UNIVERSITY OF CAMBRIDGE

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# The Efficiency of Policy Instruments for the Deployment of CCS as a Large-sized Technology

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**Abstract**

This paper analyses a set of policy instruments designed to support investment during the learning phase of CCS technology, following the demonstration stage. The focus is on specific barriers to learning investment during early-commercial deployment. We analyze imperfections in the carbon price signal and market failures from barriers to large-sized innovative technology, which justify support during the learning investment phase and the initial roll out of CCS in electricity generation. Then we analyze and compare the efficiency of different ways to help CCS technology cross the so-called "death valley": command and control instrument (CCS mandate), investment support (grant, tax credit, loan guarantee, subsidy by trust fund) and production subsidies (guaranteed carbon price, feed-in price, etc.). Three criteria are used in this comparison: effectiveness, static efficiency and dynamic efficiency. Policy instruments must be adapted to the technological and commercial maturity of the CCS system. Mandate policies must be handled with much care and subsidization mechanisms must be designed to be market-oriented.


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# The Efficiency of Policy Instruments for the Deployment of CCS as a Large-sized Technology

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## 1. Introduction

Carbon capture and sequestration (CCS) is one of the major options for reducing carbon dioxide ($CO_2$) emissions, and is 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 trying to reduce emissions by 50% by 2050 in order to limit carbon concentration to 450 ppm. Experts have expressed opinions on the urgency of rapid CCS deployment, as shown by the 2007 MIT report on coal; there are concerns about delays in the CCS demonstration stage (MIT, 2007). IEA reports (2006, 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.

Commercial-sized demo plants have not yet been developed, so public support for commercial deployment of CCS has yet to figure in the political agenda. In the conventional linear multi-stage representation of an R&D process for large-sized technology, economic theory suggests that government should contribute to the financing of demo projects under conditions of transparent information in the interests of competition: R&D creates external benefits, i.e. innovation that cannot be patented and that early developers of new technologies cannot capture. This can lead to an inefficiently low level of investment in R&D. So it has been recognized that support is needed to stimulate the CCS demonstration projects developed by private firms, something the European commission (E.C., 2008) does. For the next stage, conventional wisdom tends to consider policies complementary to the carbon price signal that issues from taxation or a cap-and-trade system as socially inefficient, as we can read in the European Commission's Impact Assessment of the 2009 CCS Directive. This argues that the carbon price signal is sufficient, and the eventual costs of subsidization mechanisms would not be compensated by the long term social benefits (E.C., 2008)[1]. It implicitly assumes that the roll-out of CCS technology would be led by the market's demand for low carbon technologies. From this perspective market forces due to the carbon price, are sufficient to stimulate any non-carbon technology when it is needed and competitive. In the end, early commercial CCS projects should be subject to the market test, including the risk of failure.

Behind this restrictive position, there are implicit beliefs that demonstration plants will help to provide sufficient knowledge to the industry so that further support will be unnecessary. But this position overestimates the effectiveness of the carbon price signal for long term decisions, an ignorance of learning externality, and a misunderstanding of the various barriers to CCS deployment that need to be analyzed in depth. It is not too early to break with this representation and to think about the possible regulatory framework for promoting CCS technologies in electricity generation; potential strategies from the main actors will be directly determined by the business models emerging from future regulations. Some critics of the European commission experts' position have already been arguing in favour of support policies for early commercial deployment (Gronenberg et al., 2008). The purpose of this paper is to develop a systematic view of market failures in the deployment of large sized technologies, such as the CCS system, and to identify the most adequate policies for supporting learning investment, besides the long term signal from carbon prices that will be, in fact, quite ineffective in stimulating CCS early deployment.

Policy instruments have to add value to new CCS equipment throughout early commercial deployment, 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. Given the capital intensiveness of future commercial capture equipment with high upfront costs and long development lead-times, these policy instruments have to provide stability and predictability for the power generators and large fossil fuel consumers to encourage them to invest in post-demonstration and early commercial projects. But different policy instruments have characteristics that make them more or less socially efficient, so a comparison must be made between them. We choose to focus exclusively on support for the early commercial development of CCS, its justification, and a comparison of possible support policies. We do not consider the issue of subsidization of R&D and demonstration projects, even if support to mid-sized demonstration projects by private investors could raise the same institutional and organizational issues. We set our approach in the context of developed economies with liberalized markets, though the issue of early commercial deployment could also be raised in large emerging, and coal

[1]We can read in the Impact Assessment of the CCS directive (E.C., 2008): "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, (…)".

economies with much more publicly regulated economic institutions, such as China and India.[2]

In the next section we analyze imperfections of the carbon price signal, and market failures inherent to the innovation barriers raised by complex and large-sized new technologies which justify support for the learning investment. Then we analyze the efficiency of different ways to support CCS technologies to cross the so-called "death valley," by complementing the deficient carbon pricing signal: command and control instrument (CCS mandate, low carbon obligation on producers), investment support under different designs (grant, tax credit, subsidy by trust fund), and subsidies to production (feed-in subsidies, $CO_2$ price guarantee). These instruments are compared according to three criteria: effectiveness, social efficiency in a static perspective, and dynamic efficiency (technology progress).

## 2. CCS learning investment and imperfections in the carbon price signal

After the demonstration stage, there is no justification for public support for the deployment of the new technology. Economic theory would say that the only efficient mechanism to pull low carbon technologies into the market is the long term signal given by the carbon price. The rationale for this laissez-faire approach is that carbon externalities are internalized in the production cost of incumbent technologies. This internalization is supposed to trigger manufacturers' and energy producers' innovation decisions, while the consumers would pay, both for the carbon emissions of the existing system, and for its transformation i.e. producers' expenses in adopting and deploying new low carbon technologies.

