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Energétiques

Working Paper n°27

January 2010

Efficiency of policy choices for the deployment of large scale low carbon technologies : the case of Carbon Capture and Sequestration (CCS)

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Abstract : This paper analyses a set of policy instruments needed to support investment during the learning phase in the deployment stage of CCS technologies following the demonstration stage. We focus on the specific barriers to learning investment during pre-commercial deployment of large scale and intertwined technologies. We first analyze the market failures inherent to the barriers to innovation that exist in the market, which justify support during the learning investment phase and the subsequent roll out of CCS capacity in electricity generation. Then we analyze and compare the efficiency of the different ways to help support CCS technologies to cross this so-called “death valley”: command and control instruments (CCS mandates, low carbon ratios on production), investment support under different designs (direct subsidy, tax credit, subsidy by trust fund) and production subsidies (guaranteed carbon price, feed-in price, amongst others). These instruments are compared and contrasted according to four criteria: effectiveness, static efficiency, dynamic efficiency and timing (adequacy to the technology development stage). We conclude that policy instruments must be adapted to the technological and commercial maturity of the CCS system at some point between the demonstration stage and the purely commercial deployment stage. In particular mandate policies must be handled with some care. With regards to subsidization mechanisms, their design must be market-oriented, this is particularly the case with auctioning, in order to limit information asymmetries between CCS investors and regulators.

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[1] CIRED (CNRS) and LARSEN.

1. Introduction

Carbon capture and sequestration (CCS) is one of the major options being considered to reduce carbon dioxide (CO2) emissions in the future, being the most straightforward approach, if it is applied to the most emitting sector: the electricity industry. It is an essential and pragmatic solution in a world which will remain heavily dependent on fossil fuels for electricity generation whilst it tries to reduce emissions by 50% by 2050 to limit carbon concentration at 450 ppm. By 2050 fossil fuel power plants, and in particular coal generation power plants will generally have to operate with CCS.

The issue of financing the development of CCS demonstration projects has attracted much political and economic debate in regional and national carbon policy processes in Europe and North America. Some have argued that expected high carbon prices driven by future cap and trade systems such as the European Union's Emission Trading Scheme (EU ETS) would provide sufficient incentives for the demonstration projects to be developed and *a fortiori* for the next stage of learning investment (EC, Assessment Report, 2008). This line of thinking ignores the existence of barriers to the deployment of new large scale technologies, and some governments have refused to give support to large scale CCS demonstration projects.

In 2007 and 2008 a number of demonstration projects were cancelled in the UK, the USA (among these was FuturGen prototype of the official program), Canada and Australia, before new reflections on the rationale to support demo plants. At the same time some expert-activists in the USA and UK have called on governments to mandate CCS on each new fossil fuel plant and make existing (non-CCS fitted) ones close in the near future, given the importance of the climate change issue, but they have been challenged by technological delays in the development of the different capture techniques. Between these two positions, other experts have expressed opinions regarding the urgency of rapid CCS deployment in the electricity sector in order to contribute to the stabilization of CO2 concentration, as shown by the 2007 MIT report on coal which shows concerns about delays of the CCS demonstration stage (Herzog et al., 2007). IEA reports (2007, 2009) show that without the rapid deployment of CCS, concentration stabilization at 550 ppm and, *a fortiori* 450 ppm in 2050 will never be achieved. Finally in recent years it has been increasingly recognized that incentive structures are needed to stimulate at least early CCS investments in demonstration (pilot) projects (as was finally the case with the European Commission).

The issue of public support for the next deployment of CCS after the demonstration stage is not yet in the political agenda, given that commercial size demo plants are not yet developed. But when the CCS post-demonstration stage is reached, the debate will come on the need to put in place a system of new clear incentives for electricity generators. Several instruments could be used: investment subsidies, loan guarantees, production subsidies, guarantees on CO2 prices or more straightforward approaches, such as a CCS mandate on any new fossil fuel generation plants.

Conventional wisdom influenced by free market orthodoxy tends to consider policies complementary to carbon price signal as useless, as we can read in the important European Commission's Impact Assessment of the draft 2009 CCS Directive, arguing that the eventual costs of subsidization mechanisms would not be compensated by the long term social benefits (European Commission, 2008)[1]. It implicitly assumed that the roll out of CCS technology would be led by the market's demand for low carbon technologies.

Behind this restrictive position there are implicit beliefs that demonstration plant realizations will help to add sufficient learning (to the industry) and thus avoid complementary support at the next stage. But this position reflects a misunderstanding of the various barriers to CCS deployment. From this perspective market forces drawn by the carbon price, are sufficient to pull any non-carbon technology when needed and competitive. At the end, post-demonstration CCS projects should be subject to the market test including the risk of failure. If CCS does not work, there will be a greater scarcity of carbon allowances, a higher carbon price and therefore more incentives to reduce emissions elsewhere.

In fact three problems arise for the roll-out of CCS systems after technological knowledge acquisitions in the demonstration process:

- the classical market barriers to which new and complex technologies are confronted, in particular technological costs and risks,
- the market risks in liberalized electricity markets, on top of which is added the uncertainty regarding the long term carbon price which amplifies long term risks on electricity prices for candidates seeking to invest in CCS technologies,
- the amplification of barriers in the case of CCS by two factors, first the large scale of the capture technology with capital intensiveness, large upfront costs and long lead-times, and second the enormous complementarity between capture, CO2 network and storage technologies, which needs narrow coordination for reducing uncertainties and risks to the capture projects,

Ignorance of the barriers to learning-phase investment is reflected by simplisitic views on low carbon technologies reaching competitiveness by spontaneous maturation and their subsequent commercial deployment being driven solely on the basis of carbon prices. It is not too early to break with this representation and to think about possible regulatory frameworks to promote CCS technologies in electricity generation because the potential strategies of the main actors will be directly determined by the business models which could emerge from future regulations. Policy instruments have to give additional value to new CCS equipments, in the same way that renewable energy promotion policies add value to the electricity produced by renewable energy facilities, via feed-in tariffs or green certificate obligations on electricity suppliers.

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[1] We can read in the Impact Assessment of the 2009 CCS directive : " There is little evidence justifying going beyond the carbon market. For mandatory CCS, the additional learning resulting from the increased deployment does not compensate for the cost of the policy, and the impact on other externalities is also not significant. For subsidy, although substantial extra investment would be leveraged, the impact on positive externalities seems not to match the level of the subsidy. For this reason, the Commission recommends to enable CCS under the ETS, but not to make CCS mandatory or consider subsidy for the technology in the post demonstration phase. Subsidy for the demonstration phase itself is a different matter,(…)" (European Commission, 2008).

In the following section we analyze first the market failures inherent to the innovation barriers which justify a support for the learning investment. Then we analyze and compare the efficiency of the different ways to support CCS technologies to cross the so-called "death valley": command and control instrument (CCS mandate, low carbon obligation on producers), investment support under different designs (tax credit, direct subsidy by public budget or by trust fund), and subsidies to production (CO2 price guarantees, feed-in subsidies). These instruments are compared according to four criteria: effectiveness, static efficiency, dynamic efficiency and timing (adequacy to the development stage).

2. Predictable market failures for CCS learning investment

In the classical multi-stage representation of an innovation process concerning a large size technology – research and development (R&D), small scale demo plants, commercial scale demo and commercial stage -, it is admitted that government contribute to the funding (for instance under a rule of 50% of cost sharing as in the clean coal US program) under the condition of transparent information for competitors[1]. R&D and learning-by-doing creates external benefits that initial developers of new technologies cannot capture (R&D spillover in innovations that cannot be patented is an external benefit that may generate an inefficiently low level of investment in R&D because it could not be appropriate by the investors). But after the demonstration stage, the technology deployment should only be market pulled.

