The early development and deployment of FGD in the US (1960s–1970s)

Final case study report as part of Work Package 2 of the UKERC project: 'CCS – Releasing the Potential?'

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Summary of key findings

The future economic and financial viability for private investors is one of the key uncertainties of Carbon Capture and Storage (CCS) (Markusson et al., 2011) and it will determine the willingness to invest in CCS as well as influence the willingness of regulators to promote its use through regulation. Consequently, the improvement of the technology's economic and financial viability is also an important rationale for policy support.

This case study is about the development and deployment of flue gas desulphurisation (FGD) technology in the US. The case study covers the period when the technology started receiving serious attention and investment in the US from the mid-1960s to the late 1970s. The focus of the case study is on economic and financial uncertainties.

The period chosen was when the first large scale plant got built, and based on that and other evidence, regulators decided to introduce a technology forcing emissions performance standard which signalled the need for FGD and opened up the market. Litigation created policy uncertainty and delayed investments. Ultimately, the standard stood up against the challenges. Subsequent regulation enacted in 1979 was more stringent and designed in a way that was effectively an FGD mandate.

FGD costs rose five-fold in the period studied, due to unforeseen – and in part unforeseeable – problems relating to technical issues, as well as technology transfer and the management of technical variety. This rise in costs was much bigger than that predicted at the time when the first large plant came on line.

Financial risk was not a key problem for the investing utilities. The utilities operated on regulated, regional monopoly markets, and were allowed to pass on abatement costs to their customers. The main investment risks related to technical, cost and policy uncertainties. Under this governance regime, the utilities were able to raise the funds to build FGD plants without subsidies. The regulation stood up against the legal challenges, and was in the end sufficient to force development and large scale build, which contributed to technical learning and, eventually, the stabilisation of costs.

The government policy strategy was two-pronged, with both forcing regulation and support for Research Development and Deployment (RD& D). Government had important roles in establishing Research and Development (R&D), and test centres, as well as providing impartial and comparable data on technology variants, encouraged information exchange.

The case study suggests that CCS technology development could be forced through regulation, but that technology forcing might increase the overall abatement cost in the short run. On the other hand and in the longer run, a mature technology could be made available to abate CO_2

emissions from fossil plants, a development which may not happen otherwise. Achieving the necessary policy certainty is not easy though, and technology forcing, like any stringent policy, comes with a high risk of industry protest. It is worth noting, however, that CCS is not yet in the position FGD was in 1971 with the first few large scale FGD plants on power plants already in operation. The case suggests that at least a period of operating experience from a few large scale plants may be necessary before technology forcing can be undertaken with some confidence of success. Also, since the UK market is so much smaller than the US one, it might be more effective to force CCS technology at the EU level to sufficiently entice suppliers, especially if several technology variants are to be developed.

It is very difficult to foresee all cost drivers of a technology before it is mature, for example from the difficulties of transferring technology and expertise from other sectors. There is a need to be sceptical of current cost estimates for CCS, produced before there is even one large scale, integrated CCS system. Cost rises and unforeseen technical problems emerging can be expected, even after the first large scale systems have come on line. Moreover, FGD is mainly an analogue for CO_2 capture, and forcing the development of the entire CCS system is arguably more difficult to manage and predict than FGD was, suggesting that costs are even more likely to rise. Claims that we are on a 'learning curve', with costs likely to go down in the near term are not plausible. Also, CCS costs are larger as a fraction of the cost of building and running a power plant, meaning that even small errors in cost estimates could have bigger financial impacts. That said, government could play an important role in providing impartial and comparable data on CCS technology performance and costs to inform both policy making and private sector decision making.

The main difference between FGD in the US in the period studied and CCS in the UK today is the different governance regimes. Financial risk will play a bigger role for CCS, unless steps were to be taken to re-regulate the power market, since power companies are likely to find it more difficult to pass costs on to consumers under a liberalised regime.

1. Introduction

This case study is about the development and deployment of flue gas desulphurisation (FGD) technology in the US. The case study covers the period when the technology started receiving serious attention and investment in the US from the mid-1960s to the late 1970s. The focus of the analysis is on economic and financial uncertainties.

The future economic and financial viability for private investors is one of the key uncertainties of CCS (Markusson et al. 2011). A technology is economically viable if it has a positive (private) cost-benefit ratio. Even if a technology is economically viable, that does not necessarily mean that it is financially viable because it may have characteristics that make it less attractive than investing in alternatives. Economic and financial viability will determine the willingness to invest in CCS as well as influence the scope for promoting its use through regulation.[1] Consequently, the improvement of its economic and financial viability is an important rationale for policy support.

Given that the technology does not produce saleable products – apart from CO_2 for Enhanced Oil (or Gas) Recovery (EOR/EGR) – there is insufficient incentive for companies to invest in the absence of policy, in one form or another. FGD is similar in this respect. As another environmental, public good type technology, it has also been crucially dependent on policy as a driver for investment. Some types of FGD produce saleable by-products, including sulphuric acid and gypsum, but this revenue has not been enough to stimulate development and investment on its own. This raises questions about how costs were assessed, how investment decisions were made, and how the funding for both development and deployment were raised, in terms of not least the balance between private and public financing.

FGD was developed mainly in the 1960s and 1970s in the US and Japan. By the early to mid 1980s the worst issues regarding reliability and high costs were resolved (Markusson 2011). Deployment started in the early 1970s, with subsequent waves of investments in the 1990s and 2000s. Throughout its history in the U.S., policy was key to development and deployment. The preferred type of policy instrument changed over time, with performance standards in the earlier period being reinforced with emissions trading from the mid-1990s. This changing policy style evolved as part of a broader trend towards market-oriented governance, and was paralleled (and to some extent preceded) by deregulation of power trading in the U.S. This case study focuses on the earlier period, from the mid 1960s to late 1970s. CCS is today undergoing development and demonstration, and has yet to be proven in practical use as a large scale, integrated system with power plants. This makes the earlier period when FGD was

[1] It is assumed that power companies had some influence on policy making, and that even though they were able to pass these costs on to their customers, they would have preferred not to have to do that.

demonstrated and first deployed most directly relevant. Clearly, though, the context in terms of the governance regime for power production was very different from the UK situation today. The US power industry in the early 1970s was dominated by regulated regional monopolies that could pass on abatement costs to their customers. In the later period, with a more directly relevant policy context, the technology was mature and very well established, and therefore a rather different investment proposition.

US policy makers and regulators made key regulatory decisions driving investment based on assessments of CCS costs and risks. Furthermore, under the regulated monopoly regime, the utilities were able to pass on abatement costs to their customers, and were therefore relatively less sensitive to costs. Key decisions relating to investment in FGD, based on assessments of its financeability, were not made just by utilities, but also by policy makers and regulators. This case study will therefore include cost and risk assessments and decisions made by both investors and policy makers and regulators.

The following criteria (Markusson et al., forthcoming) were used to guide and focus the analysis:

- Costs, including assessment of quality of cost data
- Key financial risks and 'financeability'
- Role of subsidies, other forms of economic / financial support, and other sources of finance

The case study draws on previous academic studies of FGD, eg by Taylor et al., (2005), Rubin et al., (2004), Shattuck et al., (2007) and Nalbandian Soud (2000). In addition to this, the case study draws on reports on FGD published by the EPA (the US Environmental Protection Agency) and its predecessors. Moreover, the case presents analysis of a compilation of data from a range of sources on FGD pilots and large scale systems in the US in the 1960s and early 1970s, as well as datasets publically available through the EIA and others. Finally, it draws on the records of law suits challenging regulatory decisions, as a useful source of data on stated arguments about perceived financial risks (due to technical uncertainty).

2. Contextual background of the case

2.1 Introduction to FGD

FGD is a set of technologies developed with the aim to reduce the amount of sulphur in the flue gases from electrical power plants. The sulphur dioxide in the flue gases forms sulphuric acid in contact with atmospheric water, which is then deposited as precipitation with a low pH, often referred to as acid rain.