The CCS is part of the portfolio of low carbon technologies to be developed by the market when such a carbon price emerges and increases in a predictable way within an increasingly stringent cap and trade system. From this perspective we cannot anticipate the technology mix, and there is no way that governments could pick the efficient mix. The roll-out of CCS technology should be led by market demand for low carbon technologies, so early commercial CCS projects should be subject to the market test. If CCS does not develop, there will be a greater scarcity of carbon allowances, a higher carbon price and, therefore, more incentives to reduce emissions in other ways in the electricity system.

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[2] Emerging countries have considerable interests in applying CCS system. They have initially adopted a pragmatic attitude of "wait and see", confident in their capacity of technology transfer. But since 2007-2008 the actual implementation of CCS demo projects in China is not very much behind EU and US. Further deployment policies of CCS technologies could follow a different institutional trajectory, given that the regime of electricity industries will probably be a combination of single buyer with regulated monopoly in the long term.

But this pure market-pull approach cannot ignore market failures in learning investment which creates barriers for each technology. This view must be challenged for three reasons. First, benefits of cumulative learning are not captured by the investors, while the social benefits will balance the cost of learning investment (Finon and Meunier, 2009). Second, uncertainty over the carbon price trend, and so over social benefits on a long-term basis, could deter investment in low carbon and capital-intensive technologies. Third, the characteristics of large-sized technology and the complexity of CCS systems magnify learning costs and risks, the chain of innovations being too long, too complex and diverse. Moreover, the existence of three capture technologies, which will be at three different stages of technological development, presents the risk of a lock-in on the second- or third-best technology if early commercial development is supported under a hypothetical high carbon price incentive.

## 2.1 Deficiency in internalization of carbon externality

The application of CCS technology to coal (or gas) generation leads to increased costs of electricity generation due to added capital costs, as well as operating costs due to the consumption of extra fuel. It needs the internalization of $CO_2$ costs in classical coal and gas generation to make it competitive. With an increasing carbon price from the internalization policies of a cap and trade system, CCS projects benefit from the non-payment of CO2 allowances by the generators. Net present value of projects will be provided by avoided CO2 allowances, the price of which is passed through in the generators' price bid on the hourly electricity market. In the following example, in Table 1, to become competitive, the CCS plant would need an electricity price increase of 38,3$/MWh with carbon cost pass-through in the electricity wholesale price. For reaching this price increase by pass-through, the price of carbon will have to be established at a level of 40 $/t$CO_2$. It is noteworthy that, as investment cost is important in the structure of costs while it remains exposed to significant learning risks in the early commercial plants, a risk premium added by the lender to the debt cost (currently 3%) would alter complete cost performance; consequently it would need a 55€/t$CO_2$ prospect to make it attractive for investors.

It seems very unlikely that cap and trade will facilitate early commercial deployment of CCS. Even if the price of carbon were to be established at high but variable levels, for instance between €40 to 70 per ton of CO2, price levels at which studies tend to show that CCS would be economically viable (IPCC WGIII, 2005; MIT, 2007; IEA, 2009), there is some doubt that this price anticipation would be sufficient to trigger CCS investment. Such a price range does not give any information to investors who might engage in learning investment about the risk from new CCS technology, or about the correct time to invest.

**Table 1 : Comparison of economic costs of a reference coal plant and a plant equipped with capture. (Source : MIT Coal Report, 2008)**

**Reference plant: Supercritical pulverized coal plant of 500 MW and precombustion**

| | Reference plant | Reference plant with capture | Reference plant with capture* |
|---|---|---|---|
| Investment cost (overnight) | 1910 $/kW | 3080 $/kW | Idem |
| CO2 emitted | 0,83 kg/kWh | 0,11 kg/kWh | Id. |
| Thermal efficiency | 38.5 % | 29.3% | |
| Weighted average cost of capital | 8.3% | 8.3% | 10.0% |
| Investment cost $/MWh | 38.8 | 62.4 | 74.6 |
| O&M $/MWh | 8,0 | 17.0 | Id. |
| Fuel $/MWh | 15.9 | 20.9 | Id. |
| Total cost w/o carbon price $/MWh | 62.6 | 100.3 | 112.5 |
| Total cost with carbon price of 40$/tC0$_2$ $/MWh | 105.8 | 106.0 | |
| Total cost with carbon price of 55 $/tC0$_2$ $/MWh | 122.0 | | 120.0 |

*Figures in the column *Reference plant with capture* with test of 10% WACC is from own elaboration.

Hypothesis : CCS process captures 90% of $CO_2$. Value of WACC (weighted average capital cost): 60% of debt at rate of 6% and 40% of equity at rate of 10.5% in the normal case. No integration of cost of transportation and storage (5.2 $/t + 15 $/t) in the $CO_2$ price. Reference price of coal: 39$/ton

But the carbon market prices incentive resulting from the cap and trade instrument is fundamentally uncertain. This uncertainty is related to the vagaries of the stringency and long-term commitment to regional and global climate change policies (Ellerman, 2006; 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). Emissions trading systems only favour technologies closest to maturity, but do not trigger new innovative development (Sanden and Azar, 2005). But with investment in a premature technology that can amount to well over €1000 million per 500-MW project, there needs to be a clear understanding of the long-term value of $CO_2$ and the mechanisms that will be used to determine it. In this respect a much more efficient general instrument would be an increasing general carbon taxation which has the quality of long term predictability, but it is now acknowledged that this instrument is unlikely to be applied anywhere because of its social unacceptability.