But this scheme ignores the importance of learning investment before the commercial maturity of large-scale technology. The learning costs during and the long length of the pre-commercial development period when multiple learning effects can still develop and interact with each other, are generally underestimated or ignored while they nevertheless generate intertemporal externalities by decreasing costs. These positive cost externalities from deploying the technology are not captured by the market.

In the case of CCS, this view must be challenged for three reasons. First, the uncertainty regarding the carbon price trend on a long-term basis could deter investment in low carbon and capital-intensive technologies. Second the characteristics of large scale and the complexity of the technological CCS system magnify learning costs and risks. The large commercial scale of CCS technologies in electricity generation, the degree of their capital intensiveness, the lead-time for equipment installation create large differences in the risk aversion of investors between mature technologies and CCS. For such large scale technologies with large upfront costs and intricate systems, as the CCS systems are, the transition from the

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[1] Even if the conventional linear scheme of an innovation process -- research-development & demonstration & commercial deployment -- is considered as simplistic (because in fact of the continuous combination between different learning and knowledge accumulation at different stages), it is quite relevant for large-scale technology development because these different stages are quite well identifiable. Indeed in large size and complex new technologies, R&D and demonstration steps with small-scale prototypes are followed by the upscaling of prototypes up to a commercial size prototype which is the first-of-a-kind unit for the first commercial series. Demonstration is the stage for developing the know-how associated to the scaling up of units, both for manufacturers and users. But if there is competition between several concepts, government have dilemma in the choice of the support policy at the demonstration stage between replication and variety. As learning by scaling-up is compatible with the choice of supporting a variety of technology, government should be able to choose this option.

technology push of the demonstration stage to market pull is a hurdle race. The chain of innovations is too long, too complex and diverse. Third, the existence of three capture technologies which will be at three different stages of technological development at the end of the demonstration stage presents the risk of a lock-in on the second best or third best technology if any support.

Box 1. The EU program of CCS support at the demonstration stage

The 2009 CCS Directive creates a favorable environment for the demo plants. It enables CCS as a non-emitting technology and so creates incentives by internalization of Carbon externalities in fossil fuelled technologies, and it defines two ways of EU support dedicated to demonstration projects. First there is a direct funding mechanism for demonstration plants. European Union has voted in January 2009 for its demonstration program of CCS plants (the EU technology platform for zero emission fossil fuel power plants), with a number of objectives: acceleration of learning, technological and geographical diversity. The demonstration projects must be at a scale that will allow the next project to be at the commercial scale (It combines a EUR300 million coming from the reserve allowances on the two years next after the EU Emission Allowances auctioning, and a surplus of EUR1000 million on two years for twelve projects in electricity in the framework of the Economic Recovery Program). Second there is a reward to these first projects by attributing to them emissions allowances corresponding to those avoided by the equipments. It will add a carbon value to the value resulting from carbon saving of each CCS plant. Specific additional domestic support will complement the European support without considering that they will conflict with competition law. But the European policy is not committed into a clear-cut support to CCS learning investments after the demonstration stage. It will be specific to demonstration projects.

2.1. Deficiency of internalization of externalities of competing carbon emitting technologies

The application of CCS technology to coal (or gas) generation leads to increased costs of electricity coal generation due to added capital costs of the capture transportation and storage facility, as well as operating costs due to the additional cost of the extra fuel consumed. It needs the internalization of CO2 cost in classical coal and gas generation to become competitive with the latter. With increasing carbon price emanating from internalization policies, CCS projects will benefit from non-payment of CO2 allowances by the generators, as soon as CCS can be legally considered as a non-emitting technology. Net present value of projects will be provided by avoided CO2 allowances after payment for CO2 taken away and CO2 storage[1]. If CO2 cost internalization occurs by establishing a sensibly high and foreseeable trading price for CO2, a special support scheme for non-carbon and capital-intensive technologies such as CCS should no longer be necessary. Taxation has proved to be a very effective incentive to encourage CCS operations as concretely shown by the Norwegian experience where a CO2 tax equivalent 50$/tCO2 on electricity generation encourages combination of CO2 capture and with enhanced recovery projects (von Alphen, 2008).

But the incentives by carbon market prices resulting from cap and trade instruments are fundamentally uncertain. Indeed there are two difficulties inherent to the carbon

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[1] Full auctioning of CO2 certificates will be in place in the EU ETS after 2012, and CO2 which is captured and stored will be regarded as non emitted, CO2 certificates will not have to be purchased by the CCS operators. Moreover when some CCS projects will be developed in relation with enhanced recovery oil, downstream EOR gains could be valued too.

policy based on “cap and trade” schemes. Firstly it introduces both a short-term volatility risk on the CO2 price if they are ill designed (for instance no banking between periods, no long term attribution allowing long view hedging policies on the opposite of the US SO2 cap and trade system). CO2 price risk associated with the volatility of any trading scheme allowance price, increases market price risks and can actually adversely affect all non emitting technologies, CCS, nuclear or renewables. Because marginal plants on electricity markets are fossil fuelled, power prices and CO2 prices are highly correlated, which implies that fossil fuel generation without CCS which will set the power price is largely hedged against CO2 price risk, contrary to CCS and nuclear plants.

Second a long-term uncertainty related to the vagaries of the stringency and long-term commitment to climate change policy (Ellerman, 2006). CO2 price risk is largely political in nature, depending on the results of international negotiations at the respective EU and international levels, and within this context investors may find it particularly hard to implement/design the appropriate hedging strategies (Grubb and Newbery, 2007).

Investment choice theory under uncertainty shows that the revenue threshold that triggers investment is higher when uncertainty is high, thus giving an option value to the postponement of the investment decision (Dixit, Pindyck, 1994). Price volatility creates disincentives for private companies to invest in non-carbon technologies. With investments that can mount to well over EUR500 million, there needs to be a clear understanding of the long-term value of CO2 and the mechanisms that will be used to determine it. Cap and trade will not give a sufficiently high carbon price in the mid-term future; more generally it will not guarantee price signal stability in the case of carbon cap and trade systems. Existing caps, such as those within the EU ETS and in proposed bills in the USA, are not stringent enough to trigger the high and sustainable CO2 price levels that would result in substantial CCS investments. The benefits of reducing carbon emissions to be drawn on the market are not sufficient to outweigh the costs of CCS and the market barriers.

Emissions trading systems only favour technologies closest to maturity, but do not trigger new innovative development (Sanden and Azar, 2005). Moreover it seems unlikely that cap and trade will facilitate near-term deployment of CCS because the cost of capture and storage is initially higher than the mathematical expectation on allowance price in the next decades. Even if the price of carbon were to be established at high and stable levels, for instance at €50 to 70 per ton of CO2, price levels at which studies tend to show that CCS would be economically viable (MIT, 2007, IEA, 2009), there is some doubt that this price anticipation would be sufficient to trigger CCS investments.

2.2. Learning barriers of CCS systems

Even if they can be potentially competitive with the help of high carbon and fossil fuel prices, emerging technologies meet certain difficulties for competing in existing markets because of different learning barriers inherent to large scale and nested new technological systems which are increased by the riskier context of liberalized electricity markets.

