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From demonstration to deployment: An economic analysis of support policies for carbon capture and storage

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HIGHLIGHTS

- Sensible aim of current climate policy: secure *option* of future CCS deployment.
- But policy makers require flexibility while private investors require predictability.
- Integrating CCS policy into an overall policy architecture can overcome this antinomy.
- We describe the key features of a good policy architecture and give an example.

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ABSTRACT

This paper argues that an integrated policy architecture consisting of multiple policy phases and economic instruments is needed to support the development of carbon capture and storage (CCS) from its present demonstration phase to full-scale deployment. Building on an analysis of the different types of policy instruments to correct market failures specific to CCS in its various stages of development, we suggest a way to combine these into an integrated policy architecture. This policy architecture adapts to the need of a maturing technology, meets the requirement of policymakers to maintain flexibility to respond to changing circumstances while providing investors with the policy certainty that is needed to encourage private sector investment. This combination of flexibility and predictability is achieved through the use of 'policy gateways' which explicitly define rules and criteria for when and how policy settings will change. Our findings extend to bioenergy-based CCS applications (BECCS), which could potentially achieve negative emissions. We argue that within a framework of correcting the carbon externality, the added environmental benefits of BECCS should be reflected in an extra incentive.

1. Introduction

Carbon capture and storage (CCS) is an emerging climate change mitigation technology that prevents CO_2 produced by power stations and by industrial processes from entering the atmosphere. This is achieved by collecting the CO_2 where it is produced and pumping it into deep underground storage formations where it can be trapped by rocks through a variety of physical and geophysical trapping processes (IPCC, 2005). Since the publication of the IPCC's Special Report on CCS in 2005 (IPCC, 2005), the interest in CCS in the climate change policy making community has increased significantly; a relevant role for CCS in a portfolio of measures to achieve large-scale CO_2 emissions reductions is now widely accepted (Edenhofer et al., 2010).

However, it is fair to say that CCS is currently not on the path to deliver on its promises (IEA, 2012a). CCS continues to be an emerging and technically immature abatement technology which is expensive in comparison with other options. Even though there are a few large-scale CCS projects world-wide in operation or under construction, their number falls short of what would be needed for CCS to mature to a cost-effective abatement technology.

Many reasons have been put forward to explain the currently unsatisfying state of CCS (von Hirschhausen et al., 2012). The inadequacy of governmental support policies is probably key among them. High-level political commitments by governments to support CCS are often not translated into policy programmes that effectively and efficiently drive CCS development; in addition, there are no strong expectations that the climate externality will be meaningfully addressed in the near term in a way that would lend support to CCS investment. Examples for this situation can be found in the EU where the reliance on the European Emission

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Trading Scheme to support CCS has so far not delivered a single integrated large-scale project, or in the US where relevant policy action regarding CCS is exhausted by support for demonstration projects. While it is currently unclear whether CCS will indeed develop into a cost competitive component of a future emission reduction portfolio once relevant market failures are addressed, it is clear that CCS will *not* become a viable abatement option without policy support. To secure the *option* of future deployment, a sound policy framework is needed now.

Policy options to promote CCS were analysed in work by Groenenberg and de Coninck (2008), Von Stechow et al. (2011) and Al-Juaied (2010), with the latter papers focussing on the specific application of CCS in the European and US electricity generation sector. Our contribution extends this work by presenting a comprehensive policy framework composed of multiple and mutually supporting policy instruments aimed at promoting the development of CCS from its present immature status towards a potentially cost-competitive technology that could be deployed at large scale in both industrial and power sectors. Rather than focussing on single, uniform policy instruments such as a price on CO_2 emissions, the paper proposes a policy framework for CCS where the policy mix evolves over time. Recognising that CCS may fail to become cost effective, the evolution of policies to support CCS needs to be tied to the performance of CCS relative to other technologies, and should allow for the the possibility of phasing out support for CCS.

After discussing, in the next two sections, the role of CCS for reaching stabilisation targets and examining the current status of CCS technology, we start the construction of the policy framework with a review of the different market failures faced by CCS during its various phases of development. We then proceed to analyse the main economic instruments available to correct relevant market failures, and score their suitability to support CCS at the various stages of development against a set of criteria. Much of our analysis of market failures and the choice of scoring criteria have been inspired by the work of Goulder and Parry (2008) on the selection of instruments for environmental policy. The ranking process produces a set of preferred policies, which we integrate into a policy programme through the incorporation of ‘policy gateways’. These gateways spell out the conditions for the transition of policy from one phase to the next. Their objective is to facilitate the smooth transition between different policies, to render policy evolution predictable to private sector investors, and to provide policy makers with the flexibility to learn from experience and to minimise costs.

2. Why CCS?

CCS involves the collection of CO_2 produced by large stationary sources, transport of the CO_2 to a suitable storage site, and its injection into deep geologic formations for storage where it remains contained for thousands of years. Potential storage options include deep (800 m or deeper) saline aquifers and oil fields, where injected CO_2 can enhance oil production while being stored. However, the majority of the global storage resource is found in saline aquifers, with a smaller portion of the resource being in oil fields.

Deployment of CCS, including where injection of CO_2 is used to enhance oil recovery, is exclusively driven by concerns over climate change. This feature of CCS differentiates it from other low-carbon technologies, such as renewable-based electricity generation technologies, which typically bring multiple benefits, and has implications for the policy framework that is best suited to support CCS.

The contribution that CCS could make to reaching climate change stabilisation goals is significant. The issue has been reviewed in detail by the IPCC in its 2005 Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005), and is corroborated in numerous other more recent studies (e.g. Edenhofer et al., 2010, Edmonds et al., 2007). For example, in the IEA Technology Perspectives (ETP) 2 °C Scenario (2DS), in which emissions are reduced to levels consistent with a 2 °C global average temperature increase, CCS contributes about one-fifth of the total emission reduction needed between 2015 and 2050 (IEA, 2012a). In this scenario the deployment of CCS in the electricity generation sector is driven by its cost-competiveness in relation to other low-carbon power generation options (e.g. nuclear and renewable-based generation). Certain industrial sectors, including iron and steel, cement, and natural gas processing have few, if any, technical options other than CCS for achieving deep emission reductions. Without CCS the industrial sector cannot meet emission reductions consistent with a 2 °C target (IEA, 2012a) (Fig. 1) In line with this, in the 2DS the global share of emissions reductions between 2015 and 2050 is split roughly equally between industrial applications of CCS (e.g. iron and steel, chemicals) and applications in power generation, although this global aggregate masks strong regional differences in this share (Fig. 2).