As future CCS plants will have a marginal cost less important than the without-capture coal plants or CCGT plants, they will forever be infra-marginal in the merit order on hourly electricity markets, and will benefit from infra-marginal rent which integrates carbon costs (for instance with the Table 1 data, CCS plants benefit from an infra-marginal rent of € 38/MWh if normal coal plants are marginal). In another words, the CCS cost pass-through to electricity prices is indirect; it will be done by the carbon price pass-through in electricity prices[3], provided that there is a high enough carbon price to recover the fixed cost of CCS plant. But as it is highly probable that the level of carbon price and the infra-marginal rent is insufficient for recovering fixed costs and covering risks of early commercial CCS projects, support would be needed, the rationale for which will be the learning externalities of cost decrease.

In another words, because the future carbon price has to be decided politically and needs several governments to be committed to a common climate policy through either $CO_2$ taxes or cap and trade systems, or a combination of both, there is a credibility problem in convincing actors to engage in CCS learning investment, as long as policy makers cannot guarantee a long term price level and foreseeable increases. The problem is a bit more acute if future cap and trade is chosen because the price level is much less guaranteed in the long run. Carbon price increases – or threats of future price increases – will not create a transition to CCS which is fast enough.

## 2.2. Specific learning barriers in CCS systems

Even if credible, high long term carbon prices make emerging CCS technologies competitive, there will still be a number of barriers in the existing market from incumbent fossil fuel technologies. Indeed different learning barriers are inherent to large-sized and nested new technological systems and are increased by the riskier context of liberalized electricity markets in which producers must bear all the investment risks.

From a general perspective, learning in large-sized technologies does not have the same profile as small scale technologies that can be standardized. For the manufacturer, the size of the technology at the commercial stage introduces a dimension of firm-specific knowledge for large-scale components, as well as for architect-engineering. Consequently know-how and technological knowledge tends to be firm-specific and quite difficult to diffuse between competitors. Size and complexity tend to counteract the effects of replication, as the experience of nuclear LWRs, and recent experience in the LNG industry tends to suggest. Large-sized construction may yield low learning benefits (Greaker and Sagen, 2008).

As the empirical literature shows, complex and large-scale projects tend to have large delays and cost overruns (Etsy, 2002). A second characteristic of large-

[3] The regulated electricity industries regime with public utilities does not allow the same carbon cost pass-through in electricity price or tariffs. With cost of service regulation, the ability of pass-through cost of carbon permit acquisition will refer to the effective expenses to calculate the mean cost of electricity generation of the utilities, while on electricity markets they pass-through opportunity costs Moreover in the regulated regime there could be delays and not a timely pass-through of carbon compliance costs.

sized technology is that firms' learning dynamics are slowed by long lead-times for demonstration plants and first-of-a-kind plant building. Returns from experience come slowly. When learning has also to cope with safety and environmental regulation, firms' learning processes can be curbed. These risks are high for the first-of-a-kind project. In the CCS case the increasing size of projects in CO2 capture, as well as in pipes and capacity storage increase, make risks rise in a non-linear fashion. 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 €1 billion at 2000 €/kW. A first-of-a-kind plant using CCS technology would probably take 5 years to build before generating a positive cash flow. But the more capital intensive and indivisible a project is, the more the need for revenue stability for a long period in order to trigger the investment decision, whilst carbon market prices, as well as electricity prices (which normally includes carbon cost after pass-through in the bid), will not offer such stability. The current electricity market regime in place in EU member states, Australia and half of the US jurisdictions, magnifies the risks of investing in capital intensive capacity because price risk, volumetric risk and technological risk are all borne by producers (Joskow, 2008; Green, 2008). The costs and risks of generation investment can no longer be passed through onto consumers, as was the case of large-sized nuclear innovation in the former regime of regulated utilities.

In the electricity market, anticipated net cash flows for new CCS plants to cover high fixed costs and the risks of an early commercial CCS project, will be highly dependent upon uncertainty on the carbon price level, but also on its pass-through in electricity prices.[4] At the same time, the carbon price is already highly dependent upon other sources of power price risk, such as the fuel price or other producers' market power. That means that investors will need a higher anticipated net cash flow of CCS plant production, because of the cumulative effects of these different risks.

On top of these common characters of large-sized technologies, the complexity of, and the complementarity between, three different technological modules in capture, in CO2 transport, and in storage capacity add to uncertainties. Each domain is under many influences, technological, social, legal and economic, with multiple time-scales and uncertainties. There are many issues that need to be resolved concerning the storage location of the captured CO2, responsibility for it, and what is acceptable. Costs linked to storage capacity will be important for the general economics of a capture project.[5] The decision to develop a CCS

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[4] The carbon price signal in the electricity industry will be "transmitted" to the electricity generators by the electricity wholesale market price in deregulated power industries. Indeed as firms practice marginal cost pricing on the hourly markets, carbon cost will be passed through to customers, given that long term contracts that lock-in electricity prices with retailers or large industrial consumers are absent. As future CCS plants will have a marginal cost less important than the without-capture coal or CCGT plants, they will ever be infra-marginal in the merit order on hourly electricity markets, and will benefit from infra-marginal rent which integrates carbon costs (for instance with the Table 1 data, CCS plants benefit from an infra-marginal rent of € 38/MWh if normal coal plants are marginal).

