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Christian Downie & Peter Drahos

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US institutional pathways to clean coal and shale gas: lessons for China

CHRISTIAN DOWNIE[1,2]*, PETER DRAHOS[3]

[1] Faculty of Arts and Social Sciences, The University of New South Wales, Sydney, NSW 2052, Australia
[2] Department of Urban Studies and Planning, Massachusetts Institute of Technology, Cambridge, MA
[3] Regulatory Institutions Network, Australian National University, Canberra, ACT 0200, Australia

China's 12th Five-Year Plan (2011–2015) envisages that shale gas and coal will be central to its energy future. However, for China to meet the energy security and climate change objectives set out in its 12th Five-Year Plan it will be reliant on the widespread commercial deployment of two key technologies; hydraulic fracturing combined with horizontal drilling for shale gas, and carbon capture and storage (CCS) for coal. China is moving to acquire these technologies through technology transfer and diffusion from the US, but progress has been slow, and neither is currently available in China on a commercial scale. Drawing on interviews in the US and China, this article argues that China's expectation of technology from the US may well be disappointed because of factors unique to the US institutional environment that have made the development of fracking technology possible and hinder the development of CCS technology at a commercial scale.

Policy relevance
If China is to meet the energy security and climate change objectives set out in its 12th Five-Year Plan it will be reliant on the widespread commercial deployment of fracking and clean coal technologies. While China expects to acquire these technologies via technology transfer and diffusion from the US, progress has been slow. Because of factors unique to the US institutional environment the availability of both technologies on a commercial scale in China is unlikely in the coming years. As a result, Chinese policy makers would be well-advised not to count on these technologies to meet their energy and climate goals.

Keywords: China; clean coal (CCS); climate change; shale gas; technology diffusion

1. Introduction

China's 12th Five-Year Plan (FYP, 2011–2015) envisages that shale gas and coal will be central to China in the coming decade. However, in order for China to meet the energy security and climate change objectives set out in its 12th FYP, which has been heralded as the 'greenest' in history, China will be reliant on the widespread commercial deployment of two key technologies, which have been largely advanced in the US: hydraulic fracturing (fracking) combined with horizontal drilling, and carbon capture and storage (CCS) (Thomson, 2014).

The literature on varieties of capitalism and innovation shows that the paths of technological development do not run in a smooth linear fashion but are highly dependent upon the formal rules and informal norms that make up a country's institutional starting point and lay the foundation for its

*Corresponding author. *E-mail*: c.downie@unsw.edu.au

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comparative advantage in technology (Hall & Soskice, 2001; Mowery & Rosenberg, 1999; Rosenberg, 1982). Drawing on the insights of this literature along with fieldwork data, we show that there are important institutional factors that explain technological change in these fields in the US and that are relevant to understanding the likely speed and scale of the evolution of these key technologies in China.

Fracking, the technological process in which sand, water, and chemicals are injected into the rock to release natural gas, is required if China is to develop its vast indigenous shale deposits, helping it to reduce its exposure to the vagaries of international markets (Wu, 2014). Recent estimates suggest its shale deposits dwarf those of the US. According to the US Energy Information Administration, technically recoverable shale gas resources in China amount to 1,115 trillion cubic feet (tcf), compared with 665 tcf in the US (EIA, 2013, p. 10). In its 12th FYP, China set a target of increasing the country's shale gas production from almost zero to 60 billion cubic metres (bcm) by 2020, as part of its push for natural gas to rise from 4% of the energy mix to 10% by 2020 (Tollefson, 2013).

The evidence to date suggests that replicating the US fracking technology revolution will not be easy (Gunningham, 2013; Pi, Dong, Dong, Guo, & Ma, 2015). For example, in 2014, China revised down its expected shale gas production by half, with the National Energy Administration predicting that China would produce 30 bcm by 2020, compared with the 60 bcm set as the 2020 target in 2012 (*The Economist*, 2014). Nevertheless, China remains committed to shale gas, and senior officials have proclaimed that 'shale gas has a big future in China' (interview, 2014).

