been working on advancing EGS technology for a few decades, but the technology has received limited attention and minimal financial support from either the public or private sector, with the exception of Australia's significant market investments. The high cost of drilling, which is estimated to account for a third to a half of projected costs of EGS, is a major challenge to the technology, and this drilling is more difficult than drilling associated with oil and gas exploration due to both corrosion and the large diameter of pipes needed for sufficient flow rates (Tester et al., 2005).

4. Environmental benefits and risks

Growing societal concern about climate change is changing the energy technology landscape creating a new era of energy regime instability with new opportunities for innovation. Recent

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advancement of both CCS and EGS is part of a response to this societal concern, as the potential of both technologies to generate electricity without carbon emissions is a major environmental benefit. With respect to climate change, CCS holds out significant potential for reducing carbon emissions (IPCC, 2005a, b), and to the extent that EGS displaces fossil fuel based electricity generation, it also has great potential for reducing carbon emissions.

Climate change, however, is not the only environmental pressure associated with electricity system change, and broader consideration of a range of environmental implications of energy technology options reveals significant differences between CCS and EGS. While EGS provides the potential of sustainable, renewable electricity generation capacity with minimal environmental risks, CCS reduces carbon emissions associated with coal, but does not reduce and could even exacerbate other environmental impacts of coal use including mining, water pollution, and other non-carbon air pollution.

With respect to CCS, four categories of environmental risks can be considered. Firstly, local CO_2 risks relate to the accidental release of CO_2 and include enhanced seismicity, ecological disruption, groundwater contamination, and human health impacts associated with the possibility of high concentrations of CO_2 accumulating in confined areas rather than dissipating quickly into the atmosphere (Wilson, 2004). Most studies suggest these risks are not likely to be large relative to impacts of other power generation options deployed on a large scale, although further research is needed (IPCC, 2005a, b; MIT, 2007). Secondly, global climate risks relate to the possibility of large-scale leakage of CO_2 that would negate the climate benefits of carbon storage. This set of risks could be minimized through careful site selection, through experience gained from storing CO_2 in a heterogeneous set of different geologic formations, and with the application of monitoring and verification technology (Heinrich et al., 2003). A third category of environmental risk is coal life-cycle risks including impacts associated not with CCS per se, but with the rest of the system, including coal mining, beneficiation, transportation, and combustion gases that contribute to acid rain, smog, and health hazards (Clean Air Task Force, 2001; Schneider and Padian, 2004). Coal life-cycle risks are likely to increase along with the increased requirement for coal combustion in CCS systems. A fourth category of environmental risk is the indirect risk that investment in CCS will divert resources, especially public RD&D funding and incentives, from development of energy technologies that are potentially cleaner, more renewable and even less carbon intensive than coal with CCS.

EGS, by contrast, is potentially among the most environmentally benign approaches to generating electricity. EGS facilities are relatively small and unobtrusive, and compared to other renewable energy technologies, including wind and biofuels, land use requirements and visual impacts are minimal. Unlike most hydrothermal systems, EGS operates in a closed-loop binary mode that eliminates thermal contamination of adjacent surface waters and, most critically, eliminates virtually all carbon dioxide emissions. Recent estimates suggest that up to 100 GW_es of new EGS could be economically competitive by 2050, which is about equal to the currently installed US nuclear capacity that provides one-fifth of US electricity supply (MIT, 2006). Carbon reductions resulting from this level of development would be substantial, though below those estimated for CCS. A rigorous comparison of technical and economic assumptions has not been attempted, however, and in any event, such estimations are highly uncertain at this stage of technological development.

Like all energy technologies, EGS does have environmental risks. As with CCS, induced seismicity is possible. Seismic tremors potentially linked to pilot projects in Germany and Switzerland have raised significant public and governmental concern (Kulish and Glanz, 2009). While it has been suggested that EGS-related seismicity is predictable and potentially controllable with developed injection techniques (Majer and Patterson, 2007), further research is needed to understand and minimize seismic risks and potential groundwater impacts that could compromise project permits, especially near major population centers.