[5] For a capture project in an electricity generation plant, when cost estimates of capture are set in the 40-70 €/t$CO_2$ range, the transportation and storage cost decrease from 19,8 €/t$CO_2$ (11,6 for

project would be easier if access to storage rights were to be completely transparent and not subject to alteration by social and legal uncertainty.

Moreover, transportation and storage costs for any individual project are indivisible, with a high up-front cost with some potential economies of scale. 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).[6] But such a stage of coordination could not be reached at the early coordination stage.

It is this combination of high learning costs and risks associated with large-sized and complex technology, plus market risks, that create the rationale for supporting early commercial CCS projects. It could be argued that oil firms assume large risks in investing in large-sized investment in deep off-shore drilling, that aeronautic firms develop large-sized and innovative technologies, that pharmaceutical firms are familiar with large investment in new products with high costs risks. But either the technologies are mature and progress by incremental innovation (as for oil drilling); or the basic conditions of these industries are different from the electromechanical and electricity industries (as for pharmaceutical industry in which firms might assume learning investment costs and risks with the help of protective patents system and high profits) (Pavitt, 1984); or else new programs in complex and large-sized technologies in aeronautics and spatial industries have always received public support or have benefited from spill-over from military or political programs (Pavitt, 1984).

## 2.3. Differences in learning uncertainties between capture techniques

Uncertainty is not the same for each capture technology, and the economic promise of each one is also quite different. When comparing CCS technologies (see table 1), it is difficult to predict which technology will be selected by the market in the future, bearing in mind its intrinsic quality in capture, the decrease in thermal efficiency, its economic potential, and its capacity to be added onto existing plants (IEA, 2009; Gibbins and Chalmers, 2008; Rubin et al., 2007; Herzog and Smekens, 2005). Each one has specific characteristics that could be an advantage. On the one side, loss in efficiency could be detrimental to competitiveness vis-à-vis a conventional plant. Oxycombustion will present the best impact in terms of efficiency, but the technology is not yet on the shelf.

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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).

6 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).

Retrofitted IGCC plants will be considered to have less efficiency loss than post-combustion retrofit. But post-combustion (with amines or new solvent), if equipped with the best commercial technology such as supercritical steam plants, is predicted to have higher thermal conversion than precombustion IGCC.

At this stage of development, all costs are based on estimation, and not on experience from large-sized realization. Post-combustion plants would have higher cost of generation than IGCC. Plant equipped with oxycombustion is generally assumed to be in the same cost range as pre-combustion IGCC plant and post-combustion, but technological uncertainty in oxycombustion is significantly higher because of lack of experience.

**Table 2 . Investment and efficiency of generation technology with and without CCS (Source: IEA, 2008)**

| | . 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 is available in the 2008 reference report of the IEA program on CCS (IEA, 2008)

Post-combustion technology can be used to equip all new coal and gas generation equipment which are required to be “capture ready”. IGCC with precombustion is not so well positioned because IGCC plants, despite much technological effort since 1990, have experienced great difficulties, such as turbine corrosion, poor availability and lack of flexibility.

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

# 3. Criteria for adopting policy instruments for CCS deployment

The characters of the CCS technological system -- large-sized, long lead time of construction, capital intensiveness, intertwining of technologies, social acceptability of storage -- suggest policy instruments which help to manage revenue risk (including avoided CO2 emissions costs), as well as technology risks. Public support for the CCS project must focus on the transfer of some of the costs and risks onto either the public budget, or electricity consumers via the electricity price. It is noteworthy that, besides stimulation of capture technology demand by support schemes, governments will also have to proceed with simultaneous actions to reduce risk: ensuring clear permitting procedures, providing clarity on liability for long term storage, coordinating storage locations, clustering sources and reservoirs by pipes-lines, etc.

Different support instruments refer to different principles competing to complement the market pull of the carbon price on CCS technologies: policy based on a CCS mandate instituted as a standard (zero emission by new plants and retrofitting of existing plants where possible from a specified date), and policy options which are market-oriented (investment subsidy, production subsidy). The social efficiency of each policy must be assessed from three perspectives: effectiveness, static efficiency and dynamic efficiency[7].

*Effectiveness:* This refers to the incentive characteristics of the policy tool. The support mechanism may influence the choice of technology and the trigger effect on developers' decisions. It could inherently reduce policy uncertainty; indeed visibility and stability of the support framework allows for more precocity of developers' decisions, lower capital cost, as well as simpler coordination with crucial infrastructure development (transport pipe-lines, storage capacities).

*Static efficiency:* Efficiency is determined by the incentive characteristics of the policy instrument to limit both the investment cost of each project and/or the operational cost during the asset life. The more or less risky character of the subsidy influences the capital cost of the project. This character can lie in the design of the instrument: for instance an obligation with exchangeable certificates analogous to the British Renewables obligation certificates (ROC) mechanism introduces a certificate price risk. It could also increase exposure to policy credibility risk if the support (for instance a tax credit, a carbon price guarantee, a feed-in tariff) depends on a regular parliamentary vote or is spread throughout the production stage of a project. Static efficiency is also concerned with the informational structure between regulator and CCS developers; it influences the choice of support instrument and defines the efficient level of subsidy, given the risk of moral hazard on the state of technology learning. Firms have far more cost information than governments; governments will be worried

[7] This set of criteria is an extension to this used in the 2007 ECN study "Incentivizing $CO_2$ capture and storage in the European Union" (ECN, 2007).

about costs submitted in subsidy proposals and should adapt the instrument to help transparency.