The combination of biomass energy with CCS (referred to by the acronym BECCS) has the potential to reduce the stock of atmospheric carbon as opposed to merely avoiding emissions to the atmosphere. This will be the case when the amount of CO_2 sequestered from the atmosphere during the growth of biomass and subsequently stored underground is larger than the CO_2 emissions associated with the production of biomass, including those resulting from land-use change, and the emissions released during the transformation of biomass to the final product. The relevance of BECCS for meeting aggressive reduction targets has been analysed in work by Obersteiner et al. (2001) and Azar et al. (2006). In the 2DS of the IEA scenario, BECCS accounts for 17% of the CO_2 captured between 2015 and 2050, with the majority of the CO_2 captured from production of biofuels.

3. Status

The component technologies used to capture, transport and store CO_2 are by and large technically mature. CO_2 capture is already commercially deployed in many industrial processes such as gas processing and ethanol production, and capture technologies for power generation are following close behind (IEA, 2012a). Relevant commercial experience also exists for the other two steps comprising the CCS technology chain, namely transport and injection. In the US over 6600 km of pipelines transport more that 60 million tonnes of CO_2 annually, produced primarily from geological accumulations, for the purpose of enhancing oil recovery (Bliss et al., 2010). Nonetheless, CCS is still a pre-commercial technology. There is limited experience in combining CO_2 capture, transport and storage to create integrated CCS projects, and there is a need to gain further experience with aspects related to the long-term containment of injected CO_2.

Currently there are four large-scale CCS projects in operation worldwide. Three of these projects (two in Norway, one in Algeria) are in the natural gas sector. These store CO_2 that has been captured as part of the production and processing of natural gas. These projects inject about 2.7 million tonnes of CO_2 annually into deep aquifers (Global CCS Institute, 2011). The fourth project, located in North America, involves capturing CO_2 from a synfuels plant in North Dakota and transporting it across the border to Canada, where it is used to enhance recovery from the Weyburn-Midale oil field in the Canadian province of Saskatchewan.

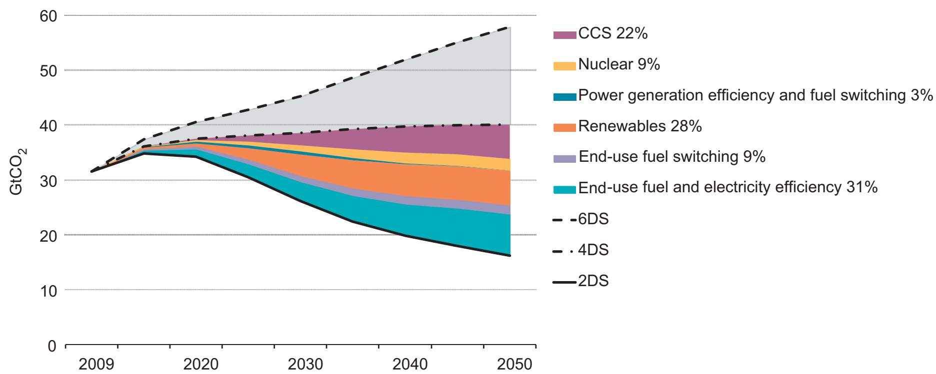

Fig. 1. CCS provides more than one fifth of the global cumulative CO_2 reductions needed to reach the 2 °C Scenario (2DS) (relative to the 4DS scenario, which includes only actions consistent with the 2009 Copenhagen climate change accord).
Source: Energy Technology Perspectives 2012 (IEA 2012a).

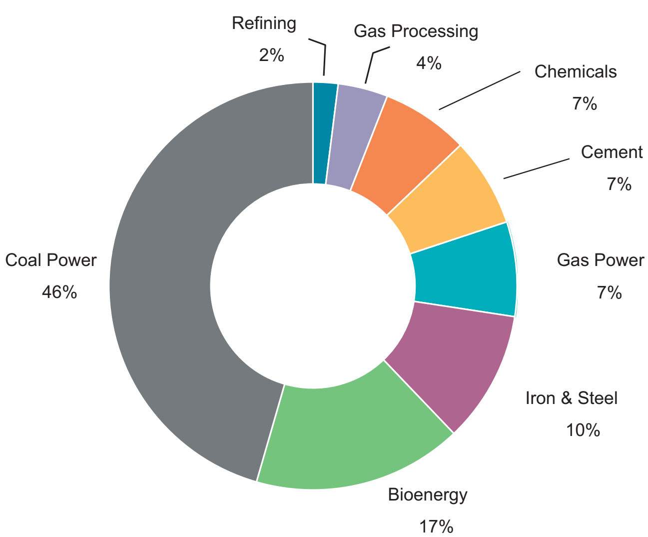

Fig. 2. CCS is not just used in power: approximately 45% of the 123 Gt CO_2 captured between 2015 and 2050 in the 2DS is captured from industrial applications.
Source: Energy Technology Perspectives 2012 (IEA 2012a).

Unlike other commercial CO_2-based enhanced oil recovery projects, whose sole objective is to enhance oil recovery and which use CO_2 as a commodity to increase oil production, the Weyburn-Midale project aims at securing and demonstrating long-term containment of the injected CO_2 through a dedicated monitoring and verification programme.

A number of CCS projects are under construction, the largest one being the Gorgon Project in West Australia which is scheduled to start injecting CO_2 in 2015 at a rate of about 3.5 million tonnes of CO_2 per annum. The project duplicates the CCS configuration of the Norwegian and Algerian projects in that CO_2 captured from natural gas processing will be injected into a deep aquifer for storage. It is expected that about eight demonstration projects will come online by 2017 for an annual injection rate of about 17 million tonnes of CO_2. Detailed overviews of the status of planned CCS projects are given in reports by the Global CCS Institute (2011).

For the technology to make a meaningful contribution to achieving emission reductions, the number of CCS projects needs to increase substantially over the next few decades. For example, the IEA's 2DS scenario, foresees 280 GW of power generation being equipped with CCS capturing about 1 billion tonnes of CO_2 from industrial applications per year by 2030. Dedicated policy intervention will be required to move CCS from the present demonstration phase to a position where full-scale commercial deployment is a feasible option. The rationale for particular policy interventions and the instruments through which they are delivered need to change along the CCS deployment path in order to optimally correct relevant market failures. In the next section we review the type of market failures obstructing CCS deployment before discussing ways to correct them.