From a general perspective, learning in large scale technologies have not the same profile than small scale and technologies that can be standardized (Sahal, 1985). During the roll-out of a technological system composed of large scale technologies, learning by doing occurs from replication in the production of equipment and accrues to manufacturers and suppliers. Equipment manufacturers that will benefit from this learning are often international firms and they are limited in numbers. But the scale of the technology introduces a dimension of firm-specific knowledge for large-scale components as well as for architect-engineering. Consequently know-how and technological knowledge tend to be firm specific and quite difficult to diffuse between competitors. Second specificity, standardization and series effects will be heavily restricted by evolutionary regulation and risk of permanent retrofitting. The same is true with specific national regulatory approaches which limit the diffusion of learning between different markets. This issue which has been largely documented in the nuclear technology case (Bupp & Derian, 1978; Koomey and Hulmann, 2007) would be replicated in the CCS case. A second characteristic of large scale technologies is that firms' learning dynamics are slowed down by long lead times for pilot (demonstration) plants and first-of-a-kind plant building. Returns from experience are long to acquire.

A last specificity of CCS system developments is the complex intrication between three different technological modules. Indeed it is an emergent engineering system with many connections between each of its different technologies, each under many influences between technological, social, legal and economic factors. Nested complexity within each technological modules as well as within their associated social systems including economics introduces multiple time-scales and uncertainties.

The high upfront cost and long lead time. Empirical literature shows that complex and large-scale projects tend to have large delays and cost overruns (Etsy, 2002). These risks are higher for the first-of-a-kind projects[1]. The increasing scale of projects in CO2 capture as well as in pipes and capacity storage increase makes risks rise in a non linear fashion. The size and complexity of projects are an important driver for the intensity of the learning effect by cumulative capacity developed by different players. It tends to countervail the effects of replication, as the recent experience of the LNG industry tends to suggest. Large-scale construction may yield low learning benefits (see Greaker and Sagen, 2008). So the more capital intensive the CCS project is, the more the need for revenue stability for a long period in order to trigger the investment decision in the CO2 capture project, whilst carbon market prices as well as electricity prices will not offer such a stability.

Financing a large scale investment with ordinary risks but long lead times is already not appreciated by financial institutions, given that the first revenues will come after long years of capital immobilization. A 500 MW coal power plant which is equipped with capture and connected to a reservoir by a pipe represents a large unitary investment of EUR1 billion at 2000€/kW. A first of a kind plant using CCS technology would probably take 5 years to build –before generating positive cash flows-. Moreover with a new and complex technology, there is the double uncertainty regarding the building time and the investment cost which makes the payout time longer because of the increase in the cost of capital.

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[1] The critical factors in large engineering projects that literature considered to be indicative of future poor performance of any large project are extra-large scale (complexity and management problems); and if they are first-of-a-kind or one-of-a-kind (lack of experience, design risks, etc.) and a high proportion of public ownership (due to soft budget). The type of project and technology does not appear to be as important a factor. Cf. Etsy, B. (2002).

The enormous complementary investments in transportation and storage infrastructures. Transportation and storage costs for any individual project are indivisible with a high upfront cost with some potential economies of scale. They will be important for the general economics of a CCS project. For a capture project in an electricity generation plant, when cost estimates of capture are set in the 40-70 €/tCO2 range, the transportation and storage cost decrease from 19,8 €/tCO2 (11,6 for storage and 8,2 for storage) for a project of 5Mt/y to 9,8 €/tC02 (5;9 for pipes and 3.9 for storage) for a project of 50 mt/y, given a pipe to be built on a 1000 km distance to off-shore aquifer (Jaud and Gros-Bonnivaud, 2007).

Coordination between private investments in transportation would increase economies of scale. Conversely the cost and the risk of uncoordinated access to transportation and storage capacity are higher than in a scenario of partial coordination between projects (Bielicki, 2008). There are many issues that need to be resolved regarding were CO2 will go and who is responsible for it and what is acceptable. The decision to develop a CCS project would be easier if access to storage rights were to be completely transparent and not subject to being altered by social and legal uncertainty.

Yet all these uncertainties interact together. Uncertainty over the size and location of future CCS sources further weakens the case for large trunk lines promoted by governmental decision. There is also uncertainty on the social acceptability of carbon storage in different onshore reservoirs along with the henceforth conventional NIMBY syndrome. Even if individual pipelines exhibit economies of scale, it may be inefficient to oversize CO2 pipelines in anticipation of demand from future users who may or may not materialize. In other economies of scale in constructing a CO2 pipeline may be offset by diseconomies of scale in other parts of the project-value chain (NERA, 2009; Bielecki, 2008).

Substantial investment will be required to guarantee the minimal CO2 pipeline infrastructure necessary for a minimal compete value chain[1]. However, pipeline permitting and rights of way, as well as accessibility to storage capacities (price, competition for access, distance of source point, reservoir characteristics and performance, local acceptability of on-shore storages) will be challenging. Consequently the mitigation of economic and legal risk of access to storage will ease the installation of the pipe. Moreover uncertainty regarding the access to storage rights will be increased by competition between CCS project developers for this access. When storage opportunities are limited, competition to reach storage rights will have to be organized to avoid foreclosure by dominant players contracting with sink owners.

In other words learning in a CCS system integrates development of institutional and regulatory innovations to allow the development of transportation pipelines as well as different storage capacities in a timely way. It will make easier decisions in

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[1] Extensive discussion should have to be developed there, considering the choice between a variety of network configuration (hub and spokes with trunk lines and clustering of sources or reservoirs, bilateral links between sources and reservoirs, etc.). The economics of a network development is widely dependent upon geographical characteristics of sources and sinks. The relative locations of these sources and sinks are a determinant of the choice of government with private players in favour of a system to be developed rather than a *laissez faire* with bilateral pipe lines projects, or eventually some local clustering of sources or reservoirs. These relative locations are an important component of the overall returns to scale for an integrated carbon capture and storage system (Bielicki, 2008, NERA, 2009).

capture equipped plants. But conversely if clear support helps investment in CCS equipped plants, it creates a clear environment to trigger legislation development in carbon storage and industrial organization to develop transport system.

The range of technological uncertainty. Different reports on state-of-the-art CCS technologies (IPCC WGIII, 2005; IEA, 2008 & 2009; MIT 2007, etc.) give a wide range of CO2 price which would make each CCS technology profitable and competitive (for instance between 30€/t CO2 to 80 €/tCO2). Such a range does not give any indication to investors to engage learning investment, the risk to bear by equipping in new CCS technology and the moment to invest. Moreover for a manufacturer and electrical company who will want to develop industrial know how in one capture technology, competition between the three capture technologies will appear as a source of uncertainty, because they have to invest a large amount of money in post demonstration projects without being sure that it will be the leading technologies.

Uncertainty is not the same for each one. Industrial knowledge in adapting and integrating each capture process in commercial generation technologies and reaching at least 90% of captured CO2 had to be developed. It is currently done with demonstration projects which had to be connected with storage, or oil field for enhanced oil recovery. But up to 2015, demonstration projects are still in the range of small-scale demonstration prototypes. A stage of commercial scale demonstration prototypes will be needed to develop the special industrial know-how inherent to large scale projects (500-800 MW) and reach significant economies of scale, before pre-commercial deployment in the learning stage. Support policies for demonstration projects should avoid favoring the most advanced technology, because uncertainty on its promises at this stage. But the same will be true for the next learning investments due in the post demonstration stage.