CCS technology would give China, much like some other developing countries, such as India, the option of continuing to exploit its large domestic coal reserves while reducing its rapidly growing GHG emissions (Román, 2011). As the world's largest coal user, producer, and importer, China dominates the global coal market (IEA, 2013b, p. 156). Yet the same FYP, which has been heralded as the 'greenest' in history, has set ambitious targets not only to move from coal to natural gas, but also to modernise the Chinese coal sector (i.e. close down old and inefficient coal plants) (Thomson, 2014, p. 1). Furthermore, in 2013, China announced that it would ban the construction of new coal-fired power plants in the Beijing, Shanghai, and Guandong regions (IEA, 2014, p. 74). Notwithstanding, the International Energy Agency (IEA) projects that given 'the massive stock of coal-fired stations already in place, combined with the country's enormous coal reserves', coal will remain the key source of electricity generation for the next two decades (IEA, 2013b, p. 156).

As a result, if China is to maintain its commitment to coal as well as continue to reduce its emissions per unit of gross domestic product, it will require the widespread deployment of CCS technology, i.e. a set of technologies that enable the capturing, transporting, and storage of CO_2. The IEA expects that if the world is to stay within the 2 °C guardrail, as recommended by the Intergovernmental Panel on Climate Change, China alone will need to account for one-third of the global total of captured CO_2 between 2015 and 2050 (IEA, 2013a, p. 5). However, the climate impact of CCS is likely to be different to that of fracking. On the one hand, CCS has the potential to decouple coal from fossil fuel use (Wilson, Zhang, & Zheng, 2011, p. 324), but, as will be discussed, in practice its limited deployment has slowed the development of coal in the US. On the other hand, the shale revolution may have reduced the US dependence on coal, which in most cases is more emissions-intensive than shale gas, but its success also threatens to entrench dependence on fossil fuels at the expense of renewables (IEA, 2011).

Nevertheless, as Chinese officials readily concede, China's capacity to meet its stated goals will be a function of its access to CCS and fracking technology developed in the US (interviews, 2014). China is moving to acquire these technologies through the mechanism of joint venture with foreign companies or by participating in demonstration projects. An example of the former is the agreement between Shell and the China National Petroleum Company in 2011 to develop well manufacturing systems, and an example of the latter is the entrance of the Huaneng Group, China's largest coal-based power generator, in 2005 into the industrial alliance that partnered with the US Department of Energy in the first FutureGen project, a project that aimed to construct the first zero-emission coal-fuelled power plant. More recently, China has embarked on a series of pilot CCS projects in cooperation with the US coal industry, including GreenGen, which is China's signature CCS project (Drahos, 2009).

Despite these and other attempts, progress in acquiring these technologies has been slow. Neither fracking nor CCS technologies are currently available in China on a commercial scale, and, as the IEA has concluded, 'China will not become a testing ground for unproven technology', such as CCS (IEA, 2009, p. 262). China's expectation has been that it would most probably acquire these technologies through processes of technology transfer and diffusion, with the origin country for these technologies most likely to be the US (Drahos, 2009; interviews, 2012).

China's expectation may well be disappointed. The history of technology cooperation between the US and China has been far from smooth, with disputes over the adequacy and enforcement of intellectual property standards by Chinese authorities being especially prominent (Yu, 2005). Our interviews with representatives from US multinationals in China revealed, not surprisingly, a prudential approach to technology issues, with those representative speaking about the need to 'blackbox' core technologies, to use trade secret protection (as opposed to patents, which require publication of the invention), and not to put core technologies into joint ventures (interviews, 2012). This prudential, secretive approach to technology may also set limits on China's capacity to use a 'leapfrogging' strategy based on technology transfer to progress CCS. China did embark on a successful leapfrogging strategy for wind energy (Dai & Xue, 2014), but technology transfer and leapfrogging strategies are highly context-dependent, and affected by variables such as the maturity of the technology and its degree of knowledge codification. As we argue in the following, CCS does not represent a mature set of technologies – indeed there is uncertainty as to whether it ever will – and innovation in fracking technologies has been more dependent on uncodified than codified knowledge.

Section 2 provides a short overview of the method of analysis. Section 3 then examines the unique institutional environment that enabled the shale revolution in the US to take place, and which is likely to prevent the clean coal revolution. Section 4 then draws some conclusions and implications for China's energy and climate policy.