The first attempts at implementing FGD systems happened in the 1930s in the UK, as a response to concerns about local impacts on grain fields (Cooper and Kyte, 1995). After a period of slow progress after the Second World War (and emphasis on high smoke stacks for dispersion), concerns about health as well as environmental impacts drove the development and deployment of FGD technology from the 1960s onwards. The US played a key role during the 1960s and 1970s, using both RD&D support and regulatory pressure to develop, scale up and deploy the technology (Rai et al., 2009). The first large scale plant in the US was built in the 1960s, but it was in the early 1970s that building rates took off. Japan also started implementing the technology in the 1970s (Nalbandian 2006). During the 1980s, wide uptake of the technology in Germany contributed to its further maturation and cost reductions (Taylor et al., 2005). Today, FGD is a relatively mature technology with over one thousand systems installed globally (Goddard, 2009).

There has been technological variety throughout the period of FGD. The most common type of FGD system today scrubs the flue gases in a mix of water and lime or limestone. Whilst this lime/limestone technology today has an 80% market share (EIPPCB, 2006), there is still technological variety. For example, there are systems using sea water or ammonia rather than lime. There are also dry systems and systems that regenerate the scrubbing agent.

In the late 1960s, it had become common practice to inject limestone into the boiler of coal plants to manage corrosion, and at the time there was great interest in a combined system, where limestone was injected into the boiler and the resulting calcined lime used in a subsequent wet scrubber process step for the removal of sulphur (TVA, 1969). Whilst wet FGD with lime/limestone received a lot of interest in the 1960s and 1970s, several other variants were also undergoing development and deployment.

As well as being part of investment projects for the building of new power plants, FGD could also be retrofitted onto existing plants.

Whilst FGD has primarily been developed and promoted as a sulphur removal option, some of these technologies produce by-products with a (limited) market value. The lime/limestone process produces gypsum, which can be used for, for example, board production (Goddard, 2009).

Investment options

FGD was one among several options available to reduce the sulphur content of the flue gases from power plants and utility portfolios. FGD competed mainly with other options to reduce emission from coal fired power plants, but to some extent also with other generation technologies (for example, natural gas has lower sulphur content).

There were some options for desulphurisation of coal-fired power. Considerable emissions reductions were feasible by switching coals, since the sulphur content in different coals (and coal-derived fuel products) could vary by more than 10 times (Ackerman and Hassler, 1980:1483). However, until the mid-70s the availability of cost-effective low sulphur coals was limited in the Eastern part of the US, where the majority of coal plants were located (Taylor, 2001:33). Imported low sulphur coal was expensive, and only after better rail transport improved access to Western, low-sulphur coals by the middle of the decade, did switching to low sulphur coals contribute significantly to abatement. Approximately half of new build utilised low sulphur coals in the late 1970s (Komanoff, 1981:234). Later, stricter regulatory standards meant fuel switching was insufficient (Taylor, 2001:48).

Moderate, 20-40%, sulphur reductions could also be achieved by cleaning the coal[2], as compared to 70-90% with FGD. In 1980, costs for coal cleaning ranged from 1-9 cent per pound SO_s, as compared to 7-45 cent with FGD (although FGD abatement costs had risen dramatically in the 1970s, whereas coal cleaning was a mature technology with more stable prices, so the difference will have been lower earlier in the decade) (Ackerman and Hassler, 1980:1483). Regulatory standards meant coal cleaning became insufficient by the end of the 1970s (Taylor et al., 2005:366).

Utilities also proposed 'intermittent control strategies', including the temporary burn of low-sulphur coals and to amend the merit order to give higher priority to cleaner plants when needed (Ackerman and Hassler, 1980:1491). Moreover, higher smoke stacks were also mentioned as a way of reducing local emissions concentrations (Ackerman and Hassler, 1980:1490), but went out of regulatory fashion during the 1970s (Taylor et al., 2001). Other options, like different combustion technologies, were only at research stage in the 1970s (Taylor et al., 2001).

In the US around 1970, there were other 'low-sulphur' investment options for power production, although coal was the dominant technology. See Figures 1 and 2 for an overview of investments per energy source.

Nuclear energy had emerged in the 1960s (Sine and David, 2003), and offered a cheaper alternative (Komanoff, 1981; Corey, 1981:420). However, public critique against the technology was growing throughout the 1960s and 1970s. Challenges included critique of the safety of the technology and its military links, but also the economic case (Gamson and Modigliani, 1989:16, 30). Significant impacts of the faltering public support included a moratorium on new build in California in 1976 (Hirsh, 1999:66-67). Construction costs were also rising from 1970s (Delmas and Heiman 2001:433). Reduced public legitimacy ultimately led to reduced government

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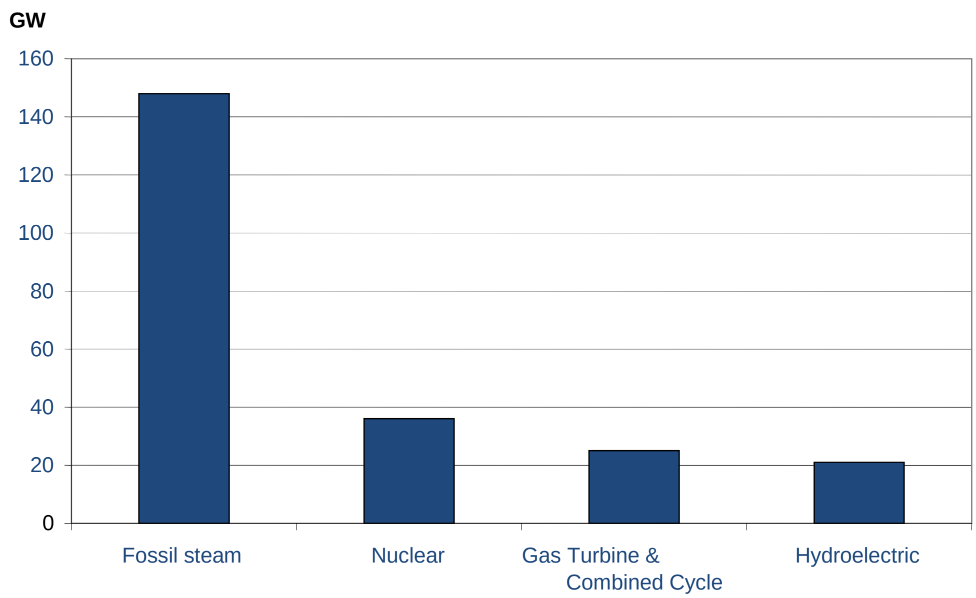
[2] Conventional coal cleaning involves the separation of different fractions of coal, with different properties, including sulphur contents. There are different technical methods for doing this.

support and hence rising transaction costs (delays to planning processes, etc.) (Delam and Heiman, 2001).

The use of natural gas (which contains virtually no sulphur) for energy purposes was also cheaper than coal fired generation (Watson, 1997). However, the first oil crisis in 1973 led to increased emphasis on 'energy independence' and political efforts to reduce the use of oil and gas for energy production (Sine and David, 2003:200). A federal law enacted in 1974 limited the use of gas for power production (Taylor et al., 2001:33; EIA 2000:115) and in 1978 new build was banned (Höök and Aleklett, 2009).

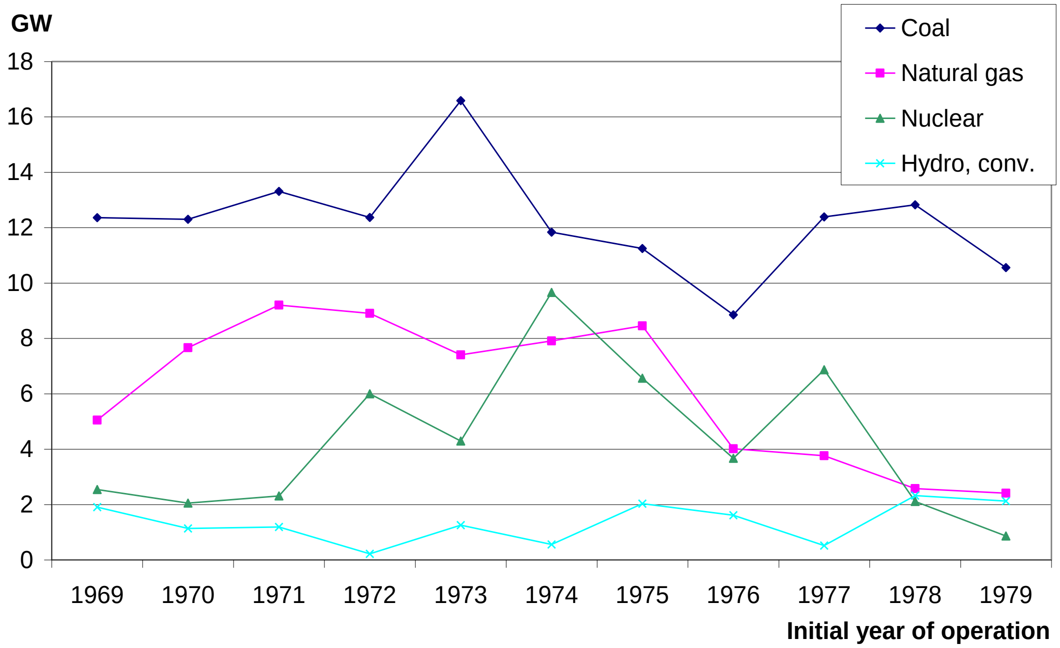
Hydro power delivered a substantive amount of power, but its expansion phase that had started before WWII came to a halt around this time (for a set of reasons unrelated to this case).