While a number of conventional geothermal systems are in operation in environmentally sensitive locations with little apparent public concern or opposition, some proposals for new EGS systems in sensitive landscapes have proven controversial (Electricity Forum, 2008). The level of environmental impact and controversy associated with transmission line development, the cost and complication of which are a major bottleneck to development of utility-scale wind and solar power, will presumably depend on the ultimate flexibility with which EGS can be sited. EGS will certainly face resistance, though its relatively low environmental profile and lack of an established opposition compared with coal with CCS suggests developmental risks due to real and perceived environmental harms maybe lower.

With both EGS and CCS, perceptions of risks and benefits vary considerably among different stakeholders, technology experts and the public. Individuals and organizations with different priorities, different disciplinary backgrounds, different sets of information, as well as different contexts for interpreting information, result in great diversity in risk perceptions (Palmgren et al., 2004; de Best-Waldhober, 2006; Shackley et al., 2007; Stephens et al., 2008). Risk perceptions of all stakeholders have potential to influence technological advancement, and public opposition to several proposed CCS projects has already proven to be an obstacle to pilot project development.

5. Competing discourses

Emerging technologies like CCS and EGS, and perceptions of their potential, are constructed not just through technical and economic processes but also through discourse, i.e. through compelling narratives about what a technology is, what a technology might become and why it is needed and preferable to competing technologies (Lounsbury and Glynn, 2001). The influence of discourse is particularly important in the innovation phases prior to commercialization when innovation activities are focused on RD&D, and when feasibility and costs of alternative systems cannot yet be tested by market dynamics. During these early phases, persuasive discourses are critical as entrepreneurs seek to accumulate resources and stimulate growth of an actor-network to enable the continued advancement of the innovation (Hansson and Bryngelsson, 2009). EGS has entered the discursive landscape with classic, small, niche technology attributes, while CCS exhibits both the attributes of a niche technology but also characteristics of a technological component that is part of the entrenched coal energy regime.

5.1. *CCS discourse: reconciling climate change and coal*

> Carbon capture and storage technologies are essential to allow the continued use of coal to generate electricity while we substantially reduce emissions of greenhouse gases to combat global warming. While the technologies are complex, the overall value of introducing them into the U.S. and global economies is undeniable (CAP, 2009).

As the foregoing quote typical of CCS proponents suggests, the discourse surrounding CCS relies heavily on the notion of the inevitability of continued use of coal; this reasoning assumes that

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coal is so cheap, abundant and embedded in existing electric power systems that its continued growing use globally is a virtual certainty. With this set of assumptions, CCS is viewed as essential to reconcile the inevitability of continued coal use with the imperative for climate change mitigation. This narrative is reinforced and gains credibility and influence from numerous projections of increased energy demand and coal use in the US and internationally (although the most recent EIA projections for US coal-fired power plants by 2030 are significantly reduced from previous projections (EIA, 2009a, b)). To proponents, the estimated 15–20 year timeframe needed to test and develop the first set of commercial-scale CCS systems is not a deterrent but rather an indication of the urgency of accelerating current development efforts.

Within the last few years, CCS has also become a critical part of a larger ‘‘clean coal’’ campaign intended to counter constructions and perceptions of coal as ‘‘dirty’’ and ‘‘old’’. The ‘‘clean coal’’ discourse dates back at least to the start of the US government's public–private Clean-Coal Program in 1986 designed to address challenges arising from ‘‘traditional pollutants’’ (e.g., NO_x, SO_x, CO) (Bañales-López and Norberg-Bohm, 2002). Throughout the 1990s, CO_2 was not widely recognized as a pollutant, and most of the fossil fuel industries were actively advocating against the notion that climate change was a significant environmental threat (Gelbspan, 2004). As societal concern about climate change mounted and denying the validity of the associated risks became unacceptable, CCS quickly become a critical part of the coal industry's clean coal discourse, which beyond ‘‘clean’’ emphasizes themes such as ‘‘advanced technology’’ ‘‘abundant,’’ ‘‘affordable,’’ ‘‘secure and reliable’’ and ‘‘near-zero emissions’’ (Americaspower, 2009). Recent analysis estimates that the coal industry is currently spending over $60 million per year on discourse construction and actor-network development through clean coal advertising and lobbying—this amount is more than the industry's proposed annual contribution to FutureGen of $400 million over 10 years (Conniff, 2008).

