DRILLING FOR LOW-CARBON ENERGY SOLUTIONS:

AN ASSESSMENT OF TWO ALTERNATIVES

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By Scott Jiusto, Jennie C. Stephens, Evan Boyd,
and Stephen McCauley

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Drilling for Low-Carbon Energy Solutions:

An Assessment of Two Alternatives

Scott Jiusto[1], Jennie C. Stephens[2], Evan Boyd[2], and Stephen McCauley[3]

[1] Interdisciplinary and Global Studies, Worcester Polytechnic Institute; 100 Institute Road; Worcester, MA 01609-2280

[2] Department of International Development, Community and Environment (IDCE), Clark University; 950 Main Street; Worcester, MA 01610-1477

[3] Graduate School of Geography, Clark University; 950 Main Street; Worcester, MA 01610-1477

Abstract: This paper employs a socio-technical systems perspective to compare two emerging energy technologies in the United States with potential to reduce greenhouse gas emissions from electrical power generation: enhanced geothermal systems (EGS) for electricity production and carbon capture and storage (CCS). CCS and EGS both involve subsurface geologic applications that, while promising, are unproven at scale and uncertain with respect to cost, feasibility and life-cycle environmental impacts. The technologies vary markedly, however, with respect to their social, technical and environmental composition and implications. CCS is an emerging technology that many argue must be developed if coal-fired electrical power production, currently the world's largest source of electricity and carbon emissions, is to be reconciled with climate change mitigation goals. The actor-network supporting coal and other fossil fuels is powerful and has garnered substantial public funding for CCS development. By contrast, EGS until recently has received little research or development support, yet its potential to contribute to a sustainability transition in electric power systems is arguably superior to CCS with respect to cost, complexity, scalability, environmental performance, investment risk and public acceptance. By comparing the socio-technical systems, including the processes and actor-network involved in these two emerging technologies in the United States context, this research highlights the importance of institutional and social influences of energy technology innovation, and, by extension, of global climate change mitigation strategies.

Keywords: socio-technical systems, sustainability transition, carbon capture and storage, geothermal power

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Introduction

> *"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).*

> *"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 the United States, coal generates half the nation's electrical power and one-third of its carbon emissions and thus is deeply enmeshed in the current controversy over how the electric power system should evolve in the face of growing climate change concern. An increasingly integral component of this controversy includes different visions and perspectives on the potential of carbon, capture and storage (CCS) technology. As the quotes above suggest, CCS is viewed by some as "essential" and of "undeniable" value and by others as a rhetorical subterfuge for defusing opposition to new coal-fired power plants and as a dangerous diversion from attention to alternative, renewable energy technologies. The debate about CCS brings into focus the high stakes of decisions regarding which technologies are included in energy portfolios of the future and it reveals the social construction of energy technology innovation decisions. Enhanced geothermal systems (EGS) for power production is an alternative renewable energy technology that, like CCS, is in an early stage of technological development, has large potential to reduce GHG emissions, is unproven at commercial scales, and relies on geological science and engineering. Despite these similarities, EGS has received minimal societal attention while support for CCS has rapidly increased.

By comparatively assessing the social and institutional environments of these two technologies within a socio-technical systems approach, this research contributes both theoretically and practically to understanding the evolving innovation environment for energy technologies. It does so by demonstrating new ways of conceptualizing innovation processes, illuminating key processes shaping emerging energy technologies, and highlighting important policy and decision-making considerations pertaining to differences in the degree of public sector support for CCS and EGS. Building upon the emerging literature on sustainability transitions, which highlights the complexities of social and institutional dynamics involved in socio-technical change (Meadowcroft, 2007, Geels, 2005, Loorbach, 2007), this research compares the actor-networks and the discursive formations that support these two emerging climate change mitigation technologies.