Comparing CCS technologies. It is difficult to predict which technology will be selected by the market in the future, considering its intrinsic quality in capture, the decrease in thermal efficiency its economic potential and its capacity to be equipped onto existing plants (IEA, 2009; Gibbons, 2008; Rubin et al., 2007). Each one has specific characteristics that could be an advantage in this respect. On the one side the loss in efficiency could be detrimental to the competitiveness vis-à-vis conventional plant. Oxycombustion will present the best impact in terms of efficiency, but the technology is not yet on the shelf. IGCC plants which will be retrofitted will be considered to have less efficiency losses than post combustion retrofit. But post-combustion (with amines or new solvent) if it equips the best commercial technology such as supercritical steam plants is predicted to have higher thermal conversion than precombustion IGCC. Concerning cost, post-combustion plants would have higher cost of generation than IGCC. Plant equipped with oxycombustion is generally assumed to be able to be in the same cost range than pre-combustion IGCC plant and post combustion, but technological uncertainty on oxycombustion is significantly higher because of least experience on it.

Concerning specific characters, post-combustion technology presents the quality for equipping all new coal and gas generation equipments which will be imposed to be “capture ready”. On its own side, IGCC with precombustion is not so well positioned because IGCC plants which have received many technological efforts since 1990 have met great difficulties which are reflected presently by turbine corrosion, poor availability and lack of flexibility.

Table 1. Investment and efficiency of generation technology with and without CCS

	Investment cost without Capture ($/kW)		Investment cost with Capture($/kW)		Loss of	Efficiency (%)
	2010	2030	2010	2030	w/o CCS	w CCS
Pulverized coal	1360	1210	2000	1600	38	29
IGCC	1430	1210	1870	1540	35	26
Natural Gas CCGT	520	450	810	660	49	41

Nb. No cost data on oxycombustion are available in the reference report of the IEA program.
Source : IEA, 2008

In any case uncertainty on each technology and their relative economic advantage will remain a looming issues even after the demonstration stage. Moreover it is likely that learning rates (and hence investment cost reduction and performances) increase, and this increase will differ between technologies. So policy mechanisms should avoid promoting “low hanging fruits” only.

Electricity market risks. The investor in CCS will require a certain degree of stability in his revenue stream. But the current electricity market regime magnifies the risks of investing in CCS capacity because price risk, volumetric risk and technological risk are all borne by producers. The cost and risk of generation investment in innovative large scale technologies can no longer be passed through on the consumers as was the case in the former regime of regulated monopolies[1]. Moreover it is noteworthy that the price formation mechanism in liberalised electricity markets is determined by the marginal bid on hourly markets which includes carbon cost because fossil fuel generation plants is an element of the short term marginal cost of bidders; consequently uncertainty and volatility risk on the carbon price increase inherent uncertainty and volatility regarding the electricity price. So specific incentives under the form of revenue guarantees by means of a production subsidy are needed to realize not only near-term demonstration CCS opportunities, but the first series of commercial CCS projects, with decreasing support.

3. Efficiency of CCS support instruments : the need of criteria adapted to the characteristics of large scale environmental technologies

First we will recall the classical terms of comparison of environmental policy instruments. Then -because it focuses on market failures resulting from both internalisation of environmental externalities and on innovation barriers for large scale technologies- we will elaborate more precise criteria related to large upfront cost equipments and long lead-times in their development and pre-commercial deployment stages in an uncertain business environment.

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[1] The CCS project manager of Vattenfall, the electricity company which leads in Europe the development of oxyfuel technology considered that “the most important part of the whole story is that we are operating in a liberalized power market “(L. Stormberg, quoted in Carbon and Capture journal, n° 1, 2008).

3.1. Classical terms of comparison of environmental policy instruments

The classic analysis of environmental policy instruments in economic theory is focused on the contrast between: standards, market-oriented instruments -such as tax or subsidies considered as a price instruments- and erstwhile market-based instruments relying on a quantity limitations creating exchangeable rights (cap and trade mechanisms). The economic literature criticizes the use of standards (such as the zero emission standard on new equipments which the CCS mandate consists in), by pointing out its social inefficiency in comparison to taxation (or subsidization) acting as a price signal (Baumol and Oates, 1972). Price instruments such as tax or subsidies create incentives for polluting agents to adjust their equipments in an optimal way (the tax acting as an externality price, or the subsidy acting as a negative tax reflecting the avoided negative externality value), while an environmental standard results in sub-optimal adaptation with no equalization between the marginal cost of pollution reduction and the social marginal value of pollution.

But this conclusion concerns mature pollution control technologies. When thinking about new technologies with a dynamic perspective and taking into account the cumulative learning effects of decreasing costs in a context of uncertainty, the conclusions are more ambiguous. When market failures associated with environmental pollution interact with market failures associated with the innovation and diffusion of new technologies, there is a strong rationale for a portfolio of public policies as the development and adoption of environmentally beneficial technologies foster emissions reduction, as Jaffe, Newell and Stavins (2004) underline[1].

When environmental policies are slow to trigger learning-phase investment in certain clean technologies due to market barriers, the aforementioned authors argue that complementary policies are needed which can have a trigger effect. In fact before reaching commercial maturity, many advances in cost can only result from learning by doing which is gained by cumulative experience. For gaining technological advances, learning investment must help to reduce cost differences between coal or gas generation with CCS and the conventional generation technologies weighed by high carbon price. Early development will have to take place when cost-price of CCS production is much higher than mainstream technologies' production costs, even after carbon cost internalization. Intertemporal learning externalities will compensate subsidization cost of learning investments. In other words the rationale of these policies is the net social benefit resulting from induced effects and externalities.

The characters of the technology -- large scale, long lead time of construction, capital intensiveness, social acceptability -- magnify qualities of policy instruments which help to manage revenue risk (including negative avoided CO2 emissions costs) as well as technology risks. As already underlined, the size and the complexity of the CCS technology add an additional dimension to the learning because they tend to countervail the effects of replication. The recent experience of LNG industry tends to suggest that installations that involve large-scale construction may yield low learning benefits (see Greaker and Sagen, 2008).

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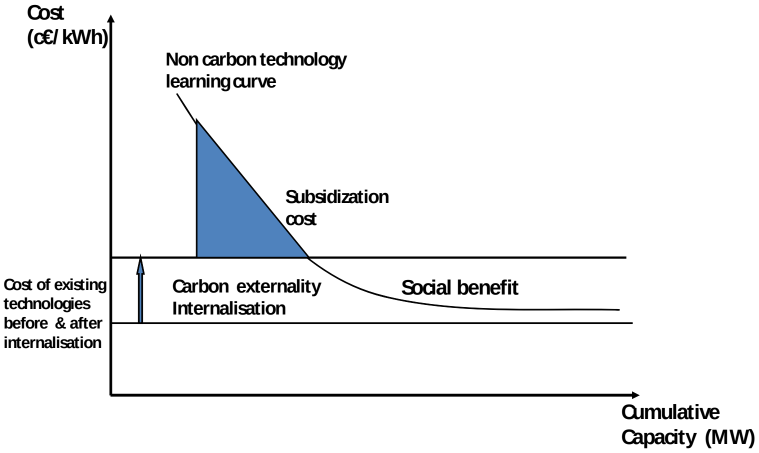
[1] In the presence of weak environmental policies, investments in the development and diffusion of new environmentally beneficial technologies are very likely to be less than would be socially desirable. Positive knowledge and adoption spillovers and information problems can further weaken innovation incentives.

Figure 1. Rationale of public support to CCS learning investments after demonstration



The characteristics of the technology tend to weaken the learning effect intensity by limiting know how diffusion from technological leader to followers. The public support for CCS project must be focused on transfer of CCS project costs and risks onto the public budget or on the electricity consumers via cost pass-through in the electricity price. Protection for new CCS technologies and feasibility of projects which depend on the benefits over the long life of the asset, could be offered in different ways of risks and costs reduction to make private actors more disposed to invest in these technologies following the demonstration stage. Support schemes will trigger learning dynamics to reach competitiveness with existing emitting technologies. Support should reduce the risks and the uncertainties of investment in capture plants and stimulate the learning process to reach commercial maturity within the time framework of long-term policies. This means that besides capture technology demand stimulation by support schemes, governments will have to proceed with simultaneous actions: ensuring clear permitting procedures, providing clarity on the liability for long term storage, coordinating storage locations, clustering sources and reservoirs by pipes-lines, etc.