Figure 1 New build generation capacity in utilities, 1971-1980



Source: EIA 2002

Figure 2 Build rates of four main generating technologies, 1969-1979



Source: EIA 2008.
Note. The data includes application in industry as well as utilities. In utilities, coal dominated even more strongly. Cf. figure 1.

All in all, it would have appeared difficult to avoid using and building coal fired power plants. In the words of Ackerman and Hassler: '[w]ith oil scarce, nuclear risky, solar embryonic, and hydro limited, the nation's rich and cheap coal reserves [called] for exploitation' (1980:1468).

2.2 Actors

Given the key role of policy, Government has of course been a central actor. Most of the policy and regulation discussed here was implemented at federal level. Government funding of development work also played a role, at least in the early stages. The main implementing body throughout most of the case study period was the EPA. It preceded the NAPCA[3] in 1970.

State and regional bodies have also played roles. Several Western states, with easy access to low sulphur coals and keen to protect their relatively clean air, introduced more stringent regulations than those at the federal level.

The utilities were the main actors investing in the technology. This was a diverse set of actors, including public bodies and cooperatives but strongly dominated by privately-owned companies. After a long period of consolidation, a system of regulated, mostly privately-owned,

[3] Which had been re-named from National Centre for Air Pollution Control (NCAPC) earlier in the 1960s.

regional monopolies were in place in the period studied here, that is mid-1960s to late-1970s (EIA, 2000). In the 1970s, the utility industry faced a set of challenges: the oil crises and the ensuing increases in the prices of fossil fuels, inflation and problems with siting and waste handling in the emerging nuclear industry (EIA, 2000).

When considering investment decisions, the fact that most utilities were regulated, regional monopolies is crucial. There was no integrated, national power market, and the utilities faced little or no competition on their respective captive regional market. Utilities thus had secure markets, which reduced the risks of investing. Pollution control costs – both capital and operating costs – could be included in the so called 'rate base', for which utilities were allowed to charge their customers (Rose and Burns, 1992: 53-54) and FGD related costs could thus be passed on to the customers. For a regulation driven investment like FGD and on a non-competitive market, the question of what was too high a cost was a matter of negotiating with the regulator and policy makers rather than something that was determined by competition for customers on a market.

Beginning in the 1960s, environmental conservation also rose rapidly on the public agenda, and sulphur emissions controls was among the key challenges facing the industry at the time. After the introduction of sulphur control policies, deployment of FGD technology took off around 1972 (cf. Markusson, 2011).

The development of the technology was done not least by technology suppliers. In response to emerging sulphur control policy debates and proposals, industry started devoting serious attention to FGD in the 1960s. Taylor et al (2005) show how patenting took off in the late 60s. Still, in 1970, there was only one large-scale FGD system in place and only one FGD supplier: Combustion Engineering Co. The number of suppliers was to increase rapidly in the 1970s, and included: Research Cottrell, Babcock and Wilcox and General Electric Environmental Services. Most of the suppliers were domestic, but there were also some foreign supplier firms, like the Japanese Chiyoda Corporation and German Thyssen Engineering. There were also a few, as mentioned below, public sector suppliers.

An important role for this case was also played by the industries involved in supplying coal. At the start of the period, there was only a limited supply of relatively expensive low sulphur coals in the more heavily industrialised North Eastern states. The average sulphur content in the coal used was approximately 2.5% (Rubin et al., 2005:7). The emergence of a coal mining industry in western US and the rail infrastructure to transport it eastwards to challenge the eastern, high-sulphur coal, was a key development during the 1970s, and an effect of the new sulphur control policies (Whiriskey 2010).

In terms of public or collective knowledge providers, the EPA built up considerable in-house expertise, including at Triangle Park, North Carolina. The Tennessee Valley Authority (TVA), a regional, semi-public body with a wide range of responsibilities, played an important role (funded not least by the EPA) for early development and testing. TVA also regularly produced cost estimates. TVA and the Bureau of Mines both supplied technology to utilities, at least in the early days of the market.

A series of symposia on FGD held from 1969 onwards (Taylor, 2001:30)[4] played a key role for dissemination of information about the technology. EPA supported these events from 1973. EPA also had a central role in commissioning comparable data on performance, and in bringing in experience from other countries' efforts.

One part of the history also played out in the courts. The stringent policies of the early 1970s were challenged all the way to the Supreme Court. As discussed later, several cases of litigation contributed to re-shaping the regulation and to delaying compliance.

3.Case analysis

3.1 Costs and quality of cost data

This section will first give a brief overview of the evolution of FGD costs, as known with the benefit of hindsight. Thereafter the analysis will turn to the availability and quality of cost data focussing on the early period leading up to the decision to introduce an emissions performance standard based on a perception that FGD was technically (and implicitly financially) feasible. Next, the section will comment on the uncertainty in the early cost data, as seen again from the vantage point of hindsight. Finally, relative costs compared to other low sulphur generation options will be discussed, as well as the revenues from sales of by-products.

Costs

Capital costs have varied substantially over time. In the 1970s, as large-scale deployment began in earnest, costs tended to rise not least due to unforeseen technical problems (Rubin et al., 2004). Early problems included scaling (from reagent precipitation) and problems with corrosion (Taylor et al., 2005). As can be seen from Figure 3, both capital and O&M costs rose by about a factor five from 1968 to the late 1970s.[5]

FGD represented a limited but rising fraction of the cost of new coal plants. The available data suggests that to abate an average sized coal fired power plant of 500MW would have costed an

[4] Called 'Lime/limestone symposia' at first, and only later 'FGD symposia'.

[5] In the case of O&M costs, the five-fold rise happened in an even shorter period of time from 1972 to the late 1970s.

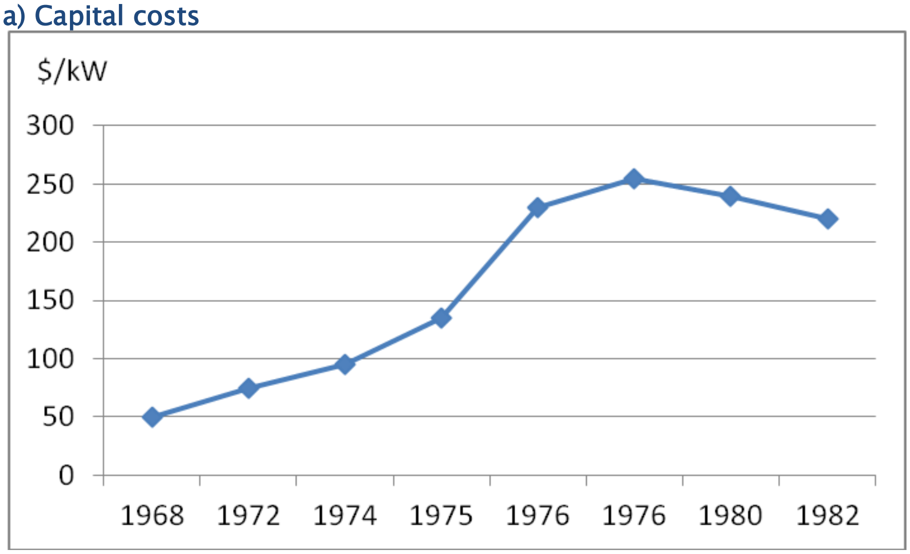
additional 6–7% in capital expenditure (as well as the additional operating expenditure) in 1971. Towards the end of the decade, this fraction had risen to around 20%. (Komanoff, (1981:217) cites 26% for the mid-1970s; Joskow and Rose (1985:20) cite 15% for 1980).