Research exploring the challenges of energy technology innovation often focus on economic and technical considerations (Isoard and Soria, 2001, Grubler et al., 2002, NCEP, 2004) and overlook the complex socio-political context within which energy technology decisions are made. This socio-political context includes diverse institutions and actors, regulations and laws, as well as business and economic factors, and is influenced by varying perceptions and levels of awareness about the risks, benefits and costs of emerging technologies. 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). 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 entire social formations with strong incentives to protect and promote the entrenched regime. In this view, socio-technical transition occurs when a niche technology gains enough traction to compete with the entrenched socio-technical regime, often as developments in the wider landscape also undermine the entrenched regime (Smith et al., 2005). Our analysis builds on a conceptual model developed to explore the likelihood of a sustainability transition in the US electrical power system (Jiusto and McCauley, In review). This model expands the conventional socio-technical system model by emphasizing several under-theorized domains in the transition process: the environment as an actor that influences the course of technological development through its on-going response to existing technologies; science as an institution that creates knowledge and shapes imaginations about the realm of the possible; the role of discourse in elevating competing technological ideas; and civil society as a set of actors that strategically work to strengthen or undermine different technological options. These critical domains operate as a complex actor-network that interacts with the state, capital, and existing technological formations to shape the broad "innovation environment" from which new technological options emerge. 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).

Both CCS and EGS include a set of technological components that have been applied in other industrial contexts but without demonstrated integration and scaling-up of these components. As such, these technologies are both embryonic, hybrid entities (part idea, part hardware, part discourse, part people) looking to be birthed. This birthing comes through the mobilization of an actor-network that can marshal resources to respond to, and ideally also influence, the innovation environment, which we view as the totality of market and non-market forces affecting technology investments (Jiusto and McCauley, In review). Energy system actor-networks achieve strength by "enrolling" people (e.g., from industry, government, finance, labor, science and environmental organizations), infrastructure, environment (e.g., sub-surface geological formations) and ideas and discourses, such that the system gains coherence, direction and power (Law, 1992).

Supporters acknowledge that CCS viability has not yet been demonstrated and that its gestation period is likely to be long, yet over the last decade the network of scientists, industry, and government actors committed to researching and resolving obstacles to CCS has grown markedly. As a case study in socio-technical innovation and sustainability transition, CCS represents an intriguing example of an entrenched energy regime extending its network to innovate a potentially major "add-on" technology to protect its vested interests. EGS, by contrast, is a case of a small, niche technology looking to evolve along with a changing innovation environment and greatly extend its range of application.

This comparative assessment of the CCS and EGS actor-networks, their relationships with the electricity sector innovation environment, and the levels of support and attention granted these two technologies is based on secondary analysis of research reports, position papers and other archival data and key stakeholder interviews. First we will provide a review of the technological status and key research questions surrounding both CCS and EGS, highlighting the potential and current limitations of each. Next, we discuss the discursive strategies and actor-networks constituting CCS and EGS and their environmental risks and benefits. We then compare research, development and demonstration (RD&D) funding and other critical forms of state support and question the imbalance in favor of CCS over EGS. The final section highlights theoretical and policy contributions stemming from this socio-technical systems analysis.

1 CCS: State of technology and research

CCS is not a single technology but rather a set of technological components for capturing, transporting and storing CO_2, which in turn is but one sub-system of a full low emissions coal-power facility. 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 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, 2005). New, experimental Integrated Gasification Combined Cycle coal power plants that facilitate CO_2 capture are more efficient, and more expensive, than standard plant designs. Capture is the most expensive component of CCS development and operation. Transportation of CO_2 is technically straight-forward, but the volume of gas to be handled would likely entail a pipeline system as large as that now in place for natural gas and hence present significant hurdles with respect to cost, siting, and public controversy.

Carbon storage involves pumping CO_2 into deep geological formations 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, but EOR sites have not been set up for monitoring and verification and questions remain regarding leakage, groundwater contamination, and acidification under varying geological conditions. EOR provides a research bridge to CCS, but EOR occurs in geological strata unlike the saline formations that constitute the overwhelming majority of potential storage capacity (MIT 2007:53). 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 tons of CO_2 per year has been injected underground since 1995 and where a long-term storage monitoring and verification program is being 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, 2005, MIT, 2007, Stephens and Zwaan, 2005). 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 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, and other advanced coal technologies including coal gasification. Just after site selection was completed, however, the Bush Administration, citing cost escalation, "restructured" the FutureGen program and dramatically reduced its financial commitment. The future of FutureGen remains uncertain, though some indications suggest a revival under the Obama administration.