The social efficiency of support is shared between the public budget and taxpayers on one side, and consumers on the other. Indeed, such policies, which will complement carbon pricing policies, will be an element of the policy for the transformation of energy and electricity systems; the cost must be paid by consumers as far as possible in order to have efficient adaptation of demand. The transformation of electricity systems via the deployment of large-sized low-carbon technologies, in parallel with the development of small-sized low-carbon technologies (renewables, etc.), cannot be paid by public subsidies. Consumers, and not taxpayers, have to participate in the transformation of the system and pay the costs of future sustainable energies while rationalizing their energy consumption. Electricity consumers already contribute via the carbon cost pass-through in the electricity wholesale price, so that all low carbon equipment production benefits from carbon rents. Admittedly, complementary support is needed to make early commercial projects risk-manageable and profitable, but second best optimality is reached if subsidy costs are paid by consumers, as far as it is politically acceptable. So the way the subsidy costs are paid will also be one criterion of social efficiency.

*Dynamic efficiency:* This focuses on technological learning and investment in infrastructure and will depend on incentives to improve technology at each post-demonstration stage before commercial maturity, and consolidation of learning on each technology by the different firms operating in the mechanical and electricity industries. A particular dynamic efficiency requirement is to maintain technological variety during early-commercial deployment before an eventual selection of the best. That means that policy instruments must avoid an untimely selection of “low hanging fruits”, i.e. of the least promising technology when the other ones are still in their infancy. Policy must be designed to give the same chance to every capture technology even though they would not benefit from the same learning experiences when to decide on the policy of early commercialization support.

We compare policy instruments by referring to different variants of them. Indeed, experience of environmental and innovation policy instruments shows that limitations and drawbacks of instruments are remediable by their adaptations, or by combination with another one, resulting in improved social performance (Jaffe et al., 2005).

## 4. The CCS mandate

A standard on CO2 emissions could be imposed in two different forms. The first is an obligation on each new fossil fuel plant to be equipped with CCS system from a specified date. In the meantime, all new plants are mandated to be capture ready, i.e. to be adapted to receive capture equipment and to be retrofitted before the obligation date (IEA, 2009). Even costlier, capture ready equipment 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 plants to be CCS equipped to those capture ready, what would be very valuable if governmental commitments increase in the future carbon regime. In the same logic of command and control, this mandatory policy can be complemented by existing coal generation plants phase-out policy.[8]

The second approach is by means of an indirect mandate: this imposes unitary emitting performance per MWh for each producer which will then decrease over the long term to the level of performances of the best available technology (BAT). It will cover all CO2 emissions by producers. In such circumstances, the new coal-fired power BAT might be defined, for instance, by reference to integrated gasification combined-cycle (IGCC) plant fitted with CCS (Sussman, 2008).

- *Advantages in effectiveness and efficiency*

In terms of *static efficiency*, a mandate policy presents some advantages if it is timed well. First, by pushing technological adoption at a time when technology is not yet competitive at the expected CO2 price, this policy will provoke an acceleration of various learning effects, possibly in the different capture technologies, but at least in one of them. It might lead to greater certainty of investment costs over the mid-term by speeding up technology development and deployment rates. It will ease the adoption of CCS coal generation by electricity producers who could refer to successful industrial projects as benchmarks.

Second, in terms of *dynamic efficiency*, capture mandate appears to be advantageous for the development of complementary infrastructure which is crucial for decisions to invest in capture. Where private decisions might be hindered by uncertainty over access to transport and storage capacity, mandate on capture would encourage players to invest in trunk lines, in networks for clustering sources or reservoirs and, at the end of the chain, in developing storage capacity. It could also favour technological diversification because the risk from innovative capture technologies (oxycombustion, complex IGCC) will be reduced when the development of the whole new technological system can be anticipated.

Third, speeding up capture technology learning could be beneficial in terms of value option (Finon and Meunier, 2009). The technology will become economically viable sooner if there is a tightening of climate change policies in post-Kyoto regimes, reflected by a rapid carbon price increase. It will be also beneficial if the other low-carbon technology developments (nuclear, renewables) meet acceptability problems or restrictions for their occupational impacts.

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[8] 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 the 2009 discussion in the US Congress (the so-called Waxman-Markey bill) would introduce an increasing obligation on new fossil fuel equipments: from 2009 to 2015, then from 2015 to 2020, and then a CCS mandate on new equipments.

Fourth, along with the fourth criterion of social efficiency in accordance with consumers participation to the cost of subsidy to learning investment, CCS mandate does not offset the learning cost of the CCS technology from the bill paid by the electricity consumers in particular. If it is a stringent content standard, the consumers implicitly pay a tax on the electricity generation with $CO_2$ emissions above the standard, this implicit tax cross- subsidize the CCS production which is below the standard.[9]

- *Drawbacks in effectiveness and efficiency*[10]

It concerns the theoretical critic addressed to environmental standard when it applies to a business when clean technology innovation process has not yet completely matured (Jaffe, Newell and Stavins, 2005). Indeed potential benefits could be muted because of large costs and inefficiencies if the mandate is applied in a non-timely way to non-commercially mature technology, including immaturity of legislation on transport and storage. The CCS mandate exposes the system to the risk that it could be imposed on generators too early in the innovation process. In particular rapid early commercial CCS deployment under pressure by the CCs on each fossil fuel plant would not be possible if access to storage capacities can not be guaranteed to investors by means of infrastructure development and stable regulation.