The key technical problems were later solved (reduced) through research, testing and the accumulation of practical experience (Nalbandian Soud 2000). During the 1980s, capital and operations costs came down. See Figure 4 for capital costs. This took place mainly in the US and Germany (Taylor et al., 2005).

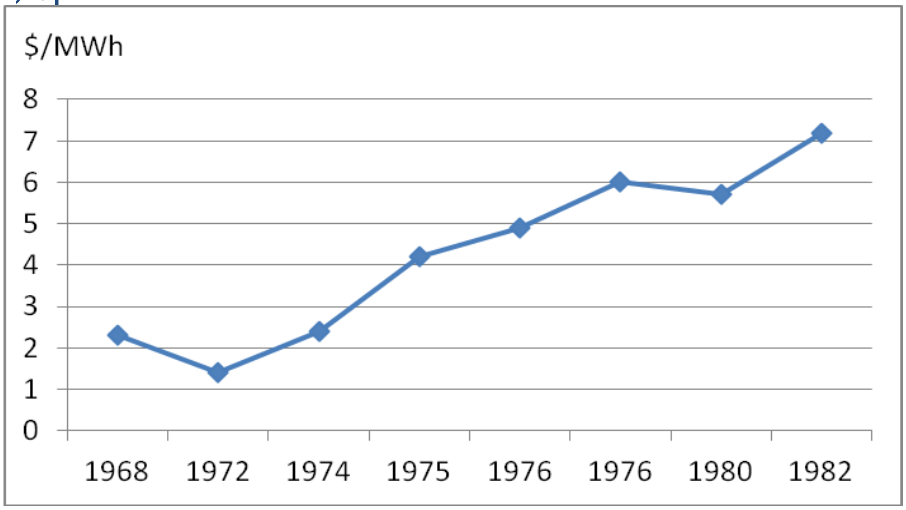
FGD costs also varied across build approaches and technology varieties. Retrofitting was 25–30% more expensive than new build (Taylor, 2011:38). There were cost comparisons across technology variants published. A TVA report from 1969 compared wet and dry lime/limestone scrubbing, and concluded that dry FGD had a lower capital expenditure, and would be competitive with wet FGD when lower abatement rates were acceptable (TVA, 1969:9). A 1971 report compared a set of twelve technology variants, with lime and lime stone scrubbing being the cheapest at 10–11% added cost of power, and zinc oxide, ammonia scrubbing and citrate FGD as the runners up, all at 16–17% added cost of power (The MW Kellogg Company, 1971:9).

Figure 3 Early costs of wet FGD systems

a) Capital costs



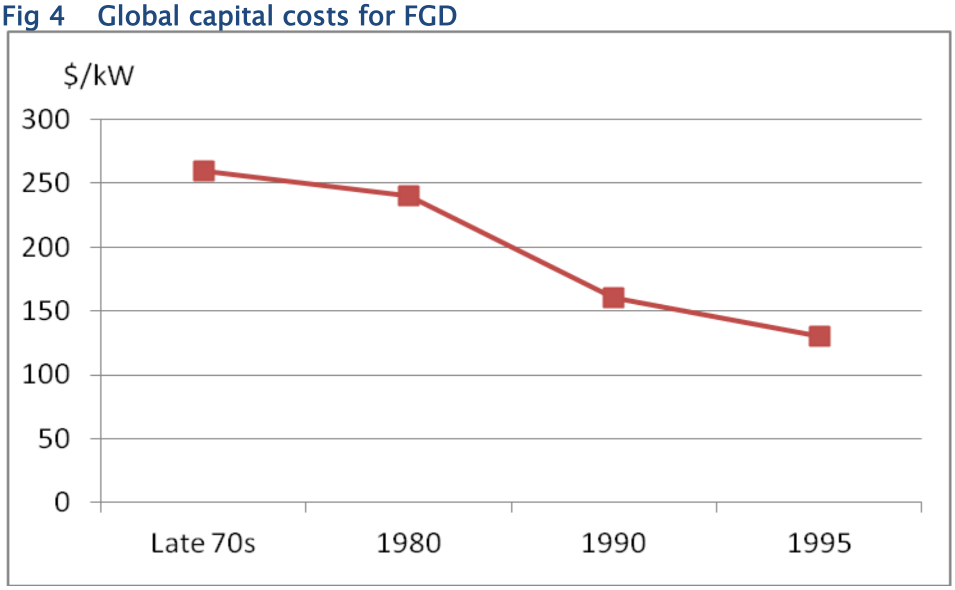
b) Operations and maintenance costs



Source: Rubin et al. (2004)

Notes: Data for wet FGD, new coal-fired power plant in the U.S. 1997$. Source does not indicate variation in costs.

Fig 4 Global capital costs for FGD



Source: Taylor et al. (2005)

Notes: Source does not indicate variation in costs. Costs given in 1997$.

The quality of cost data

The regulator commissioned TVA in the late 60s to produce cost estimates for FGD systems. The TVA produced a series of reports on conceptual designs and cost of different varieties of FGD:

- dry FGF in 1968,

- wet FGD in 1969,
- ammonia in 1970 and
- magnesia in 1973

(TVA, 1973:v).

The 1969 report on wet FGD stated as the result of the analysis of its base case a capital cost of 13.05 $/kW and an operating cost of 0.49 $/MWh (confer Figure 3 above). The report drew on various sources of information, including data provided by the Central Electricity Generation Board and Imperial Chemical Industries in the UK, as well as other early experiences from pilot plants. The pilot plants included in-house efforts at TVA, as well as early trials with wet FGD by Combustion Engineering and Detroit Edison in 1966 and 1967 (TVA, 1969:12). The report focussed on the technology variant combining limestone injection into the scrubber with a wet scrubbing step, and for the injection part of it also drew on experiences from Germany and Japan (TVA, 1969:11). The first large scale FGD plant in the US came on line in 1969, and the study did therefore not have access to data or any substantial operational experience from that plant.

The lack of experience of constructing and operating large scale FGD wet scrubbing systems with lime/limestone meant that a key source of information was the approximately 35 year old data from the ICI-Howden work on cyclic lime FGD in England (Fulham). The English experiences were drawn on not least with regard to how to combat scaling. Experience from water scrubbing type FGD systems like the one at Battersea power station in the UK was also relevant with regard to dealing with corrosion and other problems (NAPCA, 1969:109).

The report from 1969 sought to analyse the uncertainty in the cost estimates. The analysis shows that the estimates for both the capital and O&M costs varied by as much as a factor 3.2-3.3 from the lowest estimate to the highest, depending on the assumptions made, including about the fuel used and the scale of the system. '*These considerations show the wide range of costs that might be involved in applying the wet-scrubbing process to various plants, which makes economic generalization difficult*' (TVA, 1969:63).

The report also declares the lack of experience in terms of technological variety. Only data for two types of scrubbers (with hollow spheres or glass marbles) were utilised, whereas proposed designs included many other varieties, listed in the report.

Finally, the report shows the difficulty in assessing the effects of cross-sectoral technology transfer. It states, in the context of comparison between dry and wet systems, that:

> '*The dry system has the advantages of simpler operation, less tendency to operational upset, and having operating steps that are similar to those already practiced in the power plant (grinding, injection, dust removal). The wet process is a somewhat complicated chemical operation, requiring closely controlled operation of a type foreign to power plant*

practice. However, these difficulties are not subject to quantitative evaluation.' (TVA 1969:63).

The TVA was to become an authoritative voice regarding FGD. Through the commissioning of these studies (on wet FGD with lime/limestone and other varieties), TVA was given the role by government as an expert body. It was also involved in research and pilot studies, together with the NAPCA. Later, in 1972, the TVA hosted the Shawnee test centre, which came to be seen as important in FGD development efforts (Taylor, et al., 2005). The cost study analysed here was a relatively early part of this process, but it drew on some of the best available expertise and experience of the time, and has to be regarded as a good indication of how FGD costs were perceived – at least in terms of the publically available material at the time.

Furthermore, other cost estimates reported at the time were in the same range. Where the TVA report from 1969 had reported a $13/kW capital cost, a subsequent consultancy report commissioned by NAPCA reported in 1970 a capital cost of $15/kW (Envirogenics 1970b: 68). Another firm reported $10.8/kW to the EPA in 1971 (MW Kellogg, 1971: 9).