4. CCS market failures

We start with a brief description of the five market failures relevant to CCS, and a brief outline of the type of policy intervention that is most appropriate to correct them.

- **Negative externality:** *failure to internalise the cost of greenhouse gas emissions*. As the industrial demand for captured CO_2 is limited, the prominent solution to dispose CO_2 generated in power generation or in industrial production processes is to emit it to the atmosphere. As long as these emissions can occur free of charge, they create an externality. The appropriate policy response to externalities is to internalise them, which can be accomplished with varying effectiveness via straightforward pricing (e.g. via a Pigouvian tax), via the creation of property rights (e.g. emissions trading), or via command-and-control regulation.
- **Public good**: *failure to appropriate returns generated by investment in innovation.* The creation of knowledge and innovation relating to CCS has some of the characteristics of a public good. Others cannot easily be prevented from acquiring some of the know-how gained from early CCS projects, making each firm reluctant to invest and to create the information in the first place. Solutions to public good problems include direct or indirect public provision of the good in question, the introduction of an information exclusion mechanism (e.g. patents) or assurance contracts[1] between all potential beneficiaries of the new know-how.

[1] An assurance contract involves potential beneficiaries of a public good pledging to contribute to the provision of the public good. If a certain threshold is reached, the good is provided from the contributions made; if the threshold is not reached, the contributions are refunded (or not paid in), and the good is not provided.

Table 1
Main options for addressing the carbon externality.
Source: Authors.

Policy tool	Environmental effectiveness	Cost effectiveness	Ease of application	Political acceptability
Cap and trade scheme	Can be applied across wide range of sectors with knowledge that cap will be met; allowance price volatility may reduce policy efficiency; for baseline and credit scheme effectiveness depending on level of baseline	Abatement only takes place if the market reveals that it is needed to meet the cap, but cost will not be known in advance; predictable emissions trajectory may provide a dynamic incentive to research new ways of reducing emissions, but price volatility may weaken this incentive	The choice of market rules may stimulate lobbying, especially with more complex designs, e.g. setting of ceiling/floor, or of baseline (for baseline and credit scheme)	Contributes fiscal revenues; provision of free allowances can offset the total cost increase but reduces revenues; supports other low-carbon options such as fuel switching and renewable
Carbon tax	Can be applied across a wide range of sectors, but emissions will not be known in advance	Abatement only proceeds if it is cost-effective at tax rate, so cost is controlled; predictable carbon costs may provide a strong dynamic incentive to research new ways of reducing emissions	An existing tax collection infrastructure may make introduction easier but firms may lobby for exemptions/reliefs	Contributes fiscal revenue; tax exemptions or changes elsewhere in tax system can offset cost increases but reduce revenues; supports other low carbon options such as fuel switching and renewable
Hybrid: long term emission cap and trade coupled with short term price ceiling controlled by a central bank of carbon	Can be applied across a wide range of sectors, with knowledge that the cap is likely to be met; overshooting of emissions target is possible due to central bank of carbon printing additional permits	Abatement only proceeds if the market reveals that it is needed to meet the long-term cap; costs can be controlled by the central bank of carbon, which can print additional permits in the short run to cap prices	Challenging, as new institution would be required, but similarity with monetary central bank may facilitate set-up procedures; temptation for central bank of carbon to constantly print short-term permits is offset by political pressure of long-term permit owners	Free distribution of long-term permits may greatly ease introduction and create a constituency interested in a high and rising carbon price; resistance from treasury/finance ministry is possible, as an opportunity for government revenue is foregone
Feebate	Allows some flexibility around a target emissions level; difficult covering multiple sectors with one feebate	Abatement only made if costs are less than the fee rate, costs are kept within limits	Scope for lobbying for level of baseline; difficult to impose on heterogeneous sectors	Attractive mixture of environmental certainty and cost control but difficult administration
Emission performance standard	Effective in controlling emissions; ambiguous impact on demand for goods; less effective if only applied to new plant	Can impose high costs by setting the same standard for all players; costs can be reduced by making the EPS tradable	Difficult to impose on heterogeneous sectors; standards are vulnerable to lobbying	Attracts little political attention
CO_2 purchase contract	Easily measured emissions savings	Can be cost-effective, especially if they have long tenor and are competitively bid	Care is needed when drawing up contract, particularly with regards to liability arrangements; simple to administer once in place	May be unpopular with those not offered contracts; requires scarce fiscal resources

– **Capital market failures:** *underprovision of capital associated with information asymmetry and imperfect information*. Information about CCS costs and performance is likely to be unequally distributed between project developers and capital providers. Capital providers may be unwilling to provide finance for good projects if they are unable to differentiate them from bad projects. These problems can be solved via appropriate signalling, through which the project developer credibly conveys information about the quality of his project, or via detailed project screening by the capital provider. Where this is not possible, for example because the required screening or signal would be too costly, government can step in and provide capital or risk-mitigation products directly.
– **Complementary markets**: *undersupply due to dependency on complementary markets and coordination failure.* When one firm depends upon another to get its goods to market, and coordination in output planning is imperfect, the market may undersupply capacity. The interdependency between CO_2 pipelines, storage sites and capture plant, which together form the CO_2 capture and storage system, is an example of this. Solutions to this market failure include the integration of the complementary markets (though this may lead to monopoly/oligopoly concerns), capacity planning facilitated by a third party, or government regulation.
– **Imperfect competition**: this market failure may be present in CO_2 transport networks (potentially in the form of natural monopolies) and storage markets. It may also occur in CCS-related product markets. Imperfect competition can be addressed, where possible, by changing market structure (e.g. via de-mergers), the removal of barriers to entry, or regulation.

The relation between the policy instruments and each market failure is shaped by two considerations. First, at most one policy instrument should be used to correct a single market failure. Using multiple instruments to correct the same market failure may lead to duplication of effort and adverse policy interaction (cf. Fankhauser et al., 2011 and Groenenberg et al., 2011). This creates unnecessary cost increases, and may make future revisions of policy more likely, causing a corresponding drop in investor confidence. Second, aiming each policy at one individual market failure may be more effective than a single policy aimed at multiple market failures, a point made by Fischer and Newell (2008), and Philibert (2011).

This leads to an obvious conclusion for CCS policymaking: while it is appropriate to support CCS using a combination of policy instruments at any one time, each of the support instruments should target a specific market failure.