2. Method

The following institutional analysis of the US and China is based on an extensive literature review and interviews. There is a large literature on the three stages of technological development that Schumpeter (1942) first identified – invention, innovation, and diffusion. Most studies, including those in the energy sector and those relating to these technologies, identify a range of factors, such as the actors, the resources, the networks, and the regulations, among others, to understand technological development across these three stages (see, e.g., Gallagher, Grübler, Kuhl, Nemet, & Wilson, 2012; Gallagher, Holdren, & Sagar, 2006; Jacobsson & Johnson, 2000). Broadly speaking, these factors can be considered to comprise the institutional environment.

Guided by the theoretical literature on technology development 52 semi-structured interviews were undertaken. In 2012, 27 interviews were completed with Chinese actors, and in 2014, 25 interviews were completed with US actors. In both countries, interviews were conducted with state and non-state officials, including government energy agencies, energy and utility companies, and associated policy makers. The large majority of these interviews were with energy companies, including utilities, with a smaller sample of government policy makers in China and the US. Respondents were asked about their broad views on energy policy and technology development, before more specific questions were asked about their knowledge of shale gas and CCS development in the US and China.

The cases of fracking and CCS technologies were considered together because they are, as China's 12th FYP makes clear, both critical technologies that China is looking to develop. They are also paired critical cases, in that the US globally leads the innovation of these technologies, resulting in them being part of the dialogue between the US and China. By considering them together, the analysis is able to sharpen and deepen the focus on the US institutional environment that has shaped their development.

3. Results and discussion

3.1. The development of shale gas technology in the US

3.1.1. The shale gas revolution

The US 'shale revolution', as the name suggests, has led to a sharp, sudden change in the energy industry. The technology breakthroughs that have allowed producers to access the vast onshore gas reserves locked in impermeable rocks has transformed US energy markets, and indeed global markets. In 2008, the US was still processing approvals for new liquefied natural gas import terminals to meet gas demand, yet within four years it has become the world's largest gas producer and is likely to be energy-independent by the end of the decade (IEA, 2013b, p. 76).

Like most revolutions, the seeds for the shale revolution were sown more than half a century ago (Sovacool, 2014). Fracking technology was first tried in the late 1940s in the US, then advanced by the US Department of Energy in the 1970s (Credit Suisse, 2012). In the 1980s, George Mitchell, an independent oil producer, began drilling wells in Texas. After 15 years of experimenting with different wells at different points in the shale formations, Mitchell proved the fracking technology financially viable in 1997. However, it was not until a few years later, when the fracking technology was combined with horizontal drilling into the shale, which exposed even more gas-bearing rock, that the revolution was complete (Gold, 2014).

The results have been dramatic. Between 2007 and 2012, US shale gas production rose by over 50% each year, and it now accounts for around 40% of total US natural gas production (EIA, 2015). In less than five years, the US has drilled almost 200,000 wells, with the large majority located in five 'plays' (geographical areas), namely the Barnett shale in Texas, Haynesville in Louisiana, Marcellus, which spans West Virginia, Pennsylvania, and New York, Fayetteville in Arkansas, and Woodford in Oklahoma (Hughes, 2013).

3.1.2. Could it only happen in America?

While some analysts argue that the technology is easily transferrable outside the US, many others, especially those in the industry, argue that the shale revolution 'could have only happened in America' (Hefner, 2014; Morse, 2014). Moreover, even if some of the product technologies that are part of fracking and CCS are readily transferable, it does not follow that they will be sufficient to catalyse a shale revolution in China. For example, Indian pharmaceutical companies have been able to reverse-engineer pharmaceutical products produced by US pharmaceutical companies, but the transferability of these pharmaceutical products has not turned India into a global leader in biomedical innovation. As noted above, in order to understand the transformation that has occurred in US gas production it is necessary to look to institutional factors. In what follows, four factors are identified that in combination are unique to the US institutional environment, and in turn the shale gas revolution. It is argued that China will have to forge its own path to the shale revolution, a process that could take many more years than is currently anticipated in China, with uncertain results.