> Carbon capture and storage is a scam… Governments and businesses need to reduce their emissions—not search for excuses to keep burning coal. (Greenpeace, 2009)

In response to the coal industry's ‘‘clean coal’’ campaign and advertising efforts to portray CCS technology in a positive light, some environmental activists claim that there is no such thing as ‘‘clean coal’’ and have criticized CCS technology as a pipe-dream ‘‘technical fix’’. Greenpeace International (2008) calls CCS a ‘‘dangerous distraction’’ and Al Gore's Repower America in 2009 aired a highly visible television campaign lampooning clean coal (Alliance for Climate Protection, 2009). Other environmental and climate change groups support CCS-equipped coal-fired generation. While mainstream environmental advocacy groups that play an important role in shaping public perceptions about emerging energy technologies appear to be divided and/or ambivalent about CCS (Stephens and Verma, 2006), a consensus strategy maybe emerging among environmental advocates that turns the clean coal campaign against the industry by insisting that *only* coal plants with CCS should be permitted in the United States, i.e. ‘‘no new coal without CCS.’’ Given that CCS is not yet a commercially viable technology, this stipulation essentially translates in most situations to ‘‘no new coal’’. In response, some developers are instead proposing that ‘‘CCS-ready’’ plants be built, i.e. new coal-fired power plants that are designed with anticipation of the future addition of CCS. As a discursive device, the notion of a ‘‘CCS-ready’’ power plant attempts to reduce opposition to new plant development, but the actual technical definition or implication of this concept is unclear (Stephens, 2005). Despite increasing political attention to the potential of ‘‘clean coal’’ and CCS, the general public remains largely uncertain and ill-informed about the status, challenges, and opportunities associated with CCS technology (de Best-Waldhober, 2006; Shackley et al., 2007; Bradbury et al., 2008). But it is clear that a diversity of perceptions and narratives surrounding CCS are emerging among energy technology stakeholders, environmental advocates, and the general public.[2]

5.2. EGS discourse

The discourse surrounding EGS technology is much more limited than that of CCS, as the technology has received minimal political or public attention. In addition, EGS is often conflated with conventional geothermal technology, and the discourse on both is frequently clustered with that surrounding a whole range of renewable energy technologies. EGS did receive some public attention in 2008, when the Director of Climate and Energy Initiatives for Google.org, Google's philanthropic arm, argued that EGS ‘‘could be the ‘killer app’ of the energy world. It has the potential to deliver vast quantities of power 24/7 and be captured nearly anywhere on the planet.’’ This description was made during an announcement that Google was investing over $10 million in two EGS companies and related research. EGS is a centerpiece in Google's RE < C (‘‘Renewable Energy Cheaper than Coal’’) initiative ‘‘to develop electricity from renewable energy sources that is cheaper than electricity produced from coal with a goal of producing one gigawatt of renewable energy capacity – enough to power a city the size of San Francisco – in years, not decades’’ (Google, 2007).

This description of EGS as a ‘‘killer app’’ (i.e., system transforming application) represents a discourse focused on the potential of various EGS attributes including a large renewable energy resource with distributable, baseload potential and minimal environmental impact. Before Google's 2008 announcement that brought significant attention to this previously little-recognized technology, the release in 2006 of the MIT study reviewing the potential of EGS was influential in shaping EGS discourse. The MIT study incorporated familiar energy technology themes associated with urgency as well as a need for sharply increased levels of federal funding. Despite these influences, EGS is not well recognized or understood, and not given much attention in discussion surrounding climate change mitigation and the potential of renewable energy technology. An informal survey of 14 of the nation's largest environmental groups' websites suggests that EGS is not fully understood or considered competitive and is often only vaguely supported. Only 5 groups offered information about geothermal energy specifically, and each treated EGS in a small sub-section toward the end of their geothermal page and characterized EGS as a developing but quite uncertain technology. EGS is buoyed, however, by an ascendant renewable energy discourse emphasizing the environmental and economic benefits of ‘‘clean’’ or ‘‘green’’ energy (Jiusto and McCauley, 2009), the growing influence of which can be seen in the embrace of renewable energy innovation in states like California and Massachusetts, under both Republican and Democratic party leadership, and in

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[2] While in the US CCS controversy and discursive struggle is closely tied to coal, our interviews suggest that in the UK and elsewhere in Europe, CCS controversy is instead more likely to focus on perceived direct threats of carbon storage.