The IPCC (2005) 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 suggests that any projections for large-scale development remain highly uncertain.

2 EGS: State of technology and research

Enhanced geothermal systems, like CCS, are today an embryonic technology with significant engineering and economic uncertainties. EGS, however, 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, mainly in California where high-grade hydrothermal reservoirs exist within highly permeable, saturated rock formations that recharge quickly and are easily reachable (EIA, 2009). Typically, 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 technologies are designed to extend this process to the hot – but usually dry and non-porous -- rock layers that lie within 10 kilometers of the Earth's surface almost everywhere (MIT, 2006). This basically involves drilling wells and introducing water first to fracture the targeted rock layer, then to circulate and collect heat that can drive turbines located on the surface. The EGS resource base is huge, estimated to total 13 million exajoules (EJ), with 200,000 EJ, or about 2,000 times current annual US energy consumption, technically if not financially extractable using current technology (*ibid*). EGS is also attractive because, unlike other renewables, the resource is constantly available and thus can be used to generate base-load 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 forgotten until two major recent studies, one by an MIT panel (MIT, 2006) and another by DOE (2008) that critically evaluated findings of the MIT study. The MIT study found that several geological challenges surrounding EGS in 1970s -- flow short-circuiting, high injection pressure requirements, water losses, geochemical impacts, and induced seismicity -- are now manageable or fully resolved (*ibid*). 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 key remaining technical challenges relate to how best to fracture deep-rock to create sufficient connectivity within injection wells and production wells to generate adequate power without cooling the reservoir and thus reducing its lifetime and the time for investment cost recovery. Improvements are particularly needed in the areas of high-temperature electronics, and deep fracture and flow monitoring and detection systems, areas reflected in DOE's 2009 EGS grants. Commercial viability depends upon RD&D projects showing that large commercial-scale EGS reservoirs can be developed, sustained, and replicated under varying geological conditions (MIT, 2006, DOE, 2008). EGS builds largely upon techniques and insights used in oil and gas exploration, and abandoned or shut-in oil and gas fields may provide important opportunities for early EGS development due to reduced subsurface investigation and drilling costs (McKenna et al., 2005). Similarly, conventional geothermal R&D complements EGS research and offers early development opportunities on the fringes of hydrothermal reservoirs, as Ormat Technologies is doing with DOE support in Nevada. Indeed, a growing number of EGS projects are operating or in development on both a research and commercial basis in the US, France, Germany and elsewhere. The world's largest EGS project in Australia's Cooper Basin recently completed a successful 6-year proof of concept phase and is shifting to commercial demonstration, as testing confirmed the well and reservoir could produce more than 40 MW for over 20 years.

3 Competing Discourses

3.1 The clean coal case for CCS

Emerging technologies like CCS and EGS are constructed not just through technical and economic processes but also through discourse, compelling narratives about what a technology is and might become and why it is needed and preferable to competing technologies. Particularly in the innovation phase prior to commercialization, when the feasibility and costs of alternative systems cannot be tested by market dynamics, persuasive discourses are critical as entrepreneurs seek to accumulate resources and stimulate growth of an actor-network through which to realize the innovation. Both the discourse and the power and credibility of those espousing it are important.