In 1970, the federal Clean Air Act Amendments (CAAA) legislation was introduced, which required the EPA to establish air quality standards for SO_2 (Taylor et al., 2005: 357). These standards formed the basis for State Implementation Plans (SIPs) that regulated existing coal fired plants. In 1971, the EPA also introduced the emissions performance standard: the New Source Performance Standard (NSPS) for new power plants. Together, these regulations were to kick-off FGD deployment. The cost estimates mentioned above was the kind of numbers available to the policy makers and regulators at the time these policies and regulations were designed and decided. At the time, there were no substantial amount of data from large scale FGD plants in operation.

With hindsight

Given the extensive problems encountered with the operation of these systems, and the ensuing growing O&M costs, the omission of trying to analyse the difficulties in operating this unfamiliar technology was an important gap in the analysis. Later experience also showed that the scrubber designs included had serious problems (Shattuck et al., 2007), and experience of other scrubbers would have been useful, but was not available at the time.

The analysis of the TVA report indicated a cost variation of just over 300% (a factor 3). As we now know, costs increased by about a factor 5 in the first 10 years (confer Fig 1 above).[6] The TVA cost range thus did not include the kind of rise experienced in the 1970s.

[6] Inflation has been taken into account.

This could in turn be compared with the 'revealed error' in the 1990s. Ellerman et al., (2000:235) show that capital costs were about 40% lower than expected in the mid-90s, when the first boom in build driven by the introduction of emissions trading happened. The cost uncertainty in the 1990s was much lower, for the mature technology.

This analysis suggests that the cost variation indicated by the TVA report was about as accurate as could be produced at the time, within the limitations stated in the report. But it was limited by the experience available. And some sources of uncertainty that were not – and at least in some cases could not be – analysed, later turned out to be important cost drivers. Such problems included managing technological variety, dealing with technical problems like scaling, and managing operations of a kind of chemical process that was new to the power industry.

Relative costs

To understand what these perceived costs meant for the 'investability' of FGD, we need to consider also how these composts compared to the costs of alternative abatement options. As discussed above, other generating technologies with low sulphur emissions were available. Both natural gas and nuclear technology was growing in importance, and were seen to be cheaper. However, both were politically sensitive, and increasingly so in the period studied here, which restricted their feasibility as investment options, and reduced their competitiveness.

There were also low sulphur options for coal plants. Low-sulphur coals were not easily available (in the Eastern US) and expensive until the mid-70s. Coal cleaning was cheaper than FGD. Other cheaper options, like higher smoke stacks and intermittent operation were also considered in the early 70s. However, due to the regulated monopoly regime, abatement costs could be passed on to customers, making the utilities less sensitive to these cost differentials.

Actual FGD investment will be discussed in the next section, after considering also the key risks relating to these investments.

By-product revenues

To understand investment, it is also of interest to understand the revenues available from the sale of by-products. There are several by-products with an economic value (from different technology varieties) including: gypsum (calcium sulphate), elemental sulphur and sulphuric acid. Applications include building materials and fertilizers.

By-product revenues could make a substantial to production costs. The MW Kellogg Company (1971) estimated that the sale of sulphuric acid (from for example magnesium scrubbing) could offset up to a third of production costs, but that wet lime/limestone was cheaper (without considering any by-product revenues). Envirogenics (1970a:211) estimated that by-product sales might as a best case offset all of the operating costs for some technology variants. Later in the 1970s, gypsum from wet lime/limestone technology played an important role in offsetting costs (Taylor, 2001:72). By-product revenues thus clearly mattered for assessments of FGD ‘investability’, and for technology choice.

3.2 Key financial risks and ‘financeability’

This section will look at the risks considered in relation to decisions to invest in FGD systems. Since abatement costs could be passed on to customers, financial risks as such were not the main risks. Rather, uncertainty and risk relating to technology, costs (and revenues) and policy & regulation dominated. Since the relevant decisions were taken both by the regulator (and the policy makers) and by the utilities themselves, this section will look at how risks were perceived in both the decisions underlying the introduction of the 1971 sulphur regulations, and the decisions behind the first ‘wave’ of FGD systems in the early 1970s.

Risk assessments and regulatory decisions

The Clean Air Act of 1970 specified that air quality standards were to be brought in irrespective of considerations about economic or technical feasibility (Taylor et al., 2005: 357). Nor was the 1971 NSPS for new plants a technology standard but allowed compliance using different methods discussed above. However, the regulations had a basis in technology as the EPA had to assess which control technologies were adequately demonstrated to be deployed by utilities (as explicitly specified in the CAA for new plants). The standard set required further development of FGD technology was intentionally set as a technology forcing standard (Taylor et al., 2005, Rai et al. 2010). The regulations reduced technical uncertainty as they stipulated the emissions level permissible, which limited the options available, but since FGD was not a mature technology at the time a degree of technical risk remained, and was ‘built into’ the standard.

The sulphur regulations were the subject of several court cases, brought by industry, NGOs and other stakeholders. Industry claims were about the regulation being too harsh, the technology too immature and too costly. Publics, in the form of local communities (for example Navajos in Arizona) and environmental NGOs (for example the Sierra Club), did play a role. Based on their concerns about air quality, they contributed to litigations aiming to defend or even raise the ambition of the regulations.

These litigations caused uncertainty about the regulation and the underlying policy. The legal challenges and ongoing debates meant that there were clear prospects at the time that the regulation might be changed. The 1970/71 regulations by and large stood up to the legal challenges until a new amendment of the CAA in 1977 and an ensuing new NSPS entered into force in 1979 (Taylor et al., 2005:45). However, the litigations caused delays for investments. As early as in 1974 is was clear to the EPA that most existing coal plants would not meet an original 1975 deadline (Ackerman and Hassler, 1980:1490). In 1976, only 59% of power plants were in compliance (Ackerman and Hassler, 1980:1492),

These cases also give us valuable insights into the risks as perceived by the regulators, as well as some insights into industry concerns about risks. In the previous section, we saw what kind of (limited) basis the EPA (and its predecessors) had for assessing the costs of FGD. A court case against the EPA, decided by the US Court of Appeals in 1973 addressed the matter of whether the technology was sufficiently demonstrated or not (Essex Chem. Corp etc., 1973). The decision states that a new technology does not have to be in operation yet to be considered adequately demonstrated, but also warns against subjective '*crystal ball inquiry*' into the future of a technology still undergoing development. The court specified that: '*An achievable standard is one which is within the realm of the adequately demonstrated system's efficiency and which, while not at a level that is purely theoretical or experimental, need not necessarily be routinely achieved within the industry prior to its adoption*' (Essex Chem. Corp. Etc., 1973).

The court further specified the kinds of evidence available to the EPA at the time as:

1) experience from one full scale operating unit,
2) prototype testing data,
3) literature sources and
4) the predictions and guarantees of domestic equipment manufacturers for plants under construction,

and judged this to be adequate, although they remarked that the emissions reductions performance only approached rather than achieved the standard of 1.2 pounds sulphur per MBTU (Essex Chem. Corp. Etc., 1973).

The court also lists the key aspects to consider when judging the technology to be adequately demonstrated. These aspects included – apart from emissions reduction performance – reasonable reliability and efficiency and avoiding exorbitant financial and environmental costs. The court also found that the regulator should have looked into the issue of the volumes of sludge produced in more detail (Essex Chem. Corp. Etc., 1973).

Investment outcome

The power companies did not necessarily find the technology attractive. The case discussed above included a challenge that the regulator had not conducted a proper cost-benefit analysis (although the Court disagreed about this). Generally, industry preferred using cheaper options like: cleaning the coal, building higher stacks and using 'intermittent control strategies' (see section 2.1 above) where possible (Ackermann and Hassler, 1980:1490-1).

Even after the 1973 decision discussed above, there were claims about the technology not being mature enough. American Electric Power led an advertising campaign in 1974 claiming the technology was 'too unreliable, too impractical' for utility use (Parker et al., 2008:17). Union

Electric sued EPA for backing a technologically impossible standard (as required by the State Implementation Plan of Missouri, which had been approved by the EPA), but lost out in 1976 on the basis that the CAA specifies that its standards for existing plants should be achieved independently of technical and economic feasibility (Union Electric Co. etc. 1976).