So premature mandates will have two counterproductive effects. First *in terms of effectiveness,* if all new fossil-fuel generation plant is affected by CCS mandate, the investment projects that companies would have developed in conventional fossil fuel technologies will be definitively deterred; this would be problematic if in the same time deployment of other new generation plants in nuclear or renewable technologies at the same scale would be restricted by political obstacles. In one possible scenario, the emission record of the electricity generation industry would remain unchanged because producers will keep on operating their existing coal generation plants, as well as their existing CCGTs. As fossil fuel generators have to acquire $CO_2$ allowances at quite a high price, average electricity market prices will be higher and consumers would pay, while CCS diffusion will not be effectively triggered. As investment in different technologies risks to be lower than investment without a mandate, system capacity adequacy and supply reliability might be decreased.

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 its use even though it might be more expensive than alternatives. Pre-combustion could be definitively selected, despite the other two technologies

[9] The mechanism is the following: each power producer must collect this tax by charging a higher price for the high carbon production than it would be in the absence of standard, and pay the crossed subsidy by charging a lower price for the low carbon fuel than it would in absence of standard in order to meet the overall $CO_2$ emissions intensity standard.

[10] 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.

having potentially better physical and economic performances. It happened with nuclear technologies in the sixties and seventies with the lock-in of LWR technologies under the technology push by subsidization of early commercial civilian nuclear reactors (Bupp and Derian, 1979; Cowan, 1990; Koomey and Hultman, 2007). It is happening with policies of renewables support relying on a standard: in the US the biofuel content standard of fuel oils which brings selection of corn alcohol to the detriment of much less carbon emitting chains; in the UK the ROC obligation which tends to mainly encourage on-shore windpower deployment (Haas et al., 2006). The mandate would be efficient only if technological progress is at a stage where CCS could be rolled out on a large scale and, as far as possible, on every capture technology trajectory. In a perspective with a view to limiting the risk of lock-in on one technology (post combustion for, complementary investment subsidization could be offered to more innovative capture technologies that are less developed at the beginning of the policy than post-combustion technology, the leading one in the next fifteen year years.

## 5. Support to investment

Investment subsidy to favour 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, or a loan guarantee against risks. This last method where government assumes financial risk, could have a dramatic effect on the cost of early commercial projects[11]. Support could be any combination of the above.[12] Support for capture projects could also be indirectly provided via investment support for $CO_2$ transport infrastructure development. The government could enter into a public private partnership, or a public enterprise framework, and then rent out transport capacity for use by CCS operators at a low, subsidized price (NERA, 2009).

While the mandate policy cost is indirectly borne by consumers, the cost of a policy based on direct investment subsidy is borne by the public budget. Consequently this type of policy is unduly exposed to political uncertainty. So in comparing different ways of financing investment subsidies, whether through a special fund related to electricity taxation or climate policy, or private funding through a trust fund based on a fee on coal production, the need for policy stability is paramount. Electricity taxation could take the form of a segregated fund financed by a special levy on electricity consumption.[13] It could also come

[11] Loan guarantee allows a lower debt cost with no risk premium (decrease of 3%) and a financing structure with higher debt share (up to 80%) and low equity share (this decreases the complete cost of the project as in the example of Table 1 from 112$/MWh to 100$/MWh with a WACC going down from 10% to 8,3%). .

[12] In fact the concept of subsidy to investment does not capture all the range of possibilities of governmental support to early-commercial projects. The US federal support voted in the 2005 Energy Policy Act provides this range of supports to the first CCS projects as well as to the first new nuclear projects to be licensed.

[13] 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).

from a special fund that receives a part of the revenue raised by government from the auctioning of GHG allowances created under the cap-and-trade system. This will be the source of European Union funding for the completion of twelve CCS demo plants, a method that could be extended for post-demo units.

The main problem with this instrument is the determination of the optimal level of public funding that would maintain incentives to innovate and would lower investment costs. Different ways to control total subsidization costs are possible: the mechanism could be time- and volume-limited: the number of projects could be limited, or the volume of projects limited.

*In terms of effectiveness,* support by investment subsidy is well adapted to large-scale technological projects needing large upfront investment[14]; it lowers the investment cost and facilitates the financing of projects. It must be calibrated to cover a large part of the costs and risks in order to attract investors. The design of the allocation process could focus on incentives through 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 per project.

*In terms of efficiency* this instrument must be designed so that it encourages a search for the best equipment performance but also controls investment cost. Operating performance incentives are related to the timing of the technology maturation process. The investment subsidy is, in fact, better adapted to demonstration projects than to early commercial projects; as technology achieves a basic operational reliability, the focus should shift towards performance and operational efficiency. It could become inefficient to maintain investment subsidies which should then be replaced by a production subsidy to reward operational performance. Experience in renewable energy projects has shown wind power projects abandoned after operating for a few years beyond the pay-out time, a period shortened by an investment subsidy. It was then that the first technical problems occurred (Sawin, 2004).

Concerning productive efficiency by investment cost control, incentives to efficiency are not intrinsic to the investment subsidy instrument. Historically, governmental programs of large-sized technologies failed because technology producers and users assumed too little of the cost responsibility, resulting in "white elephants", as with the nuclear advanced reactor in the seventies (Finon, 1988; Bupp and Derian, 1980) and the US Synfuel program in the eighties (Frie, 1998). Reforming public R&D by increasing the share of costs and risks by private investors has introduced real incentives to efficiency, but it does not solve the issue of the size of the subsidy or the way in which costs are shared. Auctions, with a maximum volume, or a maximum share of the anticipated cost, would lead to a better allocation. Indeed investment subsidized allocation raises the issue of information asymmetry between regulator and investment candidates, as we can reasonably assume that governments have less

[14] 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 $10 billion over a 10 to 15 year period.