3.2. Criteria of the comparison of policy instruments for the promotion of large scale CCS technologies

Different support instruments compete for complementing the carbon price's market pull. Policy based on a CCS mandate instituted as a standard (zero emission by new plants and "retrofitability" of existing plants from a certain date) should have to be compared in terms of social efficiency with other policy options which are market-oriented (investment subsidy, production subsidy). For such a large-scale technology, the social efficiency of a deployment policy must be apprehended in three perspectives[1]. First effectiveness i.e. the extent to which the policy instruments can be expected to achieve the objectives in relation to the stage of the technology development after the demonstration stage. Second, static efficiency, which includes the combined notion of cost-advantage and policy cost minimization at each stage of the learning process. Finally, one must consider also dynamic efficiency, which

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[1] This set of criteria is an extension to those used in the 2007 ECN study (ECN, 2007).

covers innovation and technological momentum and includes the issue of the *timing* of the instrument, i.e. its adequacy to the stage of technological development in the pre-commercial deployment. In addition, one complementary perspective that is transversal in nature is the *equity issue* concerning the policy cost for electricity consumer and /or the impact on the public budget.

Effectiveness. In the perspective of effectiveness we identify the incentive characteristics of the policy tool used to reach the objective of technological development and deployment at a reasonable cost. The support mechanism may influence: the choice of technology, the trigger effects on developers' decisions, and impact the effectiveness of projects realization. It could inherently reduce the policy uncertainty with positive effects on projects: indeed visibility and stability of the support framework allows more precocity of developers' decisions, lower capital cost, as well as simpler coordination with the crucial development of infrastructures (transport pipe-lines, storage capacities).

Static efficiency. In this perspective, efficiency is determined by the incentive characteristics of the policy instrument to limit both the investment cost of each project and/or to operational cost during the asset life. The more or less risky character of the subsidization influences the capital cost of the project. This character can lie in the design of the instrument: for instance an obligation with exchangeable certificates such as the renewable obligation certificates (ROC) mechanism introduce a certificate price risk. Another example relevant for the CCS case is the carbon credits awarding for sequestered CO2 against independent verification; it could be considered as efficient because it is performance based and places this performance risk on CCS operators, but at the same time it makes the revenue stream largely dependent upon the uncertainty on the carbon price trend and also on market volatility. It could also increase the exposure to public policy credibility risk if the support for a project (for instance a carbon price guarantee, a feed-in tariff) is spread along a considerable long time of the production stage of a project.

On the other side of the coin, static efficiency is also concerned with the informational structure between the regulator and the CCS developers for choosing the support instrument and defining the efficient level of subsidy, given the risk of moral hazard on the state of technology development. Firms have far more information than governments on costs; governments will be worried about costs submitted in proposals for awarding subsidies and should adapt the instrument to help information revelation.

Dynamic efficiency. In this perspective -focused on technological learning and investment in infrastructures- efficiency will depend on the incentives to improve technologies at each post-demonstration stage before commercial maturity and consolidate learning on each technology from one project to new one developed by the different firms operating in the mechanical and electricity industries A particular dynamic efficiency stake is to maintain technological variety during the pre-commercial deployment before an eventual selection of the best of the three technologies. That means that policy instruments must avoid untimely selection of "low hanging fruits", i.e. of the least promising technology when the other ones are still in infancy. Policy must be designed in order to give the same chance to every capture technology while they would not benefit from the same experiences.

4. The CCS mandate

Standard on CO2 emissions could be imposed under two different forms. The first one is an obligation on each new fossil fuel plant to be equipped with CCS system from a certain date. Intermediately all new plants are mandated to be capture ready, i.e. to be adapted to receive capture equipments and to be retrofit in the period before obligation on each equipment (IEA, 2009). Even costlier, capture readiness gains a value option by the flexibility it opens for governments as it gives them the option to enlarge in the future the set of CCS equipped plants to those capture ready. So the mandate can begin by the new equipments to be built after a certain date, then it can impose retrofitting to existing plants adapted to be retrofit. In the same logic of command and control, this mandatory policy can be complemented by progressive conventional coal generation plants phase-out.[1]

The second approach is by means of an indirect mandate: it imposes unitary emitting performance per MWh for each producer which will then decrease over the long term. It will cover all emissions of CO2 by producers. In such circumstances, the best available technology for new coal-fired power plants might be defined by reference to integrated gasification combined-cycle (IGCC) plant fitted with CCS (Sussman, 2008). CCS mandate presents the advantage of not relying on public subsidies, nor on an implicit subsidy by consumer. Indeed it does not increases the average production price of electricity in liberalized electricity markets: the hourly price on markets will be made by marginal fossil fuel generators who will be offered in function of their marginal cost including the cost of carbon allowances, while the CCS plants with a lower variable cost will always be “infra-marginal”.

Advantages in effectiveness and efficiency. In terms of static efficiency, a mandate policy presents some advantages if it is timely calibrated. By pushing technological adoption at a moment when technology is not yet competitive at the expected CO2 price, this policy will provoke an acceleration of various learning effects in different capture technologies as well as in infrastructure deployment. It might lead to greater certainty over the mid-term horizon with respect to investment costs by speeding up technology development and deployment rates. It will ease the adoption of CCS coal generation by electricity producers because they could refer to successful industrial projects as benchmarks.

Second in terms of dynamic efficiency, capture mandate appears to present an advantage for the complementary infrastructure development which is crucial for the decisions to invest in capture. When private decisions without mandate can be restricted by uncertainty on development of access to transport and storage capacity, mandate on capture would limit uncertainty and risks for other players to invest in trunk lines, in networks for clustering sources or reservoirs and at the end of the chain, in development of storage capacities. Symmetrically it could play also in favor of technological diversification because the risk for potential investors in innovative capture technologies (oxycombustion, complex IGCC) will be reduced as soon as they can anticipate the development of the whole new technological system.

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[1] In the UK, the Ministry on energy and climate policy announced on April 2009 a policy of “no new coal without CCS” as soon as technologies are ready and on September 2009 that an eventual obligation will apply even to CCGT (Greenhouse Issues, n°94, June 2009). The bill on Climate in discussion in the US senate (the so-called Waxman-Markey bill) at the end of 2009 would introduce an increasing obligation on new fossil fuel equipment: from 2009 to 2015, from 2015 to 2020, and then a CCS mandate on new equipments.

Third speeding up capture technologies learning could be beneficial in terms of option value (Finon, Meunier, 2009). Indeed the technology will be economically ready sooner if there is a tightening of climate change policies in post-Kyoto regimes. It will be also beneficial if the other non-carbon technologies developments (nuclear, renewables) will meet acceptability problems or restrictions for their location. But this advantage must be compared to the effect of the other policy in this respect, knowing that mandate is widely criticized for its inefficiency in case of wrong anticipation of the technological progress.

Drawbacks in effectiveness and efficiency[1]. But there is another side to this coin. Those potential benefits could be muted because of large costs and inefficiencies if the mandate is applied in a non-timely way. The "CCS mandate equation" exposes the system to the risk that it will be imposed on generators too early in the innovation and infrastructure development process. Large-scale CCS deployment would not be possible if access to storage capacities can not be guaranteed to investors, in particular by means of infrastructure development and stable regulation. If CCS mandate costs are to be incurred on generators much before CCS systems can reach competitiveness at the expected level of CO2 price they would result in increasing social costs of climate change policy.