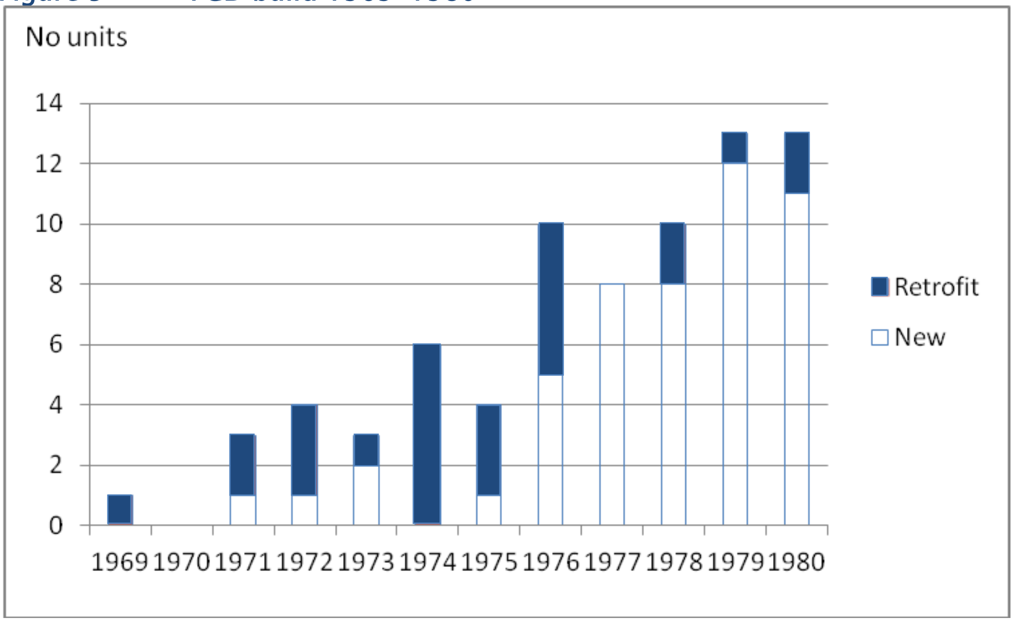
There were also uncertainties relating to input and output markets. There was a range of FGD varieties being developed in the early 1970s. Reports comparing their respective strengths and weaknesses included comments on the availability and costs of input materials, e.g. lime, as well as the possibilities of gaining revenue from sale of by-products like gypsum, or ammonium sulphate for the manufacture of fertilisers (TVA 1968; TVA 1969; Envirogenics 1970a).

The outcome in terms of FGD investments can be seen in Figure 5. The earliest years after 1969 saw mainly retrofits, with a larger number and share of new plants coming on line from 1976. Assuming an average plant size of 500MW, around 8GW were retrofitted in 1969–1975 as compared to 2.5GW new build.

This can be compared to a total coal capacity in 1970 of 255GW (Hittman Associates, Inc 1972: IV-2). Around 3% of total capacity was retrofitted up until 1975. In terms of new plants, it has been estimated that about 10% of the coal fired power plants that were commissioned in the 1970s had FGD systems (Taylor et al., 2005: 37) (Cf. Figures 6 & 7).

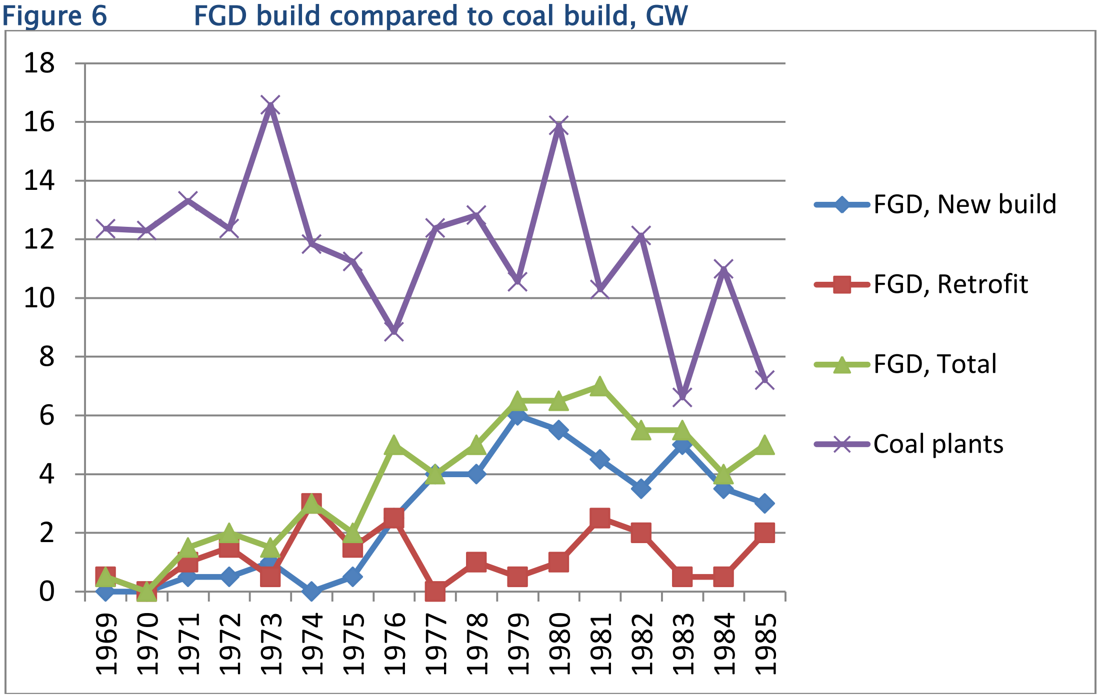
Compliance – albeit incomplete, see above – with the CAA was to a large extent achieved by the use of other, cheaper solutions, including coal cleaning and the increased use of low sulphur coals – especially as railway transport of western coals was developed during the decade, much improving the supply.

Figure 5 FGD build 1969-1980



Source: Adapted from Rubin et al. 2004:16.

Figure 6 FGD build compared to coal build, GW



Sources: Rubin et al. 2004; EIA 2008.

Notes: 1) Note that FGD on new build is a subset of overall coal build, but that FGD retrofit was likely done on older, existing plants.
2) FGD capacity estimated from average power plant size in the 1970s: 500MW.

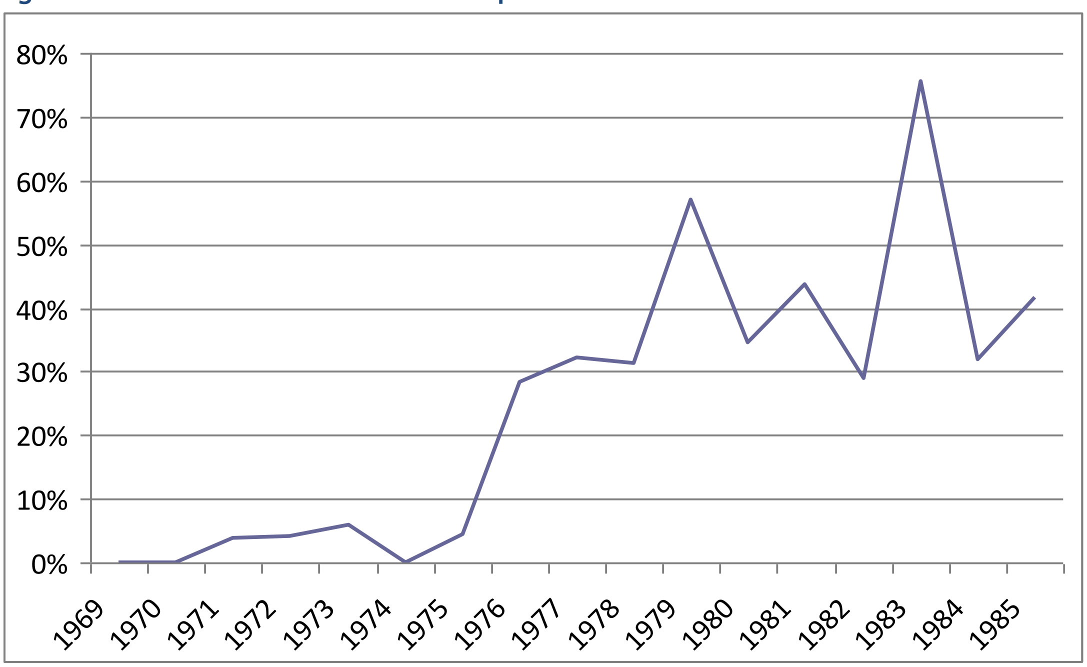
In the later half of the 1970s, with revised, more stringent regulations brought in (Markusson 2011) and cheaper low sulphur coals becoming available, the share of new build FGD increased. Around half of the new build in the late 1970s had FGD (Figure 7) with the other half opting for low sulphur coal (Komanoff, 1981:234). Unabated use of high sulphur coal for new built plants was no longer an option.