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Table 1
Frequency of CCS/EGS appearing in various media, informational outlets, and legal proceedings.

Publication Source	CCS	EGS
Google Hits	447,000	62,300
GoogleScholar Hits	4230	447
Congressional Bills	5	0
Energy Citations Index	111	87
InfoTrac Onefile: Magazine, Academic, News	1208	40
LexisNexis Academic	> 1000 in past year	51
SEC Filings (Securities & Exchange Commission)	262 in last 2 years	4 in last 2 years

its centrality in the Obama administration's economic recovery plan and legislative agenda.

5.3. Discourse comparison

Discourse is a critically influential element of socio-technical change and technological innovation, but little analysis exists to inform an assessment of current discourse about CCS and EGS and the associated likelihood that current narrative can engender the sustained financial, intellectual, and political support needed for either technology to reach maturity. Additionally the power of discourse is not entirely separable from the influence of those creating and enunciating it. While the "clean coal" narrative has entered the public domain far more extensively than has an EGS discourse, in doing so it has attracted both powerful supporters and powerful detractors. As will be detailed below, indications are that the discourse of inevitability of coal use and hence imperative for CCS has won many adherents and a concomitant strengthening of the CCS actor-network with increasing access to public resources that far exceeds those flowing to EGS. The evidence also suggests, however, that the long dormant, minimal EGS discourse has just recently gained prominence that has begun to attract significant attention and resources. For both CCS and EGS, sustaining interest for many years will be critical to the advancement of the technologies, and new rounds of discursive and political contestation will arise as more plants are proposed and subjected to intense public scrutiny.

As a broad indicator of the depth and productivity of the actor networks connected with each technology, Table 1 presents a simple quantitative comparison of the frequency with which the most basic element of the CCS and EGS discourses – the terms "carbon capture and storage" and "enhanced geothermal" – appear in various popular, scholarly, financial, and legislative forums. These data show CCS is much more widely present in the public and scholarly domain than EGS, paralleling differences in the actor-network of each technology discussed in the next section.

6. Strength and composition of actor networks

All technologies develop a network of actors and stakeholders who are involved, engaged or somehow associated and influential in the technological innovation process. This section explores the strength and composition of the evolving actor networks for both CCS and EGS, reviewing the nature of the human actor groups through which each technology is taking shape.

6.1. The CCS actor network

CCS benefits from an actor-network that is strong, diverse, growing, and increasing in its capacity to influence policy and RD&D financial flows at state and national levels. CCS has strong support from the traditional coal constituency that includes coal mining companies, the power generation industry, coal-state politicians, and labor unions, as well as support from representatives of other fossil fuel industries, utilities, government, academia, environmental groups, and others. Oil and gas companies bring an interest in geologic carbon storage, because of their internal capacity and experience relevant to adapting technologies and processes for underground reservoir management and CO_2 injection. The American Coalition for Clean Coal Electricity lobby that funds the clean coal campaign includes among its nearly 50 corporate members "the world's biggest mining company (BHP Billiton), the biggest US coal mining company (Peabody Energy), the biggest publicly owned US electric utility (Duke Energy), and the biggest US railroad (Union Pacific)" (Conniff, 2008).

A segment of the scientific community has already invested in CCS and thus self-perpetuates by influencing government funding priorities and the national discourse on climate change through research, policy engagement, and professional organizations. The CCS scientific network has grown to include annual conferences in the US and internationally (e.g., the DoE/NETL Annual Carbon Capture and Sequestration meeting recently drew ~700 attendees, and the 9th International Conference on Greenhouse Gas Control Technology had almost 1500 attendees in 2008), journals (e.g., the Carbon Capture Journal and the International Journal of Greenhouse Gas Control), supportive scientific assessments by influential organizations (e.g., MIT's (2007) interdisciplinary "The Future of Coal" report and the IPCC (2005a, b) report), several academic/industry partnerships (e.g., the Carbon Mitigation Initiative involving BP, Ford, Princeton University and Harvard University), and President Obama's science advisor, John Holdren, a long-time advocate for increased federal energy R&D funding including for CCS (Holdren, 2006). The US government supports advanced coal technologies through the DoE Carbon Sequestration Program (DoE, 2007) and other programs, and by forging international collaborations such as the Carbon Sequestration Leadership Forum which includes 22 member countries (Coninck et al., in press).