First, like China, the US has abundant shale gas resources. However, as one US expert put it, 'the shale is better in America' (interview, 2014). While geological surveys estimate that technically recoverable Chinese shale resources are around twice those in the US, they also indicate that the geological formations in the US are much easier to access. According to the US Energy Information Administration (EIA), most Chinese shale basins are tectonically complex and not conducive to shale development (EIA, 2013, p. XX–8). By contrast, the Barnett shale that George Mitchell experimented with in Texas is like a wedding cake, with smooth layers of sponge stacked upon one another, which is why horizontal drilling is so effective. In China, even in the best areas, such as the Sichuan Basin, the cake is a mess. As an engineer from PetroChina explained:

> the Sichuan Basin's considerable structural complexity, with extensive folding and faulting, appears to be a significant risk for shale development. (EIA, 2013, p. XX–9)

That is not to say that the Chinese shale cannot be accessed; instead, as an official from one US oil and gas major concluded, it is that 'China's geology is difficult' (interview, 2014). It is not simply a case of transferring the technologies that worked on US shale to Chinese shale; the different formations will require further refining and experimenting, as will be discussed.

Second, and more important than favourable geology, is the wildcatter subculture of the US oil and gas industry, which is defined by its tradition of risk taking. The shale revolution in the US was instigated by thousands of entrepreneurs – small independent oil and gas companies. An independent producer is defined as one that does not have more than US$5 million in retail gas sales in a year (IPAA, 2013). There are many thousands of such producers in the US and they have been a part of the US industry from the beginning. For example, the Independent Petroleum Association of America, which was formed in 1929, has more than 8000 members. For a long time, large multinationals such BP, Shell, and ExxonMobil believed that the future of oil and gas lay in multibillion dollar offshore projects, and, as a result, they largely ignored the smaller onshore projects in Texas and beyond (interviews, 2014). This left the independents to explore new shale basins and experiment with the combination of fracking and horizontal drilling technologies. The tradition of risk taking in these companies, the so-called 'wildcatter' culture, was epitomised by Mitchell, and thousands like him, who as one industry insider highlighted, are prepared to 'go big or bust, they can take risks and drill wells 100 different ways' (interviews, 2014).

These two dimensions of the community of independent producers – their large numbers and preparedness to experiment with drilling – help to understand how fracking came to be scaled up. The drilling behind fracking is better understood as a process of continuous experimentation and improvement. In the words of one interviewee, independent producers have this approach 'in their DNA – they are always drilling, always tweaking' (interview, 2014). The many thousands of independent producers engaged in this process meant there were many more opportunities to learn from the outcomes of experiments. Fracking would have produced results much more slowly if there had only been a small number of producers. It may also be that information about processes of successful drilling diffuses quickly among independent producers. Mitchell, for example, chose to rely on secrecy for his breakthroughs (Hinton, 2012, p. 234), but trade secret protection does not last long where there are contractors, labour mobility, and a large number of industry players all engaged in independent experimentation.

Importantly, these independents were not starting from scratch:

> We have been using fracking and horizontal drilling for 60 years and we have been combining the technology for the last 10 years. (Interviews, 2014)

In other words, the technology was not new. What was new was the application of the technologies – that was the innovation. Based on a long learning curve, dating back to the 1940s, thousands of wildcatters applied these technologies to thousands of sites in order to access gas and drive down the costs of production. This was a case of incremental innovation over a long period of time rather than a case of radical product innovation such as in the case of a drug with a new molecular structure. While many companies went bankrupt, the effect, as several respondents pointed out, is not only were there more wells, 'but they are drilling better wells' (interviews, 2014). For instance, one independent operator in the Marcellus shale reported bringing drilling and completion costs down by 50% between 2008 and 2009 by applying technical and efficiency improvements (Deloitte, 2014). Incremental innovation to improve the costs of horizontal drilling was one of the many successes that helped to transform the US gas market. When horizontal wells were first being drilled on a commercial scale in the early 1990s, their cost was anywhere between 25% and 300% more than vertical wells in the same area (EIA, 1993, p. 4).

Third, and related, the maturity of the oil and gas industry in the US meant that there was an existing industrial and financial infrastructure, which the independents could draw on to take advantage of the technological innovations. For example, North America has the largest fleet of drilling rigs for hire in the world, which enabled the independents to make quick on-site decisions during the drilling and completion processes (interviews, 2014). In 1995 there had been a little over 730 rigs in the US. From 2003 the number was over a 1000, and in 2011 it hovered above or below the 2000 mark (Baker Hughes, 2014). The extensive pipeline infrastructure also meant that in the first years of the shale revolution, there was no need to create major new infrastructure, which would have increased costs and slowed technological advances (Credit Suisse, 2012, p. 14). In addition, the independents had access to large venture capital markets with financiers willing to take risks and invest, even when there was great uncertainty about the prospect for gas (interviews, 2014). Importantly, independents did not have to justify their projects to risk-averse boards of directors (Hinton, 2012, p. 229) or, in the case of China, meet government performance targets. In the words of one US industry observer, 'the fact that this was all in place helped to drive the revolution' (interviews, 2014).