5. Policy options

In this section we discuss and assess the main policy instruments available to remedy the type of market failures discussed above. Our assessment is based on a set of criteria that is similar to the one proposed by Goulder and Parry (2008) and by

Mitchell et al. (2011) to evaluate the merits of diverse environmental policy instruments. We extend this analysis in the last part of the section to cover policy considerations relevant to support the use of CCS in conjunction with biomass, which can create negative emissions.

Policies are assessed for their overall ability to tackle the market failure they are intended to address, not just for their ability to support the deployment of CCS. In general, the removal of market failures will facilitate the deployment of CCS. The exception here is the emission externality: the most effective emission reduction policies, which score the highest in our assessment, do not necessarily offer the most support for CCS. We recognise this tension; an analysis of its implications is included as part of our assessments.

5.1. Criteria for assessment

For this particular analysis we have used the following four criteria:

Effectiveness: this criterion captures the extent to which a particular instrument is likely to achieve its stated goal. Across the range of instruments assessed, this breaks down into two primary measures of expected effectiveness. First, environmental effectiveness describes the extent to which the instrument can be expected to deliver CO_2 emission reductions in general (i.e. also including abatement from technologies other than CCS). This type of effectiveness is a function of how widely the instrument can be applied across different sectors and assets; the strength of the incentive it provides to invest in abatement, and whether or not it is likely to increase the price of products and hence reduce demand for emissions-intensive products. Second, CCS-specific effectiveness describes the extent with which the instrument can be expected to deliver CCS projects. This is not only a function of the scope and strength of the particular instrument, but also of its effect on project risk-profiles and financing.

Efficiency: this criterion captures whether or not the instrument encourages the least-cost abatement options and whether it helps to reduce costs of the individual options. For example, the cost-effectiveness of CCS can be enhanced by policy which facilitates co-ordination between investment in capture, downstream transportation and storage. This criterion also captures the dynamic incentives provided by a policy, i.e. whether the policy encourages innovation and cost reductions over time.

Ease of application: policies require different levels of institutional capability (Tompkins and Adger, 2005; Woerdman, 2004), often linked to the level of discretion needed for operating them (Gailmard and Patty, 2007). The lower the informational and institutional requirements of a policy instrument, the higher it scores on this criterion.

Political acceptability: policies may be more or less politically acceptable, depending on familiarity and confidence in the outcome, trust in institutions, impact on special interest groups, or the distribution of costs between firms, consumers and taxpayers. Political acceptability in turn is one of the main drivers of policy risk—the more accepted a policy, the lower the risk of sudden reversals or policy changes. This may in turn increase the attractiveness of a policy to private investors (Capital Markets Climate Initiative, 2012).

5.2. Assessment of policy instruments

5.2.1. Emissions externality

We assess the main types of instruments available to tackle the externality associated with carbon emissions: namely an economy-wide cap-and-trade scheme, an economy-wide carbon tax, a tax/trade hybrid pricing instrument, a CO_2 purchasing contract, a feebate scheme and an emissions performance standard. We recognise that policy instruments that address the emission externality only incidentally support CCS; their primary intention is the reduction of emissions. Nonetheless they do provide support for CCS as an abatement technology. Whether or not this support is sufficient to stimulate a widespread deployment of CCS is a separate question, and depends on the cost-competitiveness of CCS relative to competing abatement technologies, the political ambition for reducing emissions, and the particular type of emission reduction policy chosen.

Our analysis of the relative strengths and weaknesses of the instruments to correct the emission externality is summed up in Table 1. While the first three instruments can potentially be applied economy-wide, the latter three instruments are sector-specific.

Economy-wide carbon prices are preferable to command-and-control and sectoral carbon prices as they encourage the equalisation of marginal abatement costs across the whole economy. While an economy-wide carbon price is therefore likely to encourage Pareto-optimal abatement, command-and-control measures and sectoral carbon prices, insofar as they fail to stimulate low-cost abatement options, are likely to increase the costs of achieving any given emissions target. A further benefit of carbon prices is that they increase the prices of emissions-intensive products, promoting cost-effective emissions reduction 'downstream', i.e. in consumer markets. By increasing consumer prices carbon prices also lead to a reduction in demand and hence output, which Goulder and Parry identify as an important abatement channel (Goulder and Parry, 2008).

In order to make investments in long-lived low-carbon assets such as CCS attractive, investors need reasonable assurance of the returns. The volatility of carbon prices that very often accompanies cap-and-trade schemes acts to deter investment by increasing uncertainty of investment returns (Abadie and Chamorro, 2008; Laing and Grubb, 2010). A carbon tax may offer a larger degree of policy certainty, particularly if the price trajectory of the tax going forwards is known to the investor.

A hybrid instrument that combines elements of carbon taxation with emission trading has been proposed by McKibbin and Wilcoxen (2002). Long term, diminishing emission rights, distributed to firms and households, act as an overall cap on long term emissions, while a short term price ceiling caps costs, analogous to a carbon tax. The price ceiling is enforced by a 'central bank of carbon', which creates and sells additional emission rights at the short term price if required. Advantages are a long term price signal, a front-loaded payoff structure for CCS investments, and the creation of a constituency with vested interest in high carbon price. Key drawbacks are the institutional complexity and the costs of setting up a new central bank.

Should economy-wide carbon pricing not be an option, three alternative instruments are available to the policy maker:

- A feebate, i.e., a carbon tax applied to emissions above a certain baseline, combined with tax credits or cash payments if emissions are below the baseline. This provides an effective incentive structure, but requires institutional expertise so that the tax/offset as well as the baseline are calibrated appropriately.
- An emission performance standard (EPS) that limits the amount of CO_2 that can be emitted from facilities. While a tradable EPS allows abatement to occur at lower costs than a non-tradable EPS, an EPS nonetheless remains a high-cost option as trading between sectors producing incommensurable goods is impossible. For example, an EPS mandating a level of

Table 2
Policy tools used to tackle knowledge market failures and promote learning.
Source: Authors.