Other key supporters of CCS include Presidents George W. Bush and Barack Obama, both of whom have strongly embraced clean coal discourse and the technological advancement of advanced coal technology, including CCS. Several prominent environmental organizations such as the Natural Resources Defense Council support CCS (Hawkins, 2005) in part because these groups have been aware of the potential for CCS technology to enable individuals and organizations previously opposed to climate change policy to come to the table and consider a future with carbon constraints. It has been suggested that CCS offers fossil fuel industries a way to move beyond denialism (Gelbspan, 2004), and to engage more productively with the climate change challenge (Keith and Parson, 2000). Among many influential CCS supporters, the Pew Center on Global Climate Change has strong connections to policymakers, businesses, researchers and others.

6.2. The EGS actor network

The EGS actor-network is much thinner, newer, and less powerful than that of CCS, yet it benefits from association with the modestly larger, but internally well-connected and active

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conventional geothermal network. EGS stakeholders have generally characterized EGS networks as "quite good" in communication but lacking in formal organization and coordination. Three of the most active EGS companies in the US are Ormat Technologies, GeoThermex, and AltaRock Energy, each much smaller than the largest coal-affiliated companies. Internationally, at least seven Australian companies were active in EGS RD&D as of 2006 (MIT, 2006), as were geologists in Japan, France, and Iceland. Chevron, however, accounts for 50% of all privately generated conventional geothermal power worldwide and making additional advances in EGS, and other oil and gas companies like Halliburton and Schlumberger are acquiring established geothermal and geophysical companies. Chevron's involvement demonstrates the potential for companies with backgrounds in deep petroleum drilling and extraction to potentially bring important new capacities to the EGS actor-network, raising the profile and legitimacy of EGS with the DoE and other scientific research program managers. While EGS has competed for federal funding with other renewable with minimal success, a recent spark of interest in EGS, initiated in part by the recent announcement of private investment by Google may allow EGS to forge a more powerful network through linkages with "old economy" fossil fuel interests and high tech "new economy" actors.

Recent strengthening of the EGS actor network is apparent. In 2008, Stephen Chu, then Director of Lawrence Berkeley National Laboratory and now US Secretary of Energy, appeared in an online video interview with Dan Reicher of Google.org and Don O'Shei of AltaRock Energy and articulated key aspects of EGS discourse and represents a broadening of the EGS actor-network:

> Geothermal in the United States is only 0.3 percent of our electrical energy output, and it could easily go to ten, maybe even twenty percent… I would rather have enhanced geothermal in my backyard than a coal plant. Without question, most Americans don't realize that radioactivity released from a coal plant [is more than that from a nuclear power plant] …and, oh yeah, sulphur dioxide, nitrogen oxides, mercury, particulate matter that gives you lung cancer, asthma, and everything else" are other dangers of coal power (New York Times, 2008).

In Europe, EGS research is being coordinated through the Enhanced Geothermal Innovative Network for Europe (ENGINE), composed of 35 partners representing 19 countries and 6 private companies seeking to accelerate exploitation of geothermal resources and maximize its political and social benefits (Ledru et al., 2006). In 2008, the United States, Australia, and Iceland launched the International Partnership for Geothermal Technology (IPGT), a partnership akin to ENGINE. These international efforts are intended to advance research and development and accelerate the hitherto slow rate of technology transfer from successful international EGS demonstrations (MIT, 2006). The geothermal industry's two longer-standing organizations, the Geothermal Energy Association representing companies and the more educational Geothermal Resources Council, appear to focus mainly on conventional geothermal issues and to lack the institutional clout of CCS organizations. However they frequently sponsor geothermal conferences, meetings and workshops, of which approximately 11 are scheduled in the US through January, 2010. The scientific community engaged in EGS has also been quite sparse, but new DoE funding is spurring collaboration among scientists and engineers in companies, academia, and national laboratories. According to EGS stakeholders, the role of participation of academic institutions is essential to grow the EGS workforce, especially if the US is to achieve significant electricity generating potential from EGS.