The case for CCS relies primarily on a discourse of inevitability: coal is so cheap, abundant and embedded in existing electric power systems that its continued growing use globally is a virtual certainty. CCS is therefore essential to reconcile this inevitability with the imperative for climate change mitigation. This narrative gains credibility and power from numerous projections of increased energy demand and coal use in the US and internationally. To proponents, the 15 years or more needed to commercialize CCS is not a deterrent but rather an indication of the urgency of accelerating development now. CCS is part of a larger "clean coal" campaign intended to counter constructions of coal as "dirty" and "old." The industry first deployed the clean coal discourse in connection with challenges arising from "traditional pollutants" (e.g., NOx, SOx, CO) and ignored CO_2, preferring instead to argue that climate change was not a significant environmental threat (Gelbspan, 2004). CCS has subsequently become a critical part of the clean coal discourse, which beyond "clean" emphasizes themes such as "advanced technologies," "abundant," "affordable," "secure and reliable," "near-zero emissions," "American lifestyles" and US dependence on coal for power generation (Americaspower.org, 2009). So vital are the "socio" dimensions of socio-technical systems innovation that industry is spending $60 million this year on discourse construction and actor-network development through clean coal advertising and lobbying -- more than its proposed annual contribution to FutureGen of $400 million over 10 years (Conniff, 2008).

The potency of the clean coal discourse has inspired a withering counter-attack. Greenpeace (2008) calls CCS a "dangerous distraction" and Al Gore's Repower America in 2009 aired a highly visible television campaign lampooning clean coal. While mainstream environmental advocacy groups that play an important role in shaping public perceptions about emerging energy technologies are divided and/or ambivalent about CCS (Stephens and Verma, 2006), a consensus strategy may be emerging among environmental advocates that turns the clean coal campaign against the industry by insisting that *only* clean coal plants be permitted in the United States, that is, “No new coal without CCS.” Given that such plants are years off, developers are instead proposing “CCS-ready” plants. As discursive devices, “CCS-ready” plants are designed to reduce opposition to new plant development, but as technical devices their meaning is far less clear (Stephens, 2005). In an ironic complication, some coal plant developers and operators are now lobbying for carbon cap and trade legislation to improve the economic competitiveness of CCS systems (generally provided that carbon credits are granted free to existing facilities, rather than auctioned). In all, diverse perceptions and narratives surrounding CCS are emerging among key actor groups, but the general public presently has little understanding about the technology nor commitment to any particular CCS discourse.

3.2 The “Killer App” case for EGS

In 2008, Google.org’s Dan Reicher branded EGS the next “killer app” of clean energy technology and, with an investment of over $10 million in two EGS companies and a university laboratory, declared that EGS would be a centerpiece in Google.org’s RE<C 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.org, 2007). The essence of the “killer app” (i.e., system transforming) appraisal and discourse are the potential EGS attributes noted above – a very large renewable energy resource with distributable, baseload potential and little environmental impact. This announcement brought significant attention to this previously little-recognized technology and the MIT study supporting it and was accompanied by the familiar energy discourse themes of urgency and need for dramatically increased federal funding. Despite this boost, geothermal systems, and EGS in particular, are not well recognized. 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, In review), 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 its centrality in the Obama administration’s economic recovery plan and legislative agenda.

4 Actor Networks

Discourses and actor-networks are mutually constitutive. The strength of a discourse is related to the power of those enunciating it, and vice versa, though in complex and always internally contested ways. CCS benefits from an actor-network that is strong, diverse, growing and capable of influencing the innovation environment. The traditional coal constituency – the coal mining and power generation industry and coal state politicians and labor unions – has been joined by representatives of other fossil fuel industries, utilities, government, academia, environmental groups, and others. Oil and gas companies bring an interest in geologic carbon storage, both with respect to adapting technologies and processes for underground reservoir management and CO_2 injection and with respect to their own, often diversified, corporate operations. 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 U.S. coal mining company (Peabody Energy), the biggest publicly owned U.S. electric utility (Duke Energy), and the biggest U.S. railroad (Union Pacific)" (Conniff, 2008).

The scientific community invested in CCS influences government funding priorities and the national discourse on climate change through research, policy engagement, and professional organizations. The CCS scientific network now boasts annual conferences in the US and internationally (e.g., the DOE/NETL Annual Carbon Capture and Sequestration meeting that recently drew ~700 attendees), 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 (2005) 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 with 22 member countries.