Policy	Investment incentive for CCS	Cost effectiveness	Ease of application	Political acceptability
Investment tax credit	Incentive depends on size of credit; can be applied to all sectors but only relevant for firms with tax liabilities	Market selects which projects to implement; does not guarantee operation of the plant	Straightforward administration; some technical expertise required to set appropriate level	Consumes scarce fiscal resources
Production tax credit	Incentive depends on size of credit; can be applied to all sectors but only relevant for firms with tax liabilities; encourages operation	Market selects which projects to implement, and high utilisation is encouraged	Straightforward administration; some technical expertise required to set appropriate level	Consumes scarce fiscal resources
Feed-in tariff	Difficult to implement outside electricity sector; in electricity sector exposure to fluctuating fuel prices may lessen investment	Market selects which projects to implement; but increased exposure to fuel price volatility may raise risks	Templates transferable from the renewables sector	Country specific factors will determine whether resulting higher prices have lower or higher profile than fiscal measures
Premium feed-in tariff	Difficult to implement outside electricity sector; in electricity sector can be effective in delivering output	Market selects which projects to implement, and hedging of fuel costs is preserved	Templates transferable from the renewables sector	Country specific factors will determine whether resulting higher prices have lower or higher profile than fiscal measures
Portfolio standard	Unsuitable for sectors with few plants per firm; offers quantity certainty	Unit costs are not limited, but market forces may deliver least cost outcome	Similar expertise required to other instruments and templates transferable from renewables sector	Country specific factors will determine whether resulting higher prices have lower or higher profile than fiscal measures

emissions per kWh in the electricity sector does not allow for trading with a second EPS that mandates a certain level of emissions per tonne of steel.[2]

- A CO_2 purchase contract represents a commitment by the government to purchase, at a specified price, CO_2 that has been captured and stored. This contract will provide incentives for CCS that are similar to those of a carbon tax, but unlike a carbon tax it only applies to captured CO_2 and not to avoided CO_2. Other detrimental features are that it involves spending scarce fiscal resources and that it does not create beneficial cost pass-through effects that can trigger downstream abatement.

5.2.2. *Public good*

As CCS is deployed, new knowledge about the technology as well as opportunities for cost reduction cannot be captured completely by the company that makes the investment and operates the technology; others will also benefit. This leads to under-investment and socially sub-optimal levels of CCS investment and deployment. The main instruments to correct this market failure are analysed in Table 2.

The relative merits of feed-in tariffs (FIT) versus quantity-based instruments have played a prominent role in designing policies to promote renewable electricity generation. A number of studies have concluded that feed-in tariffs have been more cost-effective at securing capacity (International Energy Agency, 2008; Butler and Neuhoff, 2008; Lipp, 2007); this is corroborated by Carley (2009), who finds that a portfolio standard (i.e. a quantity instrument) has been somewhat ineffective at supporting renewables deployment in the US. However, in other cases, feed-in tariffs (FITs) have been controversial as they can provide excessive returns to investors (cf. proposed reduction of solar FITs in the UK (UK Department of Energy and Climate Change, 2012) and Germany (Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit, 2011).

Despite these findings FITs for CCS may not be as effective as they have been for renewables: a characteristic of many renewable electricity technologies is that the marginal costs of electricity production are low and stable (Grubb and Vigotti, 1997). Consequently, for most renewables, a fixed price provided through a FIT provides reasonable certainty over the profit margin on each unit. However, in the case of CCS, the energy costs of operating the CCS unit are considerable and vary as the price of fuel changes. A fixed price therefore does not translate into reasonable certainty over profit margins.

For this reason both a quantity instrument and/or a premium FIT are likely to be more effective in correcting known market failures associated with CCS than a fixed priced FIT.

During the early stages of CCS deployment, more direct support policies such as a premium FIT or a quantity instrument may be required to stimulate investment into CCS projects. Production or operating tax credits avoid both government selection of projects and the risk of installed but unused CCS equipment, which make them attractive options at a later stage. However, they only act as incentives to the extent that companies already have significant tax bills.

5.2.3. *Imperfect and asymmetric information*

Investors' lack of information regarding the performance characteristics of CCS and the transaction costs of setting up new commercial arrangements can discourage, limit or even prevent the flow of capital to CCS projects. This is likely to be a difficulty only while CCS is an early-stage technology. Over time, as the risks become better known and possibly decline, private sector investment in CCS may increase and the need for policy intervention may decline. We assess two broad types of instruments, namely direct government contributions of capital, e.g. via capital grants, equity co-investment or the provision of debt; and risk mitigation instruments such as credit guarantees and insurance products. The result of this analysis is captured in Table 3.

Both capital contribution and risk mitigation policies allow the public sector to acquire and then disseminate information, although co-investors may seek to prevent or limit the public sector from sharing the acquired information more widely. During early stages, risk mitigation measures alone may not suffice to attract private capital. At later stages on the other hand, risk instruments may allow higher leverage rates than equity investments, delivering more investment for the same amount of

[2] However, it may be possible to design an EPS that mandates a level of emissions per unit of value added. Such an EPS may allow for trading across sectors; on the downside it is likely to be administratively complex and costly.

Table 3
Policies used to tackle capital and financial market failures.
Source: Authors.

Policy	Investment incentive for CCS	Cost effectiveness	Ease of application	Political acceptability
Capital grant	Incentive varies with size and conditions of grant; can be applied to all sectors and assets	May weaken incentive to minimise costs; government may fail to pick most cost-effective projects	Expertise required to select recipients and set appropriate grant level; prone to lobbying	Consumes scarce fiscal resources
Co-investment equity	Increases scale more quickly and accelerates learning	Public participation may enable greater inter-sponsor cooperation and system integration	Requires financial and commercial expertise within government and ability to carry out due diligence on projects; only works if projects' sponsors are supportive	Depends on existing precedents and political outlook
Provision of debt	May give assurance to other debt providers and help to prove commercial models	Will not affect project costs directly, but may accelerate learning	As above	As above
Credit guarantees	Effective where projects are already close to achieving a working capital structure	Any weakening of incentives of managers or other investors is to be avoided otherwise costs may rise	As above	It may be difficult for government to take on liabilities which could be triggered by poor managerial decisions
Insurance products	May help to achieve broader capital participation, leveraging in risk-averse investors	May enhance competition between capital providers but may also reduce incentives to control specific risks	Expertise needed to decide which risks to insure against; some risks may be difficult to insure	As above, but certain risks can be placed on project developers, reducing moral hazard

government resources.[3] Over time, a shift from capital contribution to risk mitigation measures may hence be warranted.

5.2.4. Complementary markets

CCS deployment may be affected by a lack of certainty about the provision of transport and storage infrastructure; in addition natural monopolies in transport and potentially in storage could create a tendency to under-provide services. We outline three stages of transport infrastructure development, and propose policy options to alleviate the risks posed by complementary markets.