7. Investment and financial support: public and private

A primary goal of discourse and actor network formation is to attract attention and financing to support innovation. This is particularly critical during the R&D, demonstration, and deployment phases of technological innovation when costs maybe high but near-term profit potential is limited. Government, once limited mostly to the R&D phase, is now a critical funder of all phases of energy technology innovation, especially as the electrical power industry has historically invested very little (~1% of revenues) into R&D (Nemet and Kammen, 2007). More recently, venture capitalists have also become influential sources of financial support as they have entered the "clean tech" market and are willing to invest in some emerging energy technologies (Stack et al., 2007).

Estimated cost projections are available for considering the development of both CCS and EGS. There is a high degree of uncertainty in all of these cost projections due to variation in project characteristics and in potential scale, a wide range in variability in input costs, and unpredictable changes in costs over time. This section characterizes current projected costs of developing CCS and EGS and reviews levels of current public and private funding flowing to each technology.

7.1. CCS development costs and investments

For CCS, estimates of carbon abatement costs have been developed for different phases including initial demonstration plants (€60–90 per tonne of CO_2 abated), early commercial CCS plants (€35–50 per tonne of CO_2 abated), and for development of CCS beyond early commercial plants (€30–45 per tonne of CO_2 abated) (McKinsey, 2008). The recent MIT study on the future of coal estimated that a CO_2 emission price of ~$30/tonne would make CCS cost competitive with coal combustion without CCS (MIT, 2007).

In the CCS discourse, there have been increasingly frequent calls to develop 10–30 CCS demonstration plants (e.g., Pew Center on Global Climate Change, 2009); extrapolating from cost projections for the FutureGen project it is possible that funding for this scale of demonstration could require a largely public investment risk of some $15–60 billion. The Department of Energy has just recently announced that $2.4 billion of the American Recovery and Reinvestment Act of 2009 will be used to expand and accelerate the commercial deployment of CCS.

Despite electricity retail revenues of $344 billion in 2007 (EIA, 2009a, b), the electricity sector as a whole has historically invested little in R&D, and it is uncertain how much private investors will contribute toward CCS development. Prior to the federal government pulling out, industry partners had indicated a willingness to invest approximately $400 million over 10 years in the flagship FutureGen project. Comprehensive data on private clean coal expenditures are not available.

7.2. EGS development costs and investments

While the costs of CCS have been articulated in units related to CO_2 emissions, EGS cost estimates have been more general; the total cost of bringing EGS to commercial viability has been estimated at between $300 and $400 million (MIT, 2006) and $800 million–$1 billion (DOE, 2008) spread over 15 years. When compared with CCS cost projections an order of magnitude difference is apparent. The $1 billion total cost estimate for EGS is about half the most recent estimated cost of $1.8 billion for the single FutureGen plant, and only about twice the $520 million DoE spent in 2008 on coal technology RD&D, including support for

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carbon sequestration, FutureGen, and the Clean Coal Power Initiative (Stephens, forthcoming).

Federal funding for geothermal R&D has typically been \$20–\$30 million annually since 1995, with EGS only a small fraction of the total (e.g., \$5.3 million in 2004 and nothing in 2007) (Gallagher et al., 2007). In 2008, however, the DOE announced awards of up to \$43.1 million over four years to prove the technical feasibility of EGS by 2015. With recipient cost-share, the total public–private EGS investments will total \$78 million and support 21 projects, generally demonstration projects that will extend into the dry perimeter of existing hydrothermal fields rather than create new, full-scale fields. DOE is also funding a \$5–7 million project to create a national database of geothermal research designed to reduce investor uncertainty and increase private RD&D spending (Deloitte, 2008). Most significantly, the federal stimulus program adopted in February 2009 designated \$400 million for conventional and enhanced geothermal, with \$20 million designated for EGS grants in FY2009 alone. To provide some historical context, between 1980 and 2004, over \$180 million was invested in EGS in the US, but EGS advocates point out this amount is less than half the amount spent each year on fission, fusion, or solar technologies (Tester et al., 2005).

According to some EGS key informants, the DoE's recent increase in EGS funding may not be as influential as it may at first appear. There is some concern that the DoE's strategy of funding several small projects incrementally may result in insufficient funds to sustain large-scale, long-term demonstration plants needed to identify potential problems encountered over the 20-year lifespan of a typical commercial EGS power plant. Some believe larger funding amounts directed towards fewer projects would accelerate EGS learning. This perspective reflects the approach for advancement of CCS with the initial FutureGen project, i.e. funding a large-scale, highly visible project rather than several smaller-scale, shorter-term incremental projects. Government support for EGS is also often subsumed within general allocations for conventional geothermal technology; there appears to be a lack of incentive to invest specifically in EGS.