Other key supporters of CCS include Presidents George W. Bush and Barack Obama, both of whom have strongly embraced clean coal discourse. Environmental organizations such as the Natural Resources Defense Council support CCS (Hawkins, 2005) in part because the very strength of the CCS actor-network suggests that CCS may be best positioned to win needed political and public funding support amid a federal political climate that, at least until very recently, has been strongly opposed to carbon regulation and only weakly supportive of renewables and energy efficiency. Some also see CCS offering fossil fuel industries a way to move beyond denialism (Gelbspan, 2004) 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 policy-makers, businesses, researchers and others.

The EGS actor-network is much thinner, newer and less powerful than that of CCS, yet benefits from its association with the modestly larger, but internally well-connected and active conventional geothermal network. Three of the most active EGS companies in the U.S. are Ormat Technologies, GeoThermex and AltaRock Energy, all 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 is moving into 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, not least with respect to raising the profile and legitimacy of EGS with DOE and scientific research program managers. This appears to be what Google.org and Sun Microsoft founder turned renowned venture capitalist, Vinod Khosla's, interest in EGS has helped accomplish. While EGS has fared poorly in competition with other renewables for federal funding, the recent spark of interest may allow EGS to forge a more powerful network through linkages with "old economy" fossil fuel interests and high tech "new economy" actors.

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 with 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. The scientific community engaged in EGS has also been quite sparse, but as noted below, DOE funding is spurring collaboration among scientists and engineers in companies, academia, and national laboratories.

5 Environmental Risks and Benefits

The strength of the CCS actor-network is impressive and can be read either as building essential capacity to develop a large scale, low-carbon energy option or as a diversion of resources from preferable alternatives. A comparison of potential environmental risks and benefits of CCS and EGS is therefore instructive.

CCS holds out the prospect of reducing coal plant carbon emissions some 80 – 90%, but presents three kinds of environmental risk. *Local risks* relate to the accidental release of CO_2 and include enhanced seismicity, ecological disruption, and groundwater contamination. These risks do not appear large relative to impacts of most power generation options deployed on a large scale. *Global climate risks* stemming from large scale leakage of CO_2 could be minimized through careful site selection and with the application of monitoring and verification technology. *Indirect risks* of CCS deployment may be the largest category of environmental hazard and include coal life-cycle impacts associated with mining, beneficiation, transportation, and combustion gases that contribute to acid rain, smog and health hazards (Schneider and Padian, 2004, Clean Air Task Force, 2001). Indirect risks are likely to be exacerbated by the increased requirement for coal combustion in CCS systems.

By contrast, EGS is potentially among the most environmentally benign of energy resources. Facilities are comparatively small and unobtrusive and land use requirements and visual impacts 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 all carbon dioxide emissions and likely the need to treat any emissions. As with CCS, induced seismicity requires further research and may compromise project permits near major population centers. Majer & Patterson (2007) conclude that EGS-related seismicity is predictable and potentially controllable with developed injection techniques.

6 Public commitment: Funding RD&D

Fundamentally, the argument for CCS is financial and assumes coal-CCS offers an economically attractive carbon reduction option. Yet in the US, even without CCS, coal plants have become increasingly difficult to finance, site and build due to risks associated with large plant development in an increasingly competitive marketplace, volatile coal prices, high capital costs for plants, reduced demand growth, anticipated carbon regulation and anti-coal citizen activism. As a result, hundreds of new coal plants have been proposed, but only 12 built since 1990 (Pew Center on Global Climate Change, 2009). CCS would alleviate risks associated with climate regulation, but increase those associated with capital requirements, fuel, and other risks that already have private investors favoring small scale, distributed power resources over coal and nuclear power (Lovins and Sheikh, 2008). It is also quite possible that during the decade or two required for CCS development that new low-carbon alternatives, potentially including EGS, will emerge to further erode coal's competitiveness. While coal use is growing rapidly in the developing world, there, too, the question is whether investors will continue to choose coal if alternatives emerge and if required to pay the full costs of CCS. Whatever the costs for CCS may eventually be, they will be additional to existing coal power life-cycle costs that, after a century of improvements, are less likely to decrease dramatically than those for newer technologies, including renewables, that are only now receiving levels of R&D support approaching that of fossil fuels and nuclear power. The public policy question is whether CCS or EGS represents the better public investment?