So premature mandates would have two counterproductive effects. First *in terms of effectiveness,* if all fossil-fuel generation is affected CCS mandates, the investment projects that companies would have developed will be definitively cancelled without replacement by other generation plants in nuclear or renewable technologies at the same scale in the next future. In this scenario the emission record of the electricity generation industry would remain unchanged. Producers will keep in operation their existing efficient coal generation plants as well as their existing CCGTs, even if they have to acquire CO2 allowances at quite a high price. The answer to this problem could be an indirect mandate by imposing a decreasing CO2 content of MWh, but it could have as a side effect promoting the development of other non-carbon technologies which are on the shelf (nuclear, large scale renewables) rather than CCS technologies, if they will not meet political decisions. This is a problem if CCS integration in the technological portfolio is considered as a public policy need.

Second *in terms of efficiency*, if one of the three capture technologies is close to maturity (as could be the case of post-combustion), CCS mandates might lock in and force the use of technologies which potentially should have been more expensive than alternative ones with a similar CO2 profile, but more economic promises[2]. The mandate would be efficient only if technological progress is at a stage where it could be developed at a large scale and as far as possible on every

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[1] Environmental mandates have been theoretically studied by Farmer (1997) in a dynamic framework for environmental damages having cumulative effects. The optimal control model helps to predict how respectively fixed and variable costs affect current production rates, plant closure dates and cumulative production costs. It shows circumstances in which greater production goal may not be at odds with greater environmental protection Transposition of results to electricity generation by fossil fuel would have to be done.

[2] Without going in depth, we can underline not only the case of the risk of pre-combustion lock-in, but also the case of the competition between CCGT equipped by CCS and coal generation equipped by CCS. An indistinct mandate between the two technologies would eliminate CCGT from the technology portfolio. Indeed the economics of natural gas CCGT would be more altered by capture adjunction (the NGCC-CCS) because the loss of efficiency have a greater economic effect than for a conventional plant, given the higher value of gas than of coal.

capture technology trajectory. To limit the risk of lock-in, complementary subsidization could be offered to more innovative technologies the maturity of which being behind the post-combustion technology, the probable leading one in ten years.

For these last reasons, in line with the recommendations of Baumol and Oates (1988) concerning environmental policies applied to mature technologies, even with the best available technology, mandates may be less cost efficient than market-based approaches. By comparison, an investment subsidy or a production subsidy during the pay-out time of the project would incite projects the anticipated costs of which would not be above the subsidy. Production subsidies will act as the market price for a price taker on a perfect competitive market. It will encourage project cost control and improve operating performances, in particular in the case of a production subsidy.

5. Support to investment

Investment subsidies favoring CCS projects is a more market-oriented answer to learning investments than standards. It could be a straightforward support by direct subsidy, a tax credit support, a loan guarantee against risks[1], or a combination of the above. There are different ways of financing investment subsidies: public budget, special fund related to climate policy, or else private funding by a trust fund funded by a fee on coal production, each way of funding being consistently defined in relation to the design of investment subsidization. In the European Union, support could come from the special fund which will be established to receive a part of the revenues raised by governments from the auctioning of GHG allowances created under the cap-and-trade system.[2] The main problem is to determine the optimal level of public funding while maintaining the incentives to innovate and lowering investment costs.

In the case of a direct subsidy the cost of the public policy to promote CCS is assumed by the public budget. As this type of policy is unduly exposed to political uncertainty, investment subsidization should be paid by a special levy added to electricity in turn paid into a seggregated special fund in charge of allocating subsidies to each particular project.[3] Different ways to control the total subsidization costs are possible. The mechanism could be time- and volume-limited. It could be limited with respect to total project numbers and volume limited by project.

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[1] A simple subsidy to investment does not capture all the range of possibilities of governmental support to pre-commercial projects : referring to the US federal support voted in the 2005 Energy Policy Act, it provides benefits to the first CCS projects as well as to the first new nuclear projects to be licensed. In the nuclear case for which more literature exists (MIT , 2007), government offers not only loans guarantee on 80% of the project cost, which has a very important effect of decreasing the capital cost for the equipment, by allowing a much lower debt cost. It offers also standby insurance to protect against the regulatory risks, and a tax credit on production, but only for the first 6000 MW provided that the license will be asked for and authorized before a date (December 2008). These limitations incentivize electricity producers to develop more rapidly their projects and to apply for the support.

[2] Another part (around €1 billion) will be funded by a Recovery fund installed after the inancial crisis of 2008

[3] It is noteworthy that in the UK a levy on electricity has been established in November 2009 for a15-year period to finance subsidization of the four demonstration projects which have been announced by the British government. It could continue beyond the period for the next post demonstration plants (The Times, November 10, 2009).

In terms of effectiveness the support by investment subsidy is well adapted to large-scale projects in technologies with large upfront investment[1]. Indeed it lowers the investment cost for the developers and facilitates the financing of projects. It must be calibrated to cover a large part of costs and risks in order to attract developers in capture equipment. To attract candidates the design of the allocation process could focus on the incentive by competition for the subsidy: for instance to allocate funds on a first-come first-served basis for a certain budgetary envelope up to a fixed date, and for a specified number of projects and subsidy amount by project. Support for projects could also take the form of promotion of the CO2 transport network that the government could decide to promote (in a public private partnership or a public enterprise framework) and then rent out for use by CCS operators against a low subsidized price.

In terms of efficiency this instrument must be designed in a way to give the best incentives to control investment cost and to search for operational performances of the equipment and to limit rents. Concerning investment costs, incentives are not automatic. Historical governmental programs of large scale technologies show that they were insufficient and not reliable, resulting in some “white elephants” cemetery as for nuclear advanced reactor in the seventies (Finon, 1988; Bupp and Derian, 1980) and the US Synfuel program in the eighties (Frie, 1998). Reforms of public R&D with increasing cost-sharing and risk-sharing between the public budget and private investors has introduced real incentives to efficiency, but it does not solve the issue of the cost sharing and the definition of the share of subsidies. Better attribution could be based on auctioning with a maximum volume or a maximum share of the anticipated cost as we shall consider below.

Incentives to operating performance are concerned with the issue of timing. The investment subsidy is fully adapted to early pre-commercial projects as well as to demonstration projects; but as technology matures by reaching basic reliability of operation, the focus should shift towards performance and efficiency. It could become inefficient to maintain investment subsidies and should be substituted by production subsidies. Experience in renewable energy projects shows wind power projects given up after few years of operation beyond the pay-out time when technical problems occur (Sawin, 2004).

Another issue is the incentives to innovate. An excessively generous subsidy to competing technologies raises the issue of a possible disincentive to innovate –by either improving designs or searching for the best technology-. The allocation mechanism could also be stifle innovation. Indeed if the allocation of funds is dealt on a first-come first-served basis from a fixed budget envelope and up to a fixed date, the most inefficient firms could rush to secure early funding at the detriment of other firms. Moreover they would choose a technology with limited innovative characteristics.

Investment subsidies by definition in fact raise the issue of information asymmetry between regulator and candidates to invest in CCS projects, provided that as we can reasonably assume, governments have less information on the state of technological development and the costs of each technology. Firms have far more information than governments on costs; governments will be worried about costs

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[1] Along the estimation of the MIT coal report of 2008, to develop a public program to jump-start 10 post-demonstration CCS equipments will cost between USD10 billion over a 10 to 15 year period.

submitted in proposals for awarding subsidies. There is a risk of regulatory capture by the industry, about the level of projects cost and risk in the three technologies which would be at different stages of their technological development and learning. Conversely there is also the risk of allocating a too small subsidy which would not attract projects developers in the post demonstration stage.