Some EGS actors actually perceive a decreasing overall investment trend in EGS particularly in the private sector. This point has been substantiated by highlighting a growing backlash among utilities to the increased federal investment in EGS, and the fact that some entrepreneurs in the US and Canada are backing away from EGS projects and instead moving toward proven conventional geothermal projects that have a higher confidence level for near-term investment returns. The challenge of investing in risky unproven technology is an age-old problem that is difficult to overcome, and is the reason that government support for nascent technologies is so critical. Tensions between actors involved in conventional geothermal and those focused on EGS reflect another challenge niche technologies experience that of competing with other fledging technologies for resources that are already significantly less than those of the entrenched regime.

Total private sector EGS spending is difficult to quantify, but the number of actual facilities being developed with private sector involvement worldwide suggests a ramp-up strategy for EGS is less steep and less reliant on public funding, though public funding is certainly critical to underwriting the developmental risks of both systems. Google.org, in announcing its \$10.25 million EGS investment, called for federal funding for EGS to escalate quickly to \$100 million annually.

7.3. Investment comparison

Projections of production costs per kilowatt-hour of either coal CCS or EGS once fully developed are highly speculative. Both systems' costs are likely to vary significantly geographically due to differences in geological formations. But once sited, EGS maybe insulated from operating cost variability that plagues coal and other fossil fuels due to volatility in fuel and transportation costs, increasingly stringent environmental regulation, and capital risk due to the very large size of coal CCS plants.

A comparison of the level of investment given to these two emerging technologies demonstrates a sharply different financial landscape that reflects a very different societal appreciation for the potential of these two technologies. The different magnitude of public support for these two sets of technologies is acutely demonstrated through consideration of the level of support allocated for each within the American Recovery and Reinvestment Act of 2009, CCS is to receive \$2.4 billion, while \$400 million has been allocated for all of geothermal, including both conventional geothermal and EGS.

8. Conclusions

This analysis seeks to contribute to both energy policy and the emerging field of sustainability science by demonstrating a socio-technical systems approach to analyzing options for managing sustainability challenges facing society. As society moves through a rapidly changing energy context, the complexity of the interconnected socio-political factors influencing energy technology decisions at various scales and stages of innovation become increasingly critical to consider (Stephens et al., 2008; Jiusto and McCauley, 2009). A critical part of developing a "portfolio" of clean energy and energy efficiency options is exercising selectivity in determining which portfolio options merit investment, by whom, and at what level. While much socio-technical systems analysis is retrospective in nature, this research examines innovation dynamics in two contemporary, early-stage technologies to inform theory and contribute to policy deliberations.

CCS and EGS were chosen for this study because of their contrasting status with respect to the niche:entrenched system dichotomy, and their similarities with respect to their potential to reduce electrical power sector carbon emissions through geological science and engineering. Both systems also include a set of technological components that have been applied and are in use in other industrial contexts, but neither has demonstrated that the components can be integrated and scaled-up to successfully compete with other low carbon energy options. Both are at this stage embryonic, hybrid entities (part idea, part hardware, part discourse, part people) looking to be birthed as full-fledged technologies. This birthing can only come through the mobilization of an actor-network composed of people (e.g., from industry, government, finance, labor, science, and environmental organizations), infrastructure, environment (e.g., subsurface geological formations), and discourses through which the system gains coherence, direction, and power (Law, 1992).

This approach finds that CCS represents an innovative response by the entrenched coal energy regime that for a century has dominated electrical power production in the US to reconcile itself with new societal concerns about climate change. Although CCS is effectively an "end-of-pipe" solution designed to shore up the entrenched socio-technical regime, the significant redesign in coal plant operations, the large scale of the new emissions transport system, the scale and social and technical complexity of carbon storage, and the long and uncertain innovation process expected for CCS suggests that it also has many attributes and needs of a niche technology. As CCS seeks to amass financial and intellectual resources and a protected space for long-term development, it is advantaged by the strength of the actor-network established through the coal industry's long dominance,