Compared to CCS, commercializing EGS involves resolving less complicated research questions and developing smaller, more modular pilot projects, and hence the estimated RD&D costs are much less. The total cost of bringing EGS to commercial viability is estimated at between $300-$400 million (MIT 2006) and $800 million – $1 billion (DOE 2008) spread over 15 years. Even the upper figure 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 carbon sequestration, FutureGen, and the Clean Coal Power Initiative (Stephens, forthcoming). Increasingly frequent calls to develop 10-30 CCS demonstration plants (e.g., Pew Center on Global Climate Change, 2009) would entail a largely public investment risk of some $15-$60 billion dollars.

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 geothermal, with an additional $20 million designated for EGS grants in FY2009 alone.

Total private sector funding data for CCS are not available, but industry commitments for FutureGen alone are approximately $400 million over ten years. Despite electricity retail revenues of $343.7 billion in 2007 (EIA, 2009), the electricity sector as a whole has historically invested little in R&D. Total private sector EGS spending is also uncertain, 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 to escalate quickly to $100 million annually.

Projections of production costs per kilowatt-hour of either system once fully developed are highly speculative. Both systems' costs are likely to vary significantly geographically due to differences in geological formations. Once sited, EGS may be 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.

7 Conclusions

This comparison of CCS and EGS socio-technical systems highlights great variation in their social dynamics and levels of support. Both of these technologies are still early in development - they exist as complex hybrids in which scientific views as to their potential worth in the future are not an incidental but absolutely essential element in mobilizing resources for realizing that potential. At this stage the perspectives, interests and influence of researchers can play a particularly important role in determining technological winners and losers.

At this early stage of innovation, before a technology has been proven and deployed, while it is typically treated as a technology (hardware), it exists more as an idea and a hybrid entity – part science, part finance, part politics, part discourse – that some people hope will and others hope will not become a "technology". Even at this stage, however, socio-institutional complexes and discursive formations are forming around these technological ideas, exerting a strong influence on the direction of technological development. Most socio-technical studies take place after (often long after) the process has unfolded – this study looks at two nascent socio-technical systems and attempts to characterize on-going innovation processes in a way that usefully informs theory *and* frames choices. The bedrock proposition upon which sustainability science is founded -- that some choices for change are better than others and scientific inquiry can help prioritize social investment – lends sustainability research an unavoidably normative dimension. While pursuing a "portfolio" of clean energy and energy efficiency options is sensible (Pacala and Socolow, 2004), selectivity and discernment is essential in determining which portfolio options merit investment, by whom, and at what level. Sustainability transition analysis can help frame such questions, as this research seeks to do for CCS and EGS.

Differences in the socio-technical systems supporting the two technologies are substantial and include the social actors involved in supporting technology development, the management of associated R&D, finance and risks, the degree to which the technology can be scalable and distributed, and the long-term potential for the technology to contribute to an energy system sustainability transition. All of the major recommendations for advancing CCS made in the MIT study focus exclusively on US government action, a tacit acknowledgement of the scale of investment risk associated with the large cost, complexity and lead times required to develop full-scale coal-CCS facilities (MIT 2007). EGS also requires public investment to succeed, but EGS technology can more readily be advanced and deployed incrementally, in numerous smaller-scale projects, with lower costs and risks and significant private sector involvement. One pathway to EGS development, for example, is as an adjunct to conventional hydrothermal plants, allowing exploitation of dry or under-performing wells. While the large scale deployment of CCS remains, at best, a distant possibility, continued commitment to CCS technologies, through scientific advocacy, demonstration project planning, and research funding, is being used to legitimate new coal plants today. This legitimation is compounded as the socio-technical system supporting CCS grows stronger and more entrenched and path dependencies begin to have a perverse influence on the innovation environment.