Ironically, more FGD systems were installed on power plants using low sulphur coals (Devitt et al. 1976) probably because new plants had lower emissions ceilings (1.2 versus up to 4-5 pounds sulphur per MBTU) (Ackerman and Hassler, 1908:1522), and because of more stringent state-level regulations in some states (Devitt et al. 1976).

The NSPS regulation of 1979 meant that high sulphur coals had to treated with wet FGD, but that dry FGD was sufficient for low sulphur coals (Taylor, 2001:48).

The FGD systems in operation usually achieved rather high performance in terms of the sulphur removal rate, but reliability remained low and costs high until the end of the 1970s. In fact, as shown earlier, costs grew until the late 1970s.

Figure 7 Share of new build coal plants with FGD



Sources: Rubin et al. 2004; EIA 2008.

In summary, there were a number of investment risks relating to technology, economics and policy & regulation, but financial risk as such was less important than it could have been, since the industry was governed as regulated monopolies and the utilities could pass their costs on to customers. The regulation introduced mandated a 'weakly' demonstrated and comparatively costly technology, and it seems likely that abatement could have been done more cheaply using other options, at least in the short term.[7] On the other hand, the regulation successfully forced the development and deployment of the technology, which was important for the development of GFD to happen at all, and left the US well placed in terms of supplying other countries with FGD technology.

3.3 Sources of finance, including subsidies and other forms of public support

RD&D

Government supported research into sulphur abatement methods from as early as 1955 (Taylor et al., 2005), and this support continued in varying forms and with increasing amounts throughout the period. Table 1 gives an indication (albeit not a complete time series) of the amounts involved.

Table 1 Government air pollution RD&D spending

Year	Spending	Activity	Scope
1955	$5m over 5 years	Research	Included abatement methods
1963	$95m over 4 years	Incl. research	Abatement methods
1967	$125	Research	Abatement methods
1977	$43,5m over 1 year	RD&D	Air pollution control
	1.1.1.1.1.1.1 $4,9m	1.1.1.1.1.1.2 RD&D	1.1.1.1.1.1.3 FGD

Source: Taylor et al., 2005.

Notes:

1) Amounts given in the currency rate at the time and not converted to the rate of a particular year.

2) The items in the table have varying scope, and only the last line states an amount that is dedicated to FGD technology specifically.

Government also supported the construction of small and intermediate size pilot plants (NAPCA 1969). The Shawnee test facility in Kentucky operated by the TVA was involved in pilot scale work on some technology variants from the late 1960s (NAPCA., 1969:112). NAPCA funded the TVA (and their collaborators, incl. Bechtel) to do pilot scale work. TVA was also a semi-public organisation in its own right, with considerable state-level government ownership.

[7] At least at an aggregate, national level. Local emissions might have been worse.

In 1969, wet scrubbing with limestone was the only type of process in full-scale operation in the U.S. The government, however, foresaw a need for multiple technologies, not least because of their suitability on different scales of power plants (NAPCA, 1969:101). Government were involved in supporting the R&D for most of the technologies it perceived as most promising at the time. Apart from scrubbing with limestone, it recognised alkalized alumina, catalytic oxidation and potassium sulphite (Wellman-Lord process) variants.

Other parts of government were also involved in the R&D on FGD. The Bureau of Mines was involved in the development of the alkalized alumina process in the 1960s (NAPCA., 1969:102). Both the TVA and the Bureau of Mines later supplied FGD systems (Taylor et al., 2005). Most suppliers were however private companies.

In addition to direct funding of RD&D, government financial support played some additional roles. The government supported the test facilities at Shawnee (TVA) and Triangle Park (in-house at EPA).

Moreover, the government commissioned from 1967 onwards, as mentioned above, the TVA to produce conceptual designs and cost estimates, providing publically available data, on a comparable basis across technology variants. From 1973, it supported the series of FGD symposia (Taylor et al., 2005), which was an important meeting place for those interested in FGD technology. The symposia were held in the US, but attracted participants also from other countries. NAPCA and later the EPA also facilitated international knowledge transfer, by including in funded studies reports from FGD work abroad (TVA, 1969; Ando, 1972).

Large plants

Much of the financial capital needed for deployment in the period studied seems to have been provided by industry itself. It has not been possible to source data directly describing the financing of these utility investments, but some inferences may be made from the material.

Most of the investments were made by the privately owned utilities, although there were exceptions to that rule. For example in 1969, large scale FGD systems (dry and wet scrubbing with limestone) were being installed at Shawnee test station, owned by the semi-public TVA (NAPCA, 1969:107,112).

The material used for this case study does not refer to any subsidies of FGD investments. Most of the investments in larger scale plants thus appear to have gone ahead without direct government support. They are likely to have been financed as other utility investments at the time. In general, the utilities financed their investments to a large extent via loans in this period, rather than via balance sheets (EIA, 2000:115).

As mentioned above, the regulations allowed the utilities to include pollution abatement expenditure, both capital and operational costs, in the so-called ‘rate base’, for which the utilities were allowed to charge their customers (Rose and Burns, 1992: 53-54), and costs could be passed on. This will have reduced the financial risk and facilitated borrowing substantially.

It is worth noting that FGD investments were relatively minor compared to power plant investments, but far from negligible. The fraction varied over time from around 5% to around 20% of capital expenditure. (This can be compared with CO_2 capture plant investments, which are currently estimated to be of the same order of magnitude as the power plants).

The costs of electricity production using coal rose in the 1970s. Rising costs of FGD explained most of the rise of capital expenditure in the period 1971-1978 (Komanoff, 1981:177-178, 228). Other factors contributed to overall production cost rises as well though, including the rising costs of coal (Höök and Aleklett, 2009:10).

In summary, the federal US government used both ‘carrots’ and ‘sticks’. The strategy was a combination of technology forcing regulation and support for RD&D, but no subsidies for large scale investments (apart from support for a few government-owned facilities).

4. Interaction with other uncertainties

We foresaw inter-linkages between this uncertainty and most of our other uncertainties (Markusson et al., 2011). For some of these, this FGD case has yielded insights.

Policy, politics and regulation

For a policy-driven, public good technology like FGD (and CCS), policy and regulation uncertainty will always be of key importance for investment decisions. The policies and regulations introduced under the CAA were crucial to making the FGD a credible investment option and so getting the market for FGD going. The legal challenges against the CAA-based regulations created uncertainty that delayed investment in the early to mid 1970s, showing the importance of this policy and regulation related risk.

Public support for R&D, knowledge diffusion, pilot scale tests and investments played a role, although most of the finance for large scale investments was covered by industry themselves. It was regulation rather than subsidies that mattered for investability.

Conversely, estimates of FGD costs mattered to policy making. This case shows the kind of evidence base used to make the key policy decisions.

Public acceptance

It was expected that increased costs could lead to public opposition. The costs for FGD investments and operation were no doubt passed on to utility customers. However, this study has not revealed any evidence to suggest that local publics actively protested against this.

Publics, in the form of local communities (for example the Navajos in Arizona) and environmental NGOs (e.g. the Sierra Club), did play a role. Based in their concern about air quality, they contributed to litigations aiming to defend or even raise the ambition of the regulations. The main effect of this was to reduce the regulatory uncertainty and thus to increase investability.

Safe and reliable storage

A link between safe and reliable storage and economic and financial availability was expected. However, due to the different nature of by-products from FGD processes, liabilities relating to storage were not an issue.

Up-scaling and speed of deployment

The early stage up-scaling and deployment of FGD studied here were associated with rising costs, but reduced uncertainty about costs. The rising costs were primarily caused by the discovery of unexpected technical problems. Continued development and deployment led to the resolution of these problems, and after the late 1970s, costs started coming down.