Finally, the US regulatory environment was critical to aiding the development of shale gas. First and foremost was the property rights regime. As North (1991) first identified, property rights are crucial for understanding economic development, and as almost all respondents argued, this was especially so for the shale gas revolution. Whereas in most countries, including China, the state owns subsurface resources, in the US, landowners own the rights to the land and the resources under it. Based on a long-standing common law principle, landowners are entitled to reap the royalties of any exploration on their land (Spence, 2013). As a result, independent oil and gas companies could directly negotiate with individual landowners, rather than the government, for mineral rights. Given the royalties that landowners were entitled to from shale gas production, they were more willing to provide access to their land and less likely to organise the resistance movements that have characterised shale developments in Europe.

It is an open question as to whether China needs a US-style property regime to exploit its shale gas resources. China began its economic growth run in the 1980s without foundational property reforms (Huang, 2008, p. 85). Still as one Chinese lawyer in the gas and oil field pointed out, the US approach in effect creates something like a 'joint venture' between the landowner and a mining company (interviews, 2012). In other words, the cooperative effects of a private property rights regime in this field might be a quicker path to the development of the resource than relying on the appropriation powers of a strong central government. At the very least, the prospects for shale development in China would probably be improved if foreign companies had a greater commercial opportunity to exploit Chinese reserves (Wan, Huang, & Craig, 2014).

More broadly, shale gas development in the US has benefited from a supportive set of regulatory mechanisms. For example, the Natural Gas Policy Act 1978 and the Natural Gas Well-head Decontrol Act 1989 eliminated price controls, which increased natural gas prices, and in turn the incentive for wildcatters to experiment in unconventional gas markets (Credit Suisse, 2012, p. 13). The Natural Gas Policy Act 1978 turned out to be particularly important for independents like George Mitchell, because it locked in higher Federal price rewards for risky gas extraction, that is to say, gas extracted from tight formations or from below 15,000 ft (Hinton, 2012, p. 233). They were also the beneficiaries of a range of tax credits and research and development (R&D) subsidies. For example, the National Research Council in the US found that R&D support from the Department of Energy was crucial for the development of the fracking technology (NRC, 2001). In addition, and importantly given the growing concerns around the impact of fracking on water resources, the US Government exempted the industry from the Safe Drinking Water Act in 2005 (Rahm, 2011, p. 2977).

3.2. The development of clean coal technology in the US

3.2.1. The clean coal revolution?

While the shale revolution is happening, the world, and especially China, is still waiting for the clean coal revolution (Scott, Gilfillan, Markusson, Chalmers, & Haszeldine, 2013). As the IEA puts it:

> After many years of research, development, and valuable but rather limited practical experience, we now need to shift to a higher gear in developing CCS into a true energy option, to be deployed in large scale. (IEA, 2013a, p. 1)

After China, the US is the world's second-largest coal consumer, and coal accounts for about one-fifth of its energy needs and one-third of its electricity production (IEA, 2013b, p. 159). More importantly, the US has for a long time been the leader in clean coal technology development, not only at the national level, but internationally, including in cooperative arrangements with China. First, with the largest R&D base in the world and the most mature coal sector, the US has driven some of the most ambitious clean coal projects, including FutureGen, which was launched by President Bush in 2002. Second, the US has also led many of the international efforts to promote and support CCS, such as the Carbon Sequestration Leadership Forum and the Asia-Pacific Partnership on Clean Development and Climate, which both commenced under President Bush (Stephens, 2009, p. 42). While not all of these initiatives have proceeded smoothly, as will be discussed, the commitment to CCS development has largely continued under the Obama administration. For example, following the global financial crisis, the American Recovery and Re-investment Bill 2009 provided $3.4 billion in support for CCS (Haszeldine, 2009, p. 1649).