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 submitted in proposals for awarding subsidies. So with a gré-à-gré attribution there is a risk of regulatory capture by the industry, and about the level of project cost and risk in the three technologies which would be at different stages of technological development and learning. Conversely there is also the risk of allocating too small a subsidy which would not attract project developers in the early commercial stage.

If consumers are to pay the costs of these subsidies on top of the carbon price pass-through in the electricity price, CCS grants would be socially more efficient if they were paid by a special fund financed by a tax on every traded kWh, or via every kWh produced by coal (and gas) generation plants. The solution of a CCS trust fund managed by the industry, which is proposed by Rubin (2008), respects this principle, the finance coming from a fee on each ton of coal purchased by utilities.

*Dynamic efficiency* auctioning for investment subsidies allows for technological variety and the possibility of 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 has been proposed by Newbery et al. (2009). Such a separation creates a problem: given the complexity of capture technologies it will reduce the number of competition candidates to below that of a non-differentiating auction, and so increase the risk of collusion. Nevertheless, experience of auctioning in different countries 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 than direct attribution, despite the risk of collusion (Sorana, 2000).

## 6. Subsidies to production

Investors in projects with large up-front costs and with intrinsic technological risks need revenue stream visibility and stability over a long horizon. Nevertheless, they have to bear all the investment risks in a liberalized electricity market. So a third possibility to support CCS investors and producers is to shift some production costs and risks from electricity producers onto electricity consumers, or onto government by subsidization. CCS kWh could be produced by guaranteeing revenue, or a part of it, based on the benefits of long term carbon emission avoidance.

*The feed-in-subsidy system:* This consists of a long-term guaranteed purchase price for all electricity generated from facilities fitted with CCS. It has three main characteristics. First, a fixed revenue would be guaranteed per kWh produced by CCS-based generators over a long time-span (e.g.15 years) to cover the period of investment cost recovery. It is calculated from the cost price of reference equipment in each relevant technology. Second, in the market regime of electricity industry, an obligation of purchase by a public agency should allocate

CCS electricity quotas to electricity suppliers on a retail market share pro-rata basis. Third, the cost of the support mechanism is borne by consumers. Either suppliers' overcosts of their quotas of CCS electricity are reimbursed by an uplift on transmission tariffs, or competitors pass-through their overcosts in their pricing to the final end consumer market. It is noteworthy that another way to subsidize the production of post demonstration projects is support from the public budget via a production tax credit guaranteed for a number of years (e.g. 10 years) after the equipment has been commissioned.[15] But this system, which depends on the public budget has less credibility than a feed-in system because it is more exposed to government or parliament's discretionary choices.

*The CO2 price guarantee*: Either the government funds the gap between the cost of CO2 reduction by CCS technologies and the CO2 market price[16] or a factory gate fixed price. Concerning the former Newbery (2003) and Helm, Hepburn and March (2006) propose a mechanism of call option contracts, named "carbon 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.[17] The holder of the option will be entitled to receive the difference between the strike price and the carbon price that affects fossil generation costs without CCS, when the latter decreases below the level of the strike price. These option contracts would be sold by auction with selection based on bids on the strike price. It could include a price cap to lower government exposure to carbon price changes. The second option has been proposed in the US by the 2008 MIT report on coal to support five capture demo plants, but it could be used for early commercial projects beyond the demonstration period. Each technology choice and each project will require a different level of assistance in terms of $/ton CO2. Auctioning for the rights to government CO2 purchase obligations is the best selection procedure. In the two cases, one advantage of these instruments is that the support interferes as little as possible with conventional commercial practice and with the functioning of the electricity markets;

Let us now consider the advantages and limitations of these two approaches in terms of effectiveness and efficiency.

*Effectiveness of carbon price guarantee and feed-in subsidy*
Carbon price guarantee can trigger investment decisions. The options allow investors to directly hedge against the risk of low allowance prices and their effects on the electricity market price once the equipment comes online and during its lifetime, or at least during the investment cost recovery period. They make the project bankable at lower capital costs.

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[15] In the USA the federal support for renewables and the first new nuclear plants voted in the 2005 Energy Act, includes a tax credit of 1.8 c/kWh allocated for eight years for each new project.
[16] 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 $CO_2$ emissions in electricity production in the future.
[17] There is in fact a wider array of contractual arrangements with government to securitize the "economic advantage of non carbon plants, besides the call option contract ( see for instance Ismer, and Neuhoff , 2005; Grubb and Newbery, 2007).

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 enabling them to gain access to debt funding at lower capital cost.

The issue of credibility of public commitment results from the long period for which a guarantee is needed. This is not an issue with the feed-in system when the cost of the electricity price guarantee is paid by electricity consumers via a levy, but it is an issue with the CO2 price guarantee when the public budget is committed on a long period, because of the risk of government's opportunistic behaviour. So it could be a driver not to invest in CCS equipment with a long pay-back period. To insure credibility of governmental commitment, or to respect the options contracts during their long time span, Helm, Hepburn and March(2006) propose the creation of a public agency which would transmit that conviction to the private sector in legal form through contracts that bind successor governments.