First, during early stages of deployment, to minimise the scale of assets at risk of stranding, transport infrastructure is likely to develop as point-to-point links between emitters and storage projects, or as small clusters linked to storage projects. This limits the quantity of capital exposed, and means that some transport infrastructure could be delivered on a vertically integrated project basis. Structuring infrastructure in such a way would lead to an optimal risk allocation, with no coordination failures or externalities between capture plant, transport and storage operators.

Second, over time vertically integrated bilateral links could be superseded by infrastructure clusters, funded and operated by "clubs" of local capture equipment operators. This would provide better infrastructure coverage as links extend beyond simple point-to-point connexions; reduced costs through economies of scale; and higher network resilience as breakdowns on single pipelines or storage sites could be compensated by re-routing throughout a cluster. Government, acting directly or through an agent, could aggregate volume information from capture plant operators and provide planning of infrastructure system development. This would avoid legal collusion concerns, and reduce the risk of defection by individual capture equipment operators. However, it requires considerable expertise in infrastructure planning and volume prediction on the part of government.

If the widespread deployment of CCS becomes probable, infrastructure clusters may be combined into an integrated system solution with public supervision. Regulation and industry structure could be modelled on electricity transmission and distribution networks. Since the volume of CO_2 captured may be more uncertain outside the power sector, government may have a role in underwriting a proportion of the fixed network costs in other sectors.

Table 4 provides our analysis of these three infrastructure development models.

With regards to storage markets, an empirical assessment of market characteristics (for example number of viable storage sites, number of participating firms, cost structure and existence of economies of scale) will be required to determine whether competitive markets will emerge, or whether government regulation will be necessary to avoid an uncompetitive market.

5.3. A further incentive for bioenergy with CCS (BECCS)?

BECCS refers to the use of CCS technology to capture emissions from biomass processing or combustion. It can be used in a wide range of contexts, including biomass power plants, combined heat and power plants, flue gas streams from the pulp industry, fermentation in ethanol production, and biogas refining processes (UNIDO, 2010, IPCC, 2011). As of autumn 2011, one BECCS plant at commercial scale is in operation in the United States (the Illinois Basin—Decatur Project, or IBDP), another plant is due to enter service in 2013, and a third project is 'planned for construction within the next few years' (Biorecro, 2012). The IBDP injects CO_2 at a rate of 330,000 t per year, captured from a corn fermentation process that produces ethanol. It is led by the Illinois State Geological Survey at the University of Illinois, which is part of the Midwest Geological Sequestration Consortium, and is mainly financed by the US Department of Energy (Biorecro, 2012).

Contrary to conventional fossil-fuel based CCS (or renewable generation technologies), BECCS is capable of achieving negative emissions over its lifecycle (Edenhofer et al., 2010). CO_2 is taken out of the atmosphere at the beginning of the BECCS lifecycle, and deposited into underground storage at the end of it. Within a framework aimed at correcting the carbon externality, this could be reflected in an extra incentive for BECCS. Essential here is that this incentive reflects all the carbon emission impacts of biomass use, including impacts from land use and land-use changes.

There are three points at which the additional incentive for BECCS could be applied: at the biomass that sequesters CO_2 from the atmosphere, at the capture facility, or at the storage site Fig. 3).

[3] Although the concept remains subject to various conceptual and empirical challenges, evidence points to high rates of leverage from risk-based instruments. For instance, Caperton (2010) reports that leverage rates from loan guarantees to be between 6 and 10 and from policy insurance to be possibly greater than 10. Subordinated equity funds are reported to achieve a leverage rate of 2.

Table 4
Models for infrastructure development and oversight.
Source: Authors.

Model	Description	Advantages	Drawbacks
Vertically integrated point-to-point infrastructure	Bilateral link from source to storage site; integrated ownership of transport and storage, possibly by capture plant owner	Vertical integration prevents storage 'hold-up'; Volume certainty	Suitable only for demonstration phase; Early pipelines may become obsolete once demand grows
Local clusters with government support	Local sources club together to fund infrastructure; government aggregates volume information to avoid collusion and sharing of commercially sensitive information	Greater resilience; Economies of scale; Possibility of linking up multiple clusters; Risk shared out among competitors	Requires government expertise to process volume information and plan infrastructure; Risk of distorting competition by favouring some firms over others
Concession for integrated system	Comprehensive system of transport and storage infrastructure in common ownership, possibly with financially protected regulated asset base; public supervision of pricing and third party access	Low cost of capital; High resilience; Comprehensive coverage; Vertical integration prevents storage 'hold-up'	Risk of stranded assets; Natural monopoly

Applying the incentive at biological sequestration has the benefit of directly encouraging the production of biomass. However, if this incentive is to be limited to biomass used for BECCS, applying it at sequestration entails that the downstream use of biomass must be accounted for, which creates an administrative burden. Applying the incentive to all biomass, regardless of downstream usage, would remove the need for dedicated downstream monitoring, but may dramatically increase the costs of monitoring required to account for emission from biomass production and harvesting. However, these drawbacks may be mitigated somewhat by the fact that a sequestration incentive could be easily applied to any new technologies that sequester CO_2 directly from the atmosphere. This could provide a stimulus to R&D aimed at technologies that directly capture CO_2 from the air.

Applying the extra incentive at capture provides direct support for the biomass plant. It allows using the same administrative infrastructure as for administering the regular CCS incentive, which lowers transaction cost. However, if biomass from a variety of sources is used in the same plant, calibrating support to adequately reflect the associated environmental benefits may be challenging. Assessing the emissions from land use and land-use change of the biomass converted in the plant would require a monitoring system located upstream, with obvious implications on cost.

A key advantage of applying the additional incentive at storage is that the delivery risk remains with the private sector until the CO_2 has been injected. This gives BECCS operators an incentive to collaborate with transport and storage operators, potentially increasing the stability and quantity of infrastructure provisions. However, careful accounting may be needed to avoid cheating, for example through the re-designating of captured CO_2 from fossil sources as CO_2 from biomass.

In addition to the considerations above, institutional structures and overarching policy goals will affect the point of incentivisation. A country that is keen to develop its CCS industry and already has an appropriate incentive scheme in place may wish to place the incentive at the point of storage and capture, while countries for which biomass production already represent an important element of its energy supply may see value in placing the incentive at the point of sequestration. No particular point of incentivisation is hence likely to be optimal across all locations and circumstances, and the final decision will be shaped by a range of economic, political and institutional considerations.