3.2.2. Could CCS happen in America?

The question for CCS and for China is whether clean coal technology will be developed in the US at a commercial scale for widespread deployment in the near term. Again, focusing on the US institutional environment, three factors are examined that are hindering the commercial large-scale development of CCS technology, namely the technology, the energy market, and the regulatory environment. In other words, whereas the unique institutional environment in the US made the shale revolution possible, in the case of clean coal, it appears that the opposite is true.

First, the CCS technology, or set of technologies, that permit CO_2 to be captured, transported, and stored are not new, and different configurations of these technologies have already been used successfully in other industrial applications. However, as the US Government's Interagency Taskforce on Carbon Capture and Storage found in 2010, there remain barriers to the widespread demonstration and deployment of CCS technology on a commercial scale (DOE & EPA, 2010; Pollak, Phillips, & Vajjhala, 2011). Furthermore, as the IEA has shown more recently, global progress on demonstration and deployment has been 'insufficient' in the three years since. The IEA's 2009 CCS roadmap highlighted the need to develop 100 CCS projects between 2010 and 2020. As of 2013, only four large projects have been carried out, with a further nine under construction (IEA, 2013a, p. 10).

While, publicly, the US coal industry is optimistic about the potential for CCS, interviews within the coal mining and utility sector highlight the difficulties with demonstration and deployment. As one respondent pointed out 'CCS technology simply does not exist on a commercial scale ... those that say it does do not operate power plants' (interviews, 2014). The FutureGen project had been viewed as the shining light for CCS technology, but, following the US Department of Energy's decision in 2008 to reduce funding and restructure the programme, most respondents were not optimistic about the project, or failed to mention it entirely (GAO, 2009). In fact, in 2015 the US Department of Energy announced that it would withdraw further funding from the project, effectively ending the initiative (Geman, 2015).

Instead, the most promising demonstration projects, and certainly the most commonly cited by respondents in the industry, have been led by Southern Company, the fourth-largest electricity utility in the US (interviews, 2014). The largest project is the so-called Kemper County project, a 582 MW integrated gasification combined cycle plant, which aims to sequester 50% of its CO_2. The project has benefited from Southern Company's R&D base, one of the largest of any utility in the US, and support from the Department of Energy, which has contributed $270 million, on top of an estimated $133 million in investment tax credits (MIT, 2015). It also benefits from its capacity to on-sell CO_2 via newly constructed pipelines, for enhanced oil recovery operations at depleted oil fields in Mississippi (Folger, 2014). Southern Company has also led on a small pilot 25 MW CCS plant in Alabama, which has successfully captured, transported, and stored CO_2 from its subsidiary Alabama Power's Plant Barry. It too has received support from the Department of Energy, which contributed $295 million in 2009 and a further $15 million in 2011 (MIT, 2014).

Despite these favourable funding conditions, and some initial successes, respondents who have been associated with both projects acknowledged that 'there has not been enough front-end engineering' and 'that it has been difficult to add the technologies together' (interviews, 2014). Others were more direct, pointing to the 'numerous delays' and cost increases (interviews, 2014). For example, the Kemper County project is expected to cost almost $5.6 billion, more than twice the originally estimated cost of $2.4 billion (MIT, 2015). The problem with the increasing costs, as respondents noted, is that 'you need more than one demonstration project', but 'everyone chickens out because the price tag is too high' (interviews, 2014).

For any technology to diffuse there must be opportunities to experiment and learn over time (Everett, 1983). Yet this is exactly what is missing in the case of CCS in the US. As one respondent made clear:

> We lack operating experience .... With operating experience prices come down. We are starving for operating experience with CCS, we don't have that at the moment. (Interviews, 2014)

With too few demonstration plants and little opportunity to learn over time, the reliability and price of CCS technology will remain an impediment to widespread deployment at a commercial scale. This problem is magnified in the case of CCS because it is not just one technology, but three technologies – capture, transport, and storage. For instance, there are three competing technologies for carbon capture, and it is as yet unclear what will be the most competitive, which will make replication across demonstration plants slower (Haszeldine, 2009, p. 1684; Lelong, Currie, Dart, & Koenig, 2013, p. 26). As a result, existing timelines for the deployment of CCS will also need to be re-considered (IEA, 2013a). For example, as one respondent who has been associated with the Kemper County project pointed out:

> Even the Mississippi plant will require further testing for five years, to 2020. Then you have to test this technology on one, two or three new plants. And that is five years for each of those plants ... (Interviews, 2014)

As noted, the IEA has called for many more than three plants, suggesting that 100 CCS projects will be required worldwide by 2020.