From an actor-network approach, the strength of the CCS network is both an accomplishment – it is capable of garnering resources for a low carbon technology – and also a potential impediment to wiser investment of limited public and private RD&D resources. Unlike wind, solar and other renewables, the critical research and operational questions surrounding EGS viability lies within the expertise and interest domains of key CCS actors, thus the success of EGS may hinge on the extent to which geological sciences and oil and gas industry researchers, engineers and entrepreneurs can be drawn into supporting EGS. Similarly, the extent of support for EGS and resistance to coal and CCS by environmental advocacy organizations and others will also be telling. These latter groups may be motivated by the sharply divergent environmental implications of the two systems – CCS which extends and potentially exacerbates coal's life-cycle impacts and those of a highly centralized, resource-intensive electrical power system, versus EGS that may also provide baseload supply, but on a renewable, distributed, low-polluting and likely less controversial basis.

While a binary comparison between CCS and EGS greatly simplifies the complex choices and trade-offs inherent to the continuously shifting innovation environment for electricity and climate change mitigation technologies, we believe this study reveals important lessons for a sustainability transition in energy systems. The paper highlights the notion that trade-offs are inevitable, and that socio-technical systems begin developing and exerting influence on the broader innovation environment long before the technologies themselves are deployed. We emphasize themes not fully addressed in other socio-technical studies, including how science, discourse and the environment interact to shape "the realm of the possible" for future system transitions, and we argue that innovation thus depends as centrally on constructing discourse as constructing hardware. In this high stakes context of investment decisions, unpacking the complex dynamics of emerging socio-technical systems is critical.

References

AMERICASPOWER.ORG (2009) Ad Archive. American Coalition for Clean Coal Electricity.

CAP (2009) Center for American Progress Website. *Issues, Energy and Environment, Carbon Capture and Sequestration 101.* http://www.americanprogress.org/issues/2009/03/ccs_101.html.

CLEAN AIR TASK FORCE (2001) Cradle to grave: The environmental impacts from coal. Boston, Clean Air Task Force.

CONNIFF, R. (2008) The myth of clean coal. *Yale Environment 360.* Yale School of Forestry & Environmental Studies.

DOE (2007) Carbon Sequestration Technology Roadmap and Program Plan 2007. U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory. http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2007/2007Roadmap.pdf.

DOE (2008) An evaluation of enhanced geothermal systems technology. US Department of Energy, Energy Efficiency and Renewable Energy.

EIA (2009) Electric power annual 2007. Washington, DC, U.S. Energy Information Administration.

GEELS, F. W. (2005) The Dynamics of Transitions in Socio-technical Systems: A Multi-level Analysis of the Transition Pathway from Horse-drawn Carriages to Automobiles (1860-1930). *Technology Analysis and Strategic Management,* 17**,** 445-476.

GELBSPAN, R. (2004) *Boiling point: How politicians, big oil and coal, journalists and activists are fueling the climate crisis--and what we can do to avert disaster,* New York, Basic Books.

GOOGLE.ORG (2007) Google's goal: Renewable energy cheaper than coal.

GREENPEACE (2009) Greenpeace USA. News Website: http://www.greenpeace.org/usa/news/new-greenpeace-report-exposes. Accessed March 20, 2009.

GREENPEACE INTERNATIONAL (2008) False hope: Why carbon capture and storage won't save the climate.

GRUBLER, A., NAKICENOVIC, N. & NORDHAUS, W. D. (Eds.) (2002) *Technological Change and the Environment,* Washington DC, Resources for the Future.

HAWKINS, D. G. (2005) CO_2 Capture and Storage: Just Do It. *United States Energy Association.* http://www.usea.org/Ericeprogram/Presentations-Remarks/Hawkins%201100.pdf Accessed March 15, 2006.

HOLDREN, J. P. (2006) The Energy Innovation Imperative, Addressing Oil Dependence, Climate Change, and Other 21st Century Energy Challenges. *Innovations, Technology, Governance & Globalization* 3-23.

IPCC (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Geneva, Intergovernmental Panel on Climate Change, Working Group III.

ISOARD, S. & SORIA, A. (2001) Technical change dynamics: evidence from the emerging renewable energy technologies. *Energy Economics,* 23**,** 619-636.