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and thus begins with significant political, financial, and institutional resources, and at least a decade of significant public–private and scientific CCS collaboration. Given the urgency of carbon reduction efforts and the daunting barriers any breakthrough energy technology must overcome (Gallagher et al., 2006), these advantages of regime incumbency are significant. On the other hand, the fundamental rationale behind CCS – that coal will remain a dominant energy source and hence "clean coal" innovation is essential – is increasingly being challenged discursively and in the actual patterns of US energy system developments, which show that much smaller, less capital intensive power sources are increasingly favored by investors (Lovins and Sheikh, 2008). Thus, while an impressive network of industry, government, science, and environmental organizations are calling for tens of billions of dollars to be spent on some 10–30 CCS coal plants over the next two decades, the EIA estimates that market demand alone would yield only two new coal plants in that time. Arguably, then, CCS innovation has itself become the primary driver of new coal plant development, and given that long-term financial risks are high and near-term profit potential low, it is expected that CCS will for many years remain highly dependent on public funding, directly through subsidies and indirectly through government guarantees of long-term ratepayer financing.

EGS by contrast is one of many true niche technologies being investigated in response to the search for alternatives stimulated by shifts in the energy system landscape (Sine and David, 2003). While it too grows from existing technologies (conventional geothermal) that have for decades proven competitive in small niches, and while it also builds upon several decades of small-scale development efforts, experience shows that exceptionally few technologies breakthrough to realize the kind of potential that supporters suggest EGS holds. Like other renewable resources, the resource base is huge and the fundamental questions relate to whether EGS can be cost effectively developed across a sufficiently wide range of geological conditions to make a major contribution to power generation. The development pathway proposed for EGS bears striking resemblance to that of CCS—a largely government-financed, public–private partnership to answer key geological sciences and engineering questions by building one to two dozen pilot projects under varying geological conditions. The technical uncertainties and projected costs of development appear to be less than those for CCS, however, and the full life-cycle environmental costs potentially less severe, as well, though seismic risks and water requirements remain concerns. As with CCS, upfront costs associated with drilling and power plant development introduce investment risk, though these risks are likely to be lower for EGS due to lower capital costs and shorter recovery times overall, lower operational costs, and avoidance of fuel cost risks. The actor network supporting EGS is much weaker presently, and awareness of EGS among environmental organizations and scientists appears limited. It will be interesting to see what impact actors from non-traditional energy circles, such as Google and venture capitalists, may have on the development of a successful discourse and networking of resources needed to sustain EGS development over an extended time period.

This study raises questions for future research, as well as for current energy technology decision-making. We conclude by posing a few of these questions:

- Whether, how and to what extent are considerations of environmental risks and benefits of different technology options incorporating full life-cycle assessment? While CCS holds promise of reducing coal power carbon emissions, by increasing coal consumption overall, it stands to exacerbate the many other, already severe environmental and health impacts of coal use. How should these various impacts be weighed in developing a portfolio of carbon-reducing energy options, particularly relative to an option like EGS that might offer reliable power with lower environmental and health impacts than virtually all other options, including other renewables?
- How, when and why does discourse associated with specific competing technologies evolve and influence decision-making processes? We have noted the investment that both sides of the clean coal debate are expending to influence the public CCS discourse, but little is known explicitly about how different discursive practices (e.g., messages and modes of delivery) influence each of the various actor groups that impact technological decision-making: innovators, entrepreneurs, financiers, policymakers, environmental organizations, the public, and perhaps most importantly scientists.
- Can actor-network analysis reveal and explain complex relationships and power dynamics in a way that might influence society's energy choices? If so, what form might these analyses take, particularly with regards to assessing the critical, yet never entirely disinterested role that scientists and researchers play in framing for policymakers "the realm of the possible" and prioritizing public investment options (Jasanoff and Wynne, 1998)?
- What factors contribute to decision-making about the level of social investment in competing energy technology options? The level of federal funding currently flowing to clean coal, like that flowing to nuclear power, exceeds funding devoted to all other low-carbon, renewable energy options *plus* efficiency. Given the significant technical and economic uncertainties of CCS, and the comparatively large investments required over many years to resolve them, how should priorities on portfolio options be determined?

Acknowledging the complex choices and trade-offs inherent to the continuously shifting innovation environment of energy systems and climate change mitigation technologies, this analysis highlights the value of expanded analysis and more careful consideration of the complex dynamics of societal prioritization of carbon management options.

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