Two ways of resolving the issue of information exist: an auctioning for investment subsidies and financing by a privately managed trust fund.

- **Auctioning**: It is an efficient way of extracting private information, but under certain conditions for allowing technological variety and attracting a number of candidates. First of all, as three technologies are in competition at different stages of development, the risk of gathering low hanging fruit could be alleviated by organizing separate auctions for each technology, as it has been proposed by Newbery et al. (2009). Such a separation generates a problem : it will reduce the number of candidates in competition comparatively to non-differentiating auction and so increase the risk of collusion. Given the complexity of capture technologies and the large scale of projects, there will be a small set of firms which will be in the business and could bid for investment subsidies. Nevertheless experience of auctioning in different domains for one-shot investment subsidy or annual subsidies (for instance for universal service obligation, non profitable regional airways, etc.) shows that attribution by auctions is always more efficient that direct attribution, despite the risk of collusion (Sorana, 2000).

- **A CCS trust fund managed by the industry**: this is the solution proposed in the USA in reference to the model of the trust fund installed for the Interstate Highways program in the fifties and financed by a gasoline tax. Under this model, a fund is established to receive specified revenues, from a fee on each ton of coal purchased by utilities (Rubin, 2008). Such an entity has the legal capacity to spend money on designated programs or activities. This subsidization model presents a number of advantages that are similar to those observed in “hybrid organizations” (professional syndicates to define norms and standards, production cooperative, etc.) which are private institutions are gaining ground in the coordination of transactions for public policies (Ménard, 2004). First it is managed by stakeholders with interest to pull technical progress by efficient learning investments, and being motivated by the efficiency of investment. Second the attribution of subsidies to projects by technologies will not be altered by information asymmetry problems because of professional knowledge and experience returns from demonstration project. But auctioning could also be a practical way to force project developers take on their fair share of risks. Third the trustee could also program and subsidize the development of a CO2 pipe line system, which will suppress one major barrier to the decision to invest in capture equipped generation plants. This model will be valuable in particular in countries with large coal resources, because of the number of stakeholders and the magnitude of the size that the trust fund could reach.

6. Subsidies to production

A third possibility to support the CCS investors and producers is to shift the CCS investment costs and risks from electricity producers equipped with fossil fuel power plants onto electricity consumers or government by subsidization of the power production by CCS equipped plants. Investors in large upfront cost projects need visibility and stability of their revenue stream on a long horizon. So in this system governments offer a long term guarantee to investors that they will capture the benefit of the carbon emission avoidance, given the non-foreseeability of long term carbon price and its short term volatility in a cap and trade system. This guarantee could be offered on the revenue by kWh produced, given that electricity market prices which are "made" on hourly markets by marginal bids are exposed to fuel price risk as well as carbon price risk.

Four main possibilities of subsidization of production exist, which cover carbon price risk or more widely electricity price risk.

- **Carbon credit awarding for sequestered CO2**. It is a solution added for the demonstration projects in the European Union by the 2009 directive. The revenues by these credits are added to the economic advantage of a CCS plant which does not emit CO2 into the atmosphere and consequently does not have to pay for permits. This instrument could be considered as efficient because it is performance-based and puts the performance risk on CCS operators; moreover it links the subsidy level to the carbon valuation by the market. But at the same time it makes the revenue stream largely dependent upon the uncertainty on the carbon price trend and also on market volatility.

- **CO2 price guarantee**. It consists in government funding the gap between the cost of CO2 reduction by CCS technologies and the CO2 market price[1]. *A first way* suggested by Grubb and Newbery (2007) for every low carbon generation technology is the implementation of a price floor in the design of the cap and trade, which means that the government pays the difference to every owner of permits. But this system is possible to be developed at the national level only if a regional scheme such as the ETS system includes it. *A second way* that Newbery (2003) and Helm et al.(2006) propose is a mechanism of call options contracts with a public agency which would guarantee a minimum payment on a long term basis for each new non-carbon equipment over its lifetime by means of these option contracts called "carbon contracts".[2] The holder of the option will be entitled to receive the strike price less the carbon price that affects fossil generation costs without CCS. These option contracts would be sold by auctions with selection based on bids on the strike price. It could include a price cap to lower government exposures to price changes.

- **Production tax credit.** The production subsidy could be designed as a tax credit. The level of support will depend on the CO2 price and the observed evolution of technology costs. The production tax credits will guarantee that during a number of years (for instance 10 years), a new CCS generator will receive a given amount per kWh generated which roughly corresponds to the difference between the CCS electricity cost and the average electricity price. This is currently the mechanism used in the USA for the Federal support for renewables and the first new nuclear plants voted in the 2005 Energy Act, for which a tax credit of 1.8 c/kWh is allocated for eight years.

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[1] The support instrument could be designed in a more general way to cover all the large scale non-carbon technologies among which new nuclear plants, renewables and CCS to limit CO2 emissions in electricity production in the future.

[2] There would be a vast array of contractual arrangements with government to securitize the "economic advantage of non carbon plants (see for instance Ismer, and Neuhoff, 2005; Grubb and Newbery, 2007)

• **Feed-in-subsidies**. In this case, government offers a guaranteed purchase price on a long-term basis for all electricity generated from facilities fitted with CCS. It has three main characteristics:

- A fixed revenue would be guaranteed per kWh produced by CCS-based generators during a long time span (15 years for instance) covering the period of investment cost recovery. It is calculated by reference to the cost price of a reference equipment in each concerned technology.
- It is related to an obligation in the market regime by the historical supplier imposed by a public agency that allocates CCS electricity quotas to the incumbent suppliers on a market share pro-rata basis (question pro-rate of generation or supply?).
- The cost of the support mechanism is borne by consumers either by tariffs increases in the regulated monopoly regime, or by an uplift on transmission tariffs in the market regime to compensate the historic suppliers for their overcosts. In the public agency model, these overcosts are then passed through via their pricing in the final end consumer markets by the competitors obliged to acquire quotas of CCS electricity.

In any case these mechanisms need some cautious designs in order to avoid intrinsic limitations inherent to information asymmetries between the regulator and the CCS developer. Let us now consider the advantages and limitations of these three ways in terms of effectiveness and efficiency.

Effectiveness of production subsidies. Carbon price guarantee allows to trigger the investment decision. The options allow investors to directly hedge against the risk of low allowance prices and their effects on the electricity market price once the equipments come online and also during their lifetime, or at least during the investment cost recovery period. They make the project bankable at lower capital costs.

Feed-in systems offer the same advantages with more guarantees because all the electricity market price risks are covered. They have proved to be very effective in the domain of renewables. It gives investors revenue visibility who could then gain access to debt funding with lower capital cost. The risk of overshooting the target that may be present because of its attractiveness for the investors can be easily alleviated by regular adjustments of the feed-in subsidy related to technological progress and cost decrease.

An issue of credibility of the public commitment results from the long period of necessary guarantee. This is not an issue when the cost of the electricity price guarantee is paid by electricity consumers via a levy, but it becomes an issue when the public budget is reviewed on long period, because of the risk of government’s opportunistic behaviour which could be exerted in relation to the electoral cycle. So it could be a driver not to invest in CCS equipment with a long pay-back period. This issue of credibility of the governmental commitment to a long term target price, or to respect the options contracts during their long time span has been analyzed by Hepburn and Helm, (2006) in terms of independence of the public agency which would transmit that conviction to the private sector in legal form –through contracts that bind successor governments. The feed-in system because it will be financed by consumers will be much less vulnerable to arbitrary change on the time span of the governmental commitments.