JIUSTO, S. & MCCAULEY, S. (In review) Theorizing a sustainability transition in the U.S. electrical power system. *Research Policy*.

KEITH, D. W. & PARSON, E. A. (2000) A breakthrough in climate change policy? *Scientific American,* 282**,** 78-79.

LAW, J. (1992) Notes on the theory of the actor-network: Ordering, strategy, and heterogeneity. *Systems Practice,* 5**,** 379-393.

LEDRU, P., CALCAGNO, P., GENTER, A., HUENGES, E., KALTSCHMITT, M., KARYTSAS, C., KOHL, T., LOKHORST, A., MANZELLA, A. & THORHALLSSON, S. (2006) Enhanced Geothermal Innovative Network for Europe (The Engine Co-Ordination Action). *Grc Transactions,* 30.

LOORBACH, D. (2007) *Transition Management: New Mode of Governance for Sustainable Development,* Utrecht, International Books.

LOVINS, A. B. & SHEIKH, I. (2008) The Nuclear Illusion. *Ambio,* Nov 08 preprint draft.

MAJER, E. & PATTERSON, J. (2007) The impact of injection on seismicity at The Geysers geothermal field. *International Journal of Rock Mechanics and Mining Sciences. ,* 44**,** 1079-1090.

MCKENNA, J., BLACKWELL, D., MOYES, C. & PATTERSON, P. (2005) Geothermal electric power supply possible from Gulf Coast, midcontinent oil field waters. *The Oil and Gas Journal,* 103**,** 34-40.

MEADOWCROFT, J. (2007) Steering or muddling through? Transition management and the politics of socio-technical transformation. *Workshop on "Politics and governance in sustainable socio-technical transitions.* Berlin.

MIT (2006) The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st Century. Cambridge, MA, Massachusetts Institute of Technology.

MIT (2007) The Future of Coal: Options for a Carbon Constrained World. Cambridge, MA, MIT.

NCEP (2004) Ending the Energy Stalemate, A Bipartisan Strategy to Meet America's Energy Challenges. National Commission on Energy Policy.

PACALA, S. & SOCOLOW, R. (2004) Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. *Science,* 305**,** 968-972.

PEW CENTER ON GLOBAL CLIMATE CHANGE (2009) Coal and climate change facts. http://www.pewclimate.org/global-warming-basics/coalfacts.cfm.

RIP, A. & KEMP, R. (1998) Technological change. IN RAYNOR, S. & MALONE, E. L. (Eds.) *Human choice and climate change.* Columbus, OH, Battelle Press.

SCHNEIDER, C. G. & PADIAN, M. (2004) *Dirty air, dirty power. Mortality and health damage due to air pollution from power plants,* United States.

SMITH, A., STIRLING, A. & BERKHOUT, F. (2005) The governance of sustainable socio-technical transitions. *Research Policy,* 34**,** 1491-1510.

STEPHENS, J. C. (2005) Coupling CO_2 Capture and Storage with Coal Gasification: Defining "Sequestration-Ready" IGCC. *Fourth Annual Conference on Carbon Capture and Sequestration.* Alexandria, Virginia, DoE/NETL.

STEPHENS, J. C. (forthcoming) Technology Leader, Policy Laggard: Carbon Capture and Storage (CCS) Development for Climate Mitigation in the U.S. Political Context. IN MEADOWCROFT, J. & LANGHELLE, O. (Eds.) *The Politics and Policy of Carbon Capture and Storage.*

STEPHENS, J. C. & VERMA, P. (2006) Environmental Advocacy Groups' Perspectives on Carbon Capture and Storage. *Climate Change Technology Conference: Engineering Challenges and Solutions in the 21st Century.* Ottowa, Canada, Engineering Institute of Canada.

STEPHENS, J. C., WILSON, E. J. & PETERSON, T. R. (2008) Socio-Political Evaluation of Energy Deployment (SPEED): An integrated research framework analyzing energy technology deployment. *Technological Forecasting and Social Change,* 75**,** 1224-1246.

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