6. A policy architecture for CCS

Effective support policy for CCS needs to be both flexible and predictable. A policy architecture that integrates the individual policy options identified in the previous section is a promising way of reconciling these conflicting needs.

In seeking to achieve deep emission cuts at lowest possible costs, governments will want to retain flexibility in their CCS support policies: first, because of the uncertainty surrounding the costs and performance of CCS itself; second, because of the uncertainty of costs and performance of rival technologies; and third because of wider macroeconomic uncertainty. For these three reasons, governments may prefer to adjust CCS policy flexibly in response to changing circumstances. In addition, CCS is affected by multiple market failures, the relative importance of which is likely to change over time. Policy makers may wish to adjust their policy mix to respond to these changes.

However, there is also a need for CCS support policy to be predictable and stable: private investors react strongly to perceived policy uncertainty. This sensitivity to policy risk is particularly high when assets are long-lived and heavily dependent on policy support for their commercial viability (Hamilton, 2009).

While policy makers and the changing balance of market failures require flexibility, private investors require certainty. This antinomy of needs, we argue, can be overcome by integrating the different individual policy instruments analysed above into an overall policy architecture.

6.1. Outline of the evolution of CCS market failures over time

The relative importance of the five market failures discussed in Section 4 is likely to change over time. In the earlier stages of CCS deployment, the creation of knowledge about CCS (a public good problem), and overcoming capital market failures are likely to be the two dominant objectives warranting policy interventions. However, once lenders become familiar with CCS projects, and once the salient lessons have been learned from early projects, these two market failures fade in importance.

Market failures related to complementary markets and to imperfect competition are likely to persist throughout the evolution of CCS. However, once they have been addressed, for example through the integration of complementary markets and the regulation of natural monopolies, further action may not be required. On the other hand, the emission externality, as a stock

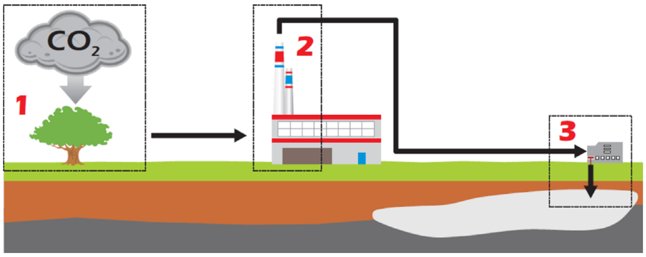

Fig. 3. Incentives for BECCS could be applied during sequestration (1), capture (2), or storage (3).
Source:International Energy Agency (2012).

problem rather than a flow problem, will grow in importance over time as the stock of CO_2 in the atmosphere increases. This suggests a need to tighten the stringency of emission reduction policies over time.

To reflect this change in the importance of different market failures over time, CCS support policy should change from initially using public funding to secure early projects and the associated learning, towards a general emission reduction policy addressing the emission externality. Regulation to correct the twin market failures of complementary markets and imperfect competition could proceed in parallel, persisting for as long as CCS projects are in operation.

6.2. *Key features of a policy architecture*

The overall objective of a policy architecture is to resolve the conflict between the needs of private investors, who desire policy certainty and predictability, and those of policy makers, who do not want to commit to CCS in case it turns out not to be required in order to meet emission targets at least cost. The policy architecture also serves to accommodate the evolution of CCS market failures, explored above, by aligning policy changes with changes in the preponderance of market failures.

Building a policy architecture for CCS would involve three activities, namely

- identifying characteristic phases in the deployment of CCS;
- specifying policy instruments that are used to support CCS in each phase;
- designing policy gateways or milestones at the end of each phase by specifying criteria which must be satisfied in order for the next set of policies to become effective, and the consequences of failing to reach these criteria.

By offering a *conditional* commitment towards specific policies in the various phases of the policy architecture, the policy framework creates the flexibility the policy maker requires. At the same time the architecture offers the private sector a high degree of predictability regarding CCS policies by making explicit what these policies are, how they change, and under which conditions they change.

6.3. *Further specification of gateways*

As part of the policy architecture, the policy maker *conditionally* commits to certain support policies. The role of policy gateways is to flesh out this conditionality. They consist of a series of criteria which must be met in order for the next phase of support policy to become operative. One of these criteria may be a deadline, specifying by when the other criteria must be met. Passing through a gateway may involve passing certain technical inspections, achieving certain cost levels, showing sufficient storage capacity in the ground, or any other conditions that the policy maker deems as relevant. The particular set of criteria for each gateway will depend on

- the particular circumstances in which the policy is expected to operate, such as current CCS and rival technology cost levels, projections of emissions and required emission targets, and macroeconomic conditions;
- and the specific risks against which a policy maker wants to hedge, for example technological non-performance risk or commercial non-performance risk.

The crucial aspect is that policy gateways inform private investors in advance about what is required of CCS technology to unlock the next stage of support policy, and by when. Thus policy gateways are primarily a *conceptual tool* to codify the evolution of CCS policy and to make it as predictable as possible.

A further important function of policy gateways is the *ex-ante* specification of governmental actions in case one or more of the gateway criteria are missed. Options governments have at their disposal include modification, withdrawal or reducing CCS incentives. The latter option may be appropriate if gateway criteria are only narrowly missed and there is scope for improvement at the margin. Key considerations shaping governmental responses to missed gateways could include the potential contribution of CCS to emission reductions, the attractiveness of alternative abatement measures, and the desire to avoid 'throwing good money after bad', i.e., continuing support for an underperforming technology.

6.4. *A possible policy framework for CCS*

A possible policy framework for CCS can be constructed by dividing the CCS development path into three phases (see Fig. 4).

1. Technical demonstration;
2. sector-specific deployment; and
3. wide-scale deployment.

Policies in phase 1 are primarily intended to address the underinvestment in CCS resulting from the inability of investors to appropriate the learning their investments generate. Public funding via capital grants and operating subsidies could overcome this market failure and ensure that a sufficient number of CCS projects are implemented to allow for technical demonstration and basic learning. To protect the policy maker from technology and cost risks, the first policy gateway could involve the demonstration of technical feasibility, a first cost threshold, and a confirmation of sufficient storage capacity, all by a specified date. If these conditions are met, policy could proceed to phase 2.