System integration

FGD does not require an infrastructure that is similar to the transport and storage of CO_2. The fate of the end-product from FGD processes was a concern, both in terms of hopes for revenue from selling the end-products from some technology variants, and concerns about disposal of the large amounts of sludge produced by other variants. The sludge was however handled locally, and posed much less containment problems. FGD therefore does not entail the same costs and financial risks as CO_2 transport and storage.

Variety of pathways

The variety of pathways had not been identified before this case study as closely linked to the economics and finance uncertainty (Markusson et al., 2011). Clearly though, uncertainty about choice of FGD technology played some role for investment decisions in the period studied, although the overall effect is ambiguous. Whilst wet scrubbing with lime or limestone was recognised early on (1969) as the most mature technology, there was throughout the period interest in and active work on – including investment in large scale systems – a variety of technologies. Given the rather rapid development and deployment in this period, it seems as if this did not seriously hinder development. It is not clear what role this variety played – it will have caused some delay as the actors tried to figure out what horse to bet on, but quite possibly also helped speed up the process as suppliers competed with different offerings, using different technologies. As discussed above, wet scrubbing was assessed to be cheap, but other varieties could compete when by-product revenues were taken into account.

5. Implications and limitations of analysis

5.1 Lessons in general

Financial risk was not very important for FGD investments in the 1970s, since most operators operated on regulated monopoly markets, and were allowed to pass on abatements costs to their customers. Investment risks related more to uncertainty about technology, cost & prices and policy & regulation.

The relative costs of FGD versus other low sulphur options mattered for investments. There was some competition from other generating technologies, but the main competition came from coal cleaning and, after the mid-1970s, switching to low sulphur coals. Later on, the 1979 NSPS made FGD virtually mandatory, thereby reducing the importance of technology competition and relative costs.

The case shows that technology forcing worked as a policy approach in that it drove the development and maturation of the technology. But the case also shows that the policy approach came with a cost, at least in the short term. More abatement per $ could have been achieved with less effective, but cheaper approaches. Especially after 1979, when the technology was virtually mandated, abatement cost is likely to have been higher than necessary.

The case also shows that industry can carry the lion share of the costs for early large-scale deployment, at least in a situation where abatement costs can be passed on to customers.

The case study shows that it was difficult to include all the relevant cost drivers in cost estimates. Costs escalated more than indicated by early cost variation estimates (5 times rather than 3 times) by knowledgeable experts. These experts were able to draw on data from pilot plants, but not any full scale FGD plant in operation.

The case also shows that publics were not concerned just by their utility bills, but also air quality. Public mobilisation and litigation helped defend the regulatory standards set. And this underpinned the policy support (as can also be seen through a comparison with the faltering support for nuclear and its weakening government support in the same period).

Industry litigation undermined the credibility of the 1971 regulations and delayed their impact on investments. Industry feared the costs of FGD. Even though abatement costs could be passed on to customers, it was presumably preferable not to incur them in the first place. And there was always a risk that the rules for what costs could be passed on would be changed. Also, the overall cost of coal based power was rising in the 1970s, potentially threatening the legitimacy of the regulated monopoly markets (Hirsh, 1999). Industry also feared insufficient maturity of FGD technology. Industry preferred to seek to gain more favourable regulation over regulatory certainty. As a policy choice, technology forcing comes with a high risk of industry protests.

Government had an important role for FGD technology development and early deployment also regarding the funding of R&D, knowledge diffusion and the provision of comparable and authoritative publicly available data.

The relationship between technical variety and costs was complex. On the one hand, there was competition between suppliers with differing technology variants. On the other hand, comparing costs across variants was difficult in the early years.

5.2 Lessons for CCS

As long as we foresee deregulated electricity markets, financial risk will matter much more for CCS in the UK than it did for FGD in the US in the 1970s. Conversely, one way to limit the impact of financial risk as an obstacle to CCS investment would be to re-regulate the UK power market. However, CCS faces investment related risks in terms of technology, costs and dependence on regulation and policy that are in some ways similar to FGD, and they will be discussed below.

Like FGD, CCS faces competition from other mitigation options. (A difference seems to be that for CCS the main competition comes from other generation technologies, unlike FGD where coal cleaning and switching to low sulphur coals were the main options.[8]). The relative cost and finance risk profiles will shape industry's response in terms of investments to any policy, unless it is a CCS mandate (either explicitly or implicitly, like the US 1979 sulphur regulations).

CCS technology development could be forced through regulation. This could be done with different policy instruments, for example a mandate or an emission standard for fossil plants set at a level which would require CCS, whereas emissions trading might, everything else equal, favour other low CO_2 options, like renewables and nuclear energy – depending on relative costs

[8] Although, coal cleaning could contribute to CO_2 mitigation, and is discussed as an important option in for example India. There is also variation in CO_2 emissions among different coals, although none has as low CO_2 emissions as the low sulphur emissions from low sulphur coals.

and risk profiles.[9] The case suggests that technology forcing would increase the abatement cost in the short run. On the other hand and in the longer run, a mature technology could be made available to abate CO_2 emissions from fossil plants, a development which may not happen otherwise, or at least much more slowly. Achieving the necessary policy certainty is not easy though, and technology forcing – like any stringent policy – comes with a high risk of industry protest.

It is worth noting, though, that CCS is not yet in the position FGD was in 1971 with the first few large scale FGD plants on power plants already in operation. The case suggests that at least some large scale plant operating experience together with suppliers willing to offer guarantees for the technology may be necessary before technology forcing can be undertaken with some confidence of success. A first 'generation' of CCS plants would need to be demonstrated before forcing CCS development is viable, or at least such forcing is less likely to succeed until that is the case. Also, since the UK market is so much smaller than the US one, it might be more effective to force CCS technology at the EU level, especially if several technology variants are to be developed.

It is very difficult to foresee all cost drivers of a technology before it is mature, for example from the difficulties of transferring technology and expertise from other sectors and managing technical variety. The case suggests that there is a need to be sceptical of currently produced cost estimates for CCS, produced before there is even one large scale, integrated CCS system. One should expect cost rises and unforeseen technical problems emerging (of a nature that likely can be resolved, but which will nevertheless cause trouble and extra costs), even after the first large scale systems have come on line. Moreover, FGD is mainly an analogue for CO_2 capture, and forcing the development of the entire CCS system is arguably more complex and difficult to manage and predict than FGD was, suggesting that costs are even more likely to rise. Common claims that we are on a 'learning curve', with costs likely to go down in the near term are not plausible. Also, CCS costs are larger as a fraction of the cost of building and running a power plant, meaning that even small errors in cost estimates could have bigger financial impacts. That said, government could play an important role in providing impartial and comparable data on CCS technology performance and costs to inform both policy making and private sector decision making.

5.3 Limitations

The most striking difference between this case and CCS in the UK today is the different modes of governing the power market. US utilities operated under a regulated monopoly regime, where negotiations with the authorities determined the price of power rather than any competition for customers on a market, and could pass on abatement costs to their captured

[9] There has been a lot of investment in FGD in the US under emissions trading during the last 15 years. FGD was then a mature, well-understood technology, and its costs much reduced since the peak in the late 1970s.

customers. This is not the case for utilities in the UK today, and financeability of CCS is therefore a much more serious concern than it was for FGD in the US in the 1970s.

Whereas FGD is a useful analogy to CO_2 capture technology, the waste/by-product treatment is quite different and the case study offers limited learning for CO_2 transport and storage. The exception may be that the use of CO_2 for enhanced carbohydrate recovery can play a similar role in offsetting some of the costs of the technology that gypsum sales has done for FGD.

The U.S. is approximately five times larger market for technology suppliers than the UK, suggesting that technology forcing could be problematic if the UK goes it alone. The UK market may be too small in itself to entice supplier to invest the resources necessary for technology development. At least, technology forcing is riskier on a smaller market.

Forcing CCS right now would be different than FGD was in 1971, since there is still no large scale, integrated CCS system on a power plant, as there was for FGD, when this policy was put in place. It could be argued that CCS is in a situation similar to what FGD was in the mid-1960s, before any large scale FGD plant had been commissioned in the US.

The costs of FGD investment and operation as a share of overall capital costs for a power plant (up to around a fifth) were much lower than for CCS today (which are estimated to be of approximately the same size as power plants, depending on the capture technology chosen).

It has not been possible, within the scope of this case study, to get hold of detailed data on the decisions made by the utilities whether to invest or not in FGD.

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