The US energy market is also hindering the commercial development of CCS, which is unlikely ever to be commercially viable without a substantial carbon price or equivalent subsidy (Haszeldine, 2009, p. 1650; Stephens & Jiusto, 2010, p. 2029). Yet, in the current US energy market, the problem is not only investment in demonstration plants, but perhaps more importantly, it is investment in coal-fired power plants themselves. The structural decline of coal in the US energy market, and uncertainty about its future, given the shale gas revolution, has probably reduced the appetite for investors to fund new plants, which can require up to three decades to amortise the costs (interviews, 2014).

Over the last two decades, coal has experienced a sharp decline in the US. Its share of electricity generation has fallen from more than half in 1990 to just over a third today (IEA, 2013b, p. 159). The impact of the shale revolution and falling gas prices has been dramatic. Between 2007 and 2012 the share of the contribution to electricity net generation by gas increased from around 20% to 30%, largely at the expense of coal (EIA, 2015). As those in the coal industry were quick to concede, ‘the shale revolution became so prolific and cost-effective it changed the competitive market for coal’ (interviews, 2014). Furthermore, as others have pointed out, this has negatively affected the investment environment for coal plants (interviews, 2014). In addition, most projections ‘expect this trend to continue’ (IEA, 2013b, pp. 159–160; Lelong et al., 2013, p. 23). This is compounded by the fact that electricity demand in the US has flat lined, and gains in energy efficiency are expected to offset any increase (EIA, 2014).

Finally, as coal industry respondents pointed out, in an energy market with falling coal prices and flat demand there is little justification for new coal infrastructure (interviews, 2014). In the absence of a substantial increase in existing US government funding, this leaves the utility sector to lead the investment on CCS technology, as Southern Company has done. However, given the cost and delays of Southern Company’s ventures, this seems unlikely. As one respondent argued, ‘it is not the role of utilities to keep the coal industry alive’ (interviews, 2014). Although coal is still the dominant fuel in the utilities sector, there is a growing recognition of the need to diversify. One of the first movers has been NRG Energy, a large US utility, which has announced plans to reduce its coal purchases by approximately 25% (Gross, 2014). While NRG Energy remains an outlier in the industry, for utilities that are maintaining their investment in coal, CCS technology continues to be a high-risk investment, given the immaturity of the technology. Unlike the wildcatters in the oil and gas industry, there is not the tradition of risk taking in an industry where utilities often have a monopoly position with near-guaranteed returns. As one utility noted, ‘this is a cautious industry when it comes to taking risk – it is a steady return type of business’ (interviews, 2014).

The US regulatory environment is further restricting the likelihood that new investments will be undertaken in coal-powered generation, limiting the possibility that CCS technology will be demonstrated at a commercial scale. Since President Obama came to power in 2008, the US Environmental Protection Agency (EPA) has instigated a series of initiatives to address air pollution, which have, and are likely to have, a direct impact on the US coal industry. The Mercury and Air Toxic Standards (MATS), which were finalised in 2011 and are being implemented in 2015, aim to restrict specific pollutants from coal plants over 25 MW. While some respondents argued that this will lead to widespread closures of coal-fired plants and damage the industry, there is no evidence to suggest that it has severely affected the profitability of the industry, and most estimates suggest that the MATS regulations will result in around 20 GW of coal-fired generation being shut down (IEA, 2013b, pp. 159–160; Lelong et al., 2013, pp. 5–6). More importantly, in 2013, President Obama outlined his Climate Action Plan, which aims to reduce US GHG emissions from power plants by 30% by 2030 (The White House, 2014). As part of the plan, the EPA has proposed rules for existing and new power plants. The latest revision of the rules issued in September 2013 limits new plants to emissions of 499 kg/MWh. In effect, the proposed rule would require all new plants to be equipped with CCS technology (EPA, 2013; interviews, 2014).