Policies in phase 2 could consist of a quantity support mechanism, e.g. a government CO_2 purchasing contract or a portfolio standard, together with infrastructure support policy, such as contract regulation, and loan guarantees replacing the capital grants used in phase 1. These policies would allow capital market players to become familiar with the characteristics of CCS projects, thereby overcoming the capital market failures of imperfect information. The policies would also make a contribution to addressing the emission externality, even though that would not be their primary purpose at this stage. At the end of phase 2 CCS should have been deployed throughout a pilot sector, so that its cost relative to other abatement options are fully apparent.

To protect the policy maker from endlessly supporting an uncompetitive technology, the third gateway could check for further cost reductions by a certain date, for example five or ten years after entering phase 2. In addition, satisfactory infrastructure development and the geological availability of appropriate storage locations could constitute criteria for proceeding to the next phase of support policies. Phase 3 would see a gradual phasing out of

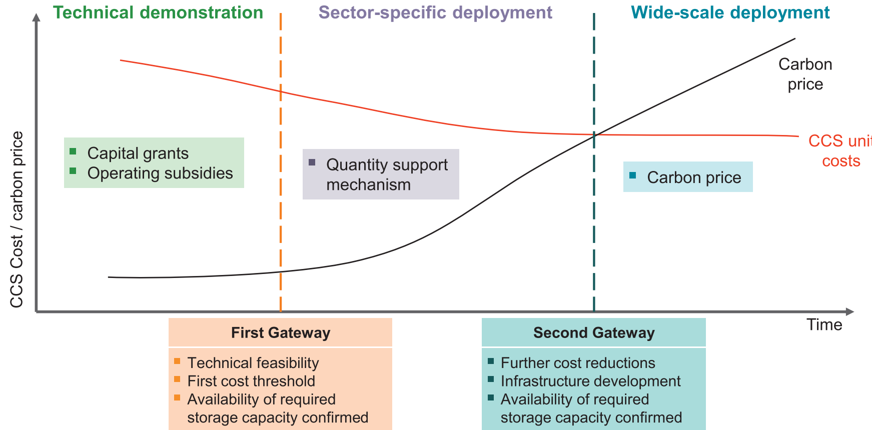

Fig. 4. An illustrative policy architecture for CCS
Source: International Energy Agency (2012).

CCS-specific support, a firming up of the regulatory regime, and the facilitation of commercial structures between capture, transport and storage operators by governmental regulation. If sufficient cost reductions are achieved and abatement targets are sufficiently ambitious, a carbon pricing mechanism, for example a carbon tax, may suffice to support widespread deployment and operation of CCS. Besides CCS-specific regulation, phase 3 would not involve any CCS-specific support policy.

The aim of phases 1 and 2 is to secure the *option* of CCS deployment in the future; whether or not it is then widely deployed in phase 3 would depend on the cost performance of CCS relative to other abatement technologies, and on the ambition of emission targets. The price trajectory indicated in Fig. 4 for example assumes that targets are ambitious enough and CCS cost competitive enough for this to be the case.

To sum up, in our framework policy instruments change in accordance with the relative importance of the four market failures identified above. Initially the policy objective is to correct the public good and imperfect information market failure; as CCS deployment progresses over time, and more and more of the relevant information is generated, this type of market failure decreases in importance. Eventually the carbon externality becomes the single most significant market failure requiring policy intervention. The issue of complementary markets is present throughout the CCS deployment path, and is best addressed with solutions that depend on the scale of infrastructure and storage required, as explored in Section 5.2.4.

7. Conclusions

CCS has the potential to significantly reduce GHG emissions that cause dangerous climate change. When used in combination with bioenergy (BECCS), it is actually one of the very few technologies available to reduce the atmospheric stock of CO_2, as opposed to merely avoiding additional emissions to the atmosphere. However, to secure the option of possible future deployment at scale, the number of CCS projects needs to increase substantially over the next few decades. Such an increase requires support policies that establish CCS as a mature technology that can potentially compete commercially with other abatements options when CO_2 emissions are priced.

As CCS will encounter multiple market failures with changing importance on its development path, support policies need to involve multiple instruments over time. The paper outlines a policy architecture for CCS that is structured into 3 phases, namely technical demonstration, sector-specific deployment and wide-scale deployment, and corrects market failures related to

- the negative externality from greenhouse gas emissions;
- the public good from the creation of knowledge and innovation;
- the asymmetry of information which discourages the provision of capital;
- the presence of complementary markets when one firm depends upon another to get its goods to market; and
- imperfect competition where transport and storage can be natural monopolies.

The immediate implication is that a policy that only corrects the emission externality, for example by putting a price on CO_2 emissions, will not suffice to secure the option of future CCS deployment. Pricing instruments need to be complemented by instruments that tackle the underinvestment in CCS that results from the public good character of innovation in CCS technology, and by instruments that hedge the risks for capital providers that lack the information relevant for making informed CCS investment decisions. As regard to the former a premium feed-in tariff or a quantity-based instrument may be effective, while information asymmetries could be obviated by public provision of investment capital or guarantees.

To tackle issues related to complementary markets, government may facilitate and coordinate the formation of CO_2 transportation networks connecting multiple capture plants to storage facilities. Public supervision through regulation could then be modelled on electricity transmission and distribution networks, in order to address the question of imperfect competition and natural monopoly.

As CCS evolves over time, the significance of different market failures will change, requiring in turn changes in support policy. Specifically, governments will want to retain the option of reducing or ending CCS support policy because of the uncertain costs and technical performance of CCS in relation to rival technologies. However, private investors seek certainty and may hesitate to invest unless an appropriate degree of policy stability is achieved. We set out a solution to this dilemma: support within the policy framework hinges on meeting certain conditions. By offering only *conditional* policy commitments, policy makers can hedge against risks. At the same time, by making explicit what these policies are, and what the private sector needs to deliver for governments to continue supporting CCS, the architecture offers the private sector a high degree of predictability.

This allows government to commit funds without the risk of overstretching its resources or imposing poor value-for-money obligations on others.

The deployment of BECCS faces the same type of market failures as conventional, fossil-fuel based CCS, so that the insights gained so far also apply to BECCS. However, public support for BECCS should be commensurate with its environmental benefits which potentially exceed that of conventional, fossil-fuel based CCS.

To develop economy-specific policy recommendations, the present qualitative analysis would need to be supplemented by quantitative economic modelling. While relevant work is available (e.g., van der Zwaan and Gerlagh 2006), a quantitative analysis of an integrated policy architecture for CCS appears not to have been undertaken to date.

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