*Efficiency of production subsidy and carbon price guarantee*

In the economic literature on instruments for the promotion of renewables, criticisms have focused on the efficiency of uniform feed-in tariffs by technology, and their eventual rigidity (Haas et al., 2006, Mitchell et al. 2006, Finon et Perez, 2007). The same criticisms could be addressed to the feed-in subsidy for CCS technologies. First, incentives by production subsidies are socially inefficient because they create rent opportunities for projects with different development costs, depending on the location and the technology maturity. Second, if the production subsidy is generous, it could be successful in terms of effectiveness, but costly for electricity consumers or the public budget. In this case a solution is to make regular adjustment in relation to technological progress and cost decreases. For example, by revising the policy when installed capacity reaches a given level in each capture technology; once each capture technology has matured, maintaining this form of subsidy can no longer be justified.

Third, a stable feed-in system could also discourage further technological innovations. It would involve the risk of de-incentivizing ongoing innovation in CCS technologies so it must be frequently revised in order to limit the rent on future equipment. Fourth, as for the investment subsidy instrument, there are intrinsic limitations from information asymmetries between regulator and CCS developer. A solution to these problems in the case of a feed-in system, as well as in the case of a carbon price guarantee, is the allocation of contracts for new CCS projects by auction with bids on the feed-in price. Within the existing renewable promotion mechanisms, a system of auctioning for large-sized innovative technology installations (off-shore wind, biomass electricity) has been quite successful at creating incentives to promote project bidding and, thereafter, the execution of capital intensive and risky projects. Financial investors do not hesitate to lend money without risk premium because investment is securitized by long-term contracts at fixed prices (Finon, and Perez, 2007).

## 7. By way of conclusion: The efficiency of supports to CCS early commercialization.

We argue that CCS will not be introduced unless it is initially subsidized, in combination with carbon price policies, at the early commercialization stage. The imperfection of the carbon price signal and learning investment externality combine to reduce the forward cost of the technology. A large externality arises when the benefits of information in terms of technological know-how, an understanding of how to build, connection to storage and plant operation, cannot be captured by the investor. Support to CCS projects will not only help to reduce uncertainty on future cost levels, but also to support this externality of the learning process.

A counter argument is that subsidies applied beyond demonstration projects will be socially inefficient; that the transformation of the electricity system by deploying large-sized low carbon technologies, including CCS, cannot be paid for by public subsidies. Consumers should participate in this transformation and pay the costs of future sustainable energies. But support to early commercial CCS projects would not be in opposition to this view, for three reasons. First, support for learning investment in low carbon technologies should be organized only during the early commercialization stage. Second, the support will come on top of the incentive given by a carbon price which is already passed-through in electricity prices. CCS support will not impose distorting incentive structures, because there will be a high carbon cost for any existing and new fossil fuel plants not equipped with CCS. It will help CCS power generation units which will be built next to the supported early commercial investments to be fully in the market, and meet competitiveness with new non-CCS equipped fossil fuel plants. And third, in several policy options, support costs are indirectly paid by consumers, and this could be one of the relevant criteria for selecting between different modes of subsidization.

Concerning policy instruments which are needed in top of carbon pricing, there are no clear-cut arguments to choose between different principles of support for learning investment because there is always one or another way to remedy the flaws of an instrument. But five insights from the previous analysis help the search for effectiveness and efficiency in CCS policy beyond the demonstration stage.

First, even with the best available technology, mandates may be less cost-efficient than market-based approaches if they are not applied in a timely way and if it is unsuitable with the maturity of the different CCS technologies. Mandate could provoke costly adaptation towards other low carbon technologies, or else underinvestment which could be reflected in deficit in capacity adequacy for guaranteeing supply reliability in electricity systems. So all determined announcements of CCS mandates on any new fossil fuel plants in the short term, such as those we observe in some European countries or in the USA in 2009 and 2010, appear to be unsuitable. More accurate will be capture-ready mandates which have a value option which balances the overcost. Second, the timing dimension is indeed essential. Investment support schemes which lower investment cost and risk are suitable mainly for the demonstration stage where the main barriers are construction costs and risks. Production support in different forms (carbon price guarantee, feed-in-subsidy...) is more adapted to the early-commercial stage of the technology than an investment subsidy which is not output-performance 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 in the post-demonstration stage if investment or production subsidies are not sufficient to attract investors and create learning momentum.

Third, in terms of technological diversity prior to the commercial stage, mandate is the least adaptable solution, unless it is complemented by grants. Investment support, as well as feed-in subsidy, could be designed to differentiate between technologies. Fourth, given the strong complementarity of transportation and storage infrastructure development with early-commercial capture project deployment, the instrument to support capture projects must reflect a determined policy because it could help the reduction of legal and political uncertainty on the development of pipes-lines and storage capacities. Using the same logic, the choice of an instrument such as the mandate, or generous support for the first post-demonstration projects, would reduce uncertainty for investors in pipes lines and in reservoirs.

Finally we argue in favour of modes of subsidization which are not directly financed by the taxpayer but by the electricity consumer. For that reason, direct grants to investment, as well as tax credit for production, should be used only if other policies (mandates, standards or preferably feed-in subsidies or trust fund grant which are funded by a tax or uplift on electricity transmission price) are not politically acceptable. All that being said, the advantage of public support consisting in making financial risks assumed by the government, via loan guarantee or else by a carbon price guarantee can also be considered to be a very effective support for entrepreneurship in the early commercial diffusion stage by dramatically decreasing the capital cost of large-sized CCS projects.

# Appendix

## Qualities and drawbacks of different CCS support mechanisms

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

*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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