Efficiency of production subsidy and carbon price guarantee. In the economic literature on instruments for the promotion of renewables, criticims have been focused on the efficiency of uniform feed-in tariffs by technologies and their eventual rigidity in time (Haas et al., 2006, Mitchell et al. 2006, Finon et al., 2003). For CCS technologies, the same criticisms could be addressed to the feed-in subsidy.

- First incentives by production subsidies are pointed out as socially inefficient because they create rent opportunities for projects with different development costs, depending upon the location and the technology maturity.
- Second if the production subsidy is generous, it could be successful in terms of effectiveness, but costly for the electricity consumers or the public budget. In this case a solution is to make regular assessments. For instance by including a provision of revision when installed capacity reaches a given level in each capture technology. Going further, once each capture technology has matured, maintaining this form of subsidy can no longer be justified.
- Third it could also discourage further technological innovations. A stable feed-in tariff would involve the risk to de-incentivize ongoing innovation in CCS technologies.
- Fourth from a political economy perspective, this type of long term support instrument appears to be more exposed to interest groups pressures than the previous one; Downward adjustments of feed in tariffs for new equipment because of technological progress may meet resistance among producers. Interest groups lobby for preserving technological rent, and given that consumers are paying, government would be less incline to adjust the support to cost decrease.

A solution to these problems in the case of feed-in system is the allocation of contracts by auctioning of the feed-in-price. Within the existing renewable promotion mechanisms, a system of auctioning for large scale innovative technology installations (off shore wind, biomass electricity) has been quite successful at creating incentives promoting project bidding and thereafter the execution of capital intensive and risky projects. Financial investors do not hesitate to lend money because investment is securitized by long-term contracts at fixed prices (Finon, 2007). But the main argument remains that auctioning obliges developers to reveal their information on their anticipated cost of the project while they will bear the project risks to control their costs.

7. Conclusion : the adequacy of support schemes to economic maturity of CCS system

Once sufficient technological knowledge has been gained with large scale demonstration plants, learning investments are needed by successive realization of n-of-a-kind equipments in different capture technologies. Besides the expected value of carbon allowances which gives a negative opportunity cost, additional government incentives remain important at this stage because investment scale and economic risks are increasing in combination while interdependencies with transport and storage developments accentuate uncertainties for investors in CCS projects. Clarity of government commitment over the long run to support pre-commercial capture projects will be essential to trigger organizational investment around development of infrastructures in transport and storage.

There are no clear-cut arguments to choose between the different instruments, given the particular characteristics of large scale and intertwined technological systems that CCS presents. These characteristics partly invalidate theoretical recommendations based on the standard representation of innovation process as a short run probabilistic learning on divisible technologies. Not only the belief that carbon price will be sufficient to pull CCS technologies after the scaling up demonstration stage, but all the market based instruments are not convenient to support learning investment. Anyway from the previous analysis some principles could be drawn to seek for effectiveness and efficiency of a CCS policy beyond the demonstration stage.

First along with Baumol & Oates's conclusion on environmental policy instruments in a context of standardized technologies, mandate might be less cost-efficient than the market-based approach. By comparison, an investment subsidy or a production subsidy during the pay-out time of the project would increate incentives to develop projects with anticipated overcosts which would not be covered by the subsidy. The subsidy will act as a price cap or as the market price for a price taker. It will encourage project cost control. In the case of production subsidy, it incentives the improvement of operating performance as well as carbon capture efficiency. But this recommendation could be challenged in a long run perspective in introducing the large-scale technology dimension. Indeed because of the difficulty to channel learning investment, CCS mandate could present advantages in terms of decreasing costs by higher replication effects resulting from the forcing of technological orientation on electricity generation. In any case economic considerations should orient the start-up of obligation (a notion of a cost threshold).

Second the timing dimension is indeed essential. For the earlier post-demonstration stage of the technology where the main barriers are construction costs and risks, the most efficient mechanism is the one focused on the investment to be supported with subsidies which lower the investment cost and risk. Production subsidies under different forms (carbon price guarantee, feed-in-subsidy, ..) is more adapted to the pre-commercial stage of the technology than the investment subsidy which is not output performances based. It helps to increase the reliability of the units and the performance in terms of thermal efficiency. At the same time, CCS mandates could have some virtues after the post-demonstration stage if investment subsidies are not sufficient to attract investors and create learning momentum.

Table 2. Possible timing of incentive policies for CCS technologies in the post-demonstration stages

	Commercial scale demonstration 2015-2020	**Post demonstration 2020-2030**	**Precommercial 2030-2045**
Mandate			Yes
Investment subsidy	Yes	Yes	
Production subsidy		Yes	Yes

Third, given the strong complementarity of transportation and storage infrastructures development with pre-commercial capture projects deployment, the instrument to support capture projects must reflect a determined policy which in parallel copes with the reduction of legal and political uncertainty on the development of reservoirs. In the same logic the choice of an instrument such as the mandate, or a generous support for the first post-demonstration projects would reduce uncertainty about the source side for the investors in pipes lines and in reservoirs.

Fourth, in terms of control of policy cost by alleviating information asymmetries, market-oriented mechanisms would help to get round this issue. Auctioning for investment subsidy, or else for production subsidy is an efficient solution proposed by economic theory.

Fifth, policy credibility is more demanding with production subsidies because it supposes a political commitment for guaranteeing long-term revenues over a long term horizon for each new plant. If the financing comes from electricity consumers via an uplift payment, and not from the public budget, credibility is better guaranteed.

Sixth in terms of technological diversity which will have to be sought up to the pre-commercial stage, mandate is the least adaptable solution to this goal. Investment support as well as feed in subsidy could be designed with differentiation of support between technologies.

Finally, as there is not a clear-cut argument in favor of one instrument, the selection of mechanisms should be influenced by the resource endowment of each country -- importance of fossil fuel resources, importance of potential CO2 reservoirs --, and the cultural and political context. It will be influenced first by the coal share in the electricity generation mix which is determined by coal resource. Indeed when an electricity generation system is called to remain heavily dependent upon fossil fuel generation, government will be inclined to choose determined support and even more a radical solution as CCS mandate. On the political and cultural side, dominant market culture will probably be the most influencing factor over the choice towards market-based solutions, but the public’s perception of CCS urgency could even bring governments to choose CCS obligations.

Annex. Qualities and drawbacks of different CCS support mechanisms

	Cap and trade only	**CCS mandate**	**CCS subsidy on Investment***	**CCS production subsidy****
Effectiveness	Insufficient to trigger learning investment	Rapid deployment When timing is appropriate	Help financing by debt	If stable source of funding. **Faster pace of Deployment** and technology development.
Static efficiency	Carbon price risk Regulatory risk	Cost inefficiency by forcing deployment. Incite to performance (developers bear risks). Crucial importance of good timing	Policy cost control	Output performance based
Informational asymmetry		No	Yes except if auctioning	Yes except if auctioning
Dynamic efficiency Cost decrease		Learning cost decrease by rapid deployment.		
Technological Variety	Low hanging fruit	But low hanging fruit	Variety	Variety
Risk with credibility of public commitment	No	No	A bit	Yes
Who pays?		Electricity consumers	Public budget (eventually from allowances bid revenue) or Electricity consumers (Trust fund)	Electricity consumers (FIT) or Public budget (PTC, CPG)

*Investment subsidy variants : Public budget subsidy, CCS trust funding, Loan guarantee. ** Production subsidy variants: Feed in tariffs (FIT), Production tax credit (PTC), Carbon price guarantee (CPG).

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