Respondents in the industry broadly described the rules as an 'unprecedented' attack on the coal industry, but it remains to be seen what the ultimate regulations will look like (interviews, 2014). The proposed regulations are not due to be implemented until June 2016, and they are almost certain to face a legal challenge. In the long US tradition of 'adversarial legalism', those in the industry had no hesitation in pointing out that they are already working on technical comments to 'build a record for the courts . . . to undermine the legislation' (Kagan, 1991; interviews, 2014). Whether they will be successful is another question, and may take years of litigation to answer, but the 'uncertainty alone is detrimental' (interviews, 2014).

This is the problem for the development of CCS technology. In the short term, the proposed EPA regulations are having a chilling effect by reinforcing the impact of the energy market that investment in the coal industry and associated technology is a high-risk investment. As one utility company observed:

> Our big concern is that courts will decide this but in the interim we have to make investments and we need to be sure that we can recover our costs – we need to be able to make the argument to Wall Street. (Interviews, 2014)

This observation is not an outlier. A recent report by GoldmanSachs stated that 'investment in new coal-fired capacity can be discouraged simply by the risk of new regulations, such as the rules under consideration by the EPA' (Lelong et al., 2013, p. 20). The ultimate effect of the current regulatory environment therefore is to hinder CCS demonstration and deployment for the simple reason, as one generator put it:

> If you can't build new plants, you can't test [CCS] technology and make it reliable and affordable. (Interviews, 2014)

4. Conclusions and policy implications

China's continued reliance on coal and its planned increasing reliance on shale gas in turn rely heavily on the commercialisation of carbon capture and storage (CCS) and the large-scale deployment of fracking technologies in China. CCS and shale gas were both expressly mentioned as areas of greater cooperation by presidents Obama and Jinping in their joint announcement on climate change of November 2014 (The White House, 2014). Statements of cooperation from the world's two largest economies are always welcome, but the evidence presented here indicates that CCS and the shale gas revolution are unlikely to find their way from the US to China through cooperation, transfer, or more general spillover processes.

First, the shale revolution that has transformed the US energy market would not have been possible without the innovations in fracking technology. To varying degrees, four factors were crucial: the geological structure of US shale resources; a distinctive wildcatter subculture within the US oil and gas industry; the existing industrial and financial infrastructure; and the regulatory environment. None of these factors will be easy to replicate in China, especially the wildcatter culture of the independent oil and gas companies and their history of experimentation with fracking technology. To put it simply, in the US it has taken more than half a century and 200,000 wells to establish the shale revolution. In comparison, China began research into shale exploration only a decade ago, and the first exploration activities did not commence until 2009 (Wu, 2014, p. 8). In addition, Chinese shale exploration has been dominated by large state-owned companies, such as Sinopec, which do not have the same tradition of risk taking (EIA, 2013). Clearly, the fracking revolution in the US cannot be transferred to China in some simple turnkey fashion.

Second, whereas the unique institutional environment in the US made the shale revolution possible, in the case of clean coal it appears that the opposite is true. Three factors are crucial; the failure of the industry to successfully demonstrate CCS technology on a commercial scale, the structural decline of coal in the US energy market, and the existing regulatory environment. The result is that there is little, if any, appetite in the US for investment in new coal plants or CCS technology for the foreseeable future. While the US still has more large-scale CCS projects (a total of 19) running than any other country in the world (Global CCS Institute, 2014, p. 47), as some respondents pointed out, the number of CCS demonstration plants in the US has not reached a level that makes the commercialisation of CCS a likelihood. Other countries studying the US CCS experience should reflect on the fact that US institutions of innovation, which have delivered a track record of successful post-war innovation not matched by any other country, have had comparatively little success with CCS, at time when its development has been seen as urgent. Moreover, Southern Company's experience of cost blowouts with CCS technology is likely to deter investors from supporting proposals for new coal-fire electricity units, thereby reducing the demand for clean coal technologies. In addition, the US Environment Protection Agency, under the Obama Administration, has continued to push plans and proposals aimed at cutting carbon emissions from the power sector, placing even more regulatory pressure on coal.

In short, if one concludes that there are deep institutional barriers to the arrival of CCS and the timely arrival of the shale gas revolution, then the case for further intensifying one's efforts on policy initiatives such as carbon taxes, emissions trading, and feed-in tariffs, as well as ratcheting up the targets around renewable energy, becomes much more compelling.

Disclosure statement

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