Working Paper 05/2016

Promoting CCS in Europe: A case for green strategic trade policy?

Rolf Golombek, Mads Greaker, Simen Gaure, Sverre A.C. Kittelsen and Knut Einar Rosendahl

The CREE Centre acknowledges financial support from The Research Council of Norway, University of Oslo and user partners.
ISBN: 978-82-7988-225-1
ISSN: 1892-9680
http://www.cree.uio.no

Abstract in Norwegian:

CREE - Working Paper 05/2016

Hvordan bør karbonfangstteknologier støttes?

Rolf Golombek, Mads Greaker, Simen Gaure, Sverre A.C. Kittelsen and Knut Einar Rosendahl

Det internasjonale energibyrået IEA predikerte for noen få år siden at karbonfangstteknologier - Carbon Capture and Storage (CCS) – kan komme til å bidra med en sjettedel av CO2-utslippsreduksjonen i 2050. Det er likevel få tegn i dag som tilsier at markedsandelen for CCS-teknologier skal få et markant oppsving; det er færre enn 10 fullskala CCS anlegg på verdensbasis. IEA mener derfor at det er avgjørende å få etablert støtteordninger for CCS.

I denne rapporten studerer vi hvordan støtteordninger for CCS kan utformes. Bør en primært satse på å subsidiere utvikling av teknologien – oppstrømssubsidier – eller snarere å subsidiere anskaffelse av teknologien – nedstrømssubsidier? Vi drøfter dette spørsmålet både innenfor en teoretisk modell og ved å benytte en stor numerisk modell for de europeiske energimarkedene.

Det er fremdeles bare et fåtall utviklere av CCS-teknologien både i EU og utenfor EU. Det lave antallet tilsier at myndighetene bør iverksette tiltak for å unngå oligopolprising med tilhørende effektivitetstap. Vår teoretiske analyse tar inn over seg den manglende konkurransen mellom CCS utviklerne. Vi viser at det er optimalt å støtte utviklerne av CCS-teknologien innenfor EU, ikke kjøperne av CCS-teknologien. En slik politikk vil bidra til å stimulere til økt utvikling og salg fra EU-utviklerne, til fortrengsel for utviklerne utenfor EU.

Den empiriske analysen bekrefter hovedkonklusjonen fra den teoretiske modellen. Vår numeriske modell inkluderer flere effekter som er utelatt i den teoretiske modellen, bl.a. gevinsten av lavere CO2-utslipp og strategiske handelseffekter som følge av at EU er en stor importør av både kull og naturgass. Begge disse faktorene tilsier at støtten til kullkraftverk med CCS teknologi bør være større enn støtten til gasskraftverk med CCS teknologi.

Abstract

We study to what extent promotion of CCS in Europe should be through subsidising development and production of CCS technologies – an upstream subsidy – or by subsidising the purchasers of CCS technologies – a downstream subsidy. This question is examined theoretically in a stylized model and numerically by using a well known economic model of the European energy market.

For the numerical study, we develop a new approach that integrates strategic trade policy with CGE models. The numerical simulations confirm that upstream subsidies should be preferred over downstream subsidies. Furthermore, the numerical simulations cover effects that are not included in the theoretical model. These are the welfare effects of lower CO2 emissions, obtained through increased use of CCS, and terms-of-trade effects, reflecting that the EU is a major importer of both coal and gas and demand for these fossil fuels increases when CCS subsidies are offered. Both factors rationalize a higher subsidy to CCS coal than to CCS gas.

1. INTRODUCTION

In its 2013 report on carbon capture and storage (CCS), the IEA predicts that CCS will contribute to one sixth of the required CO2 emissions reductions by 2050 (IEA, 2013). Yet, current CCS projects have been facing severe challenges. The EU launched the Zero Emission Platform in 2007, and aimed to have 12 full scale CCS plants in operation by 2015. Today, it seems like at most one of the projects will be realized. Similarly, the Norwegian government planned to have a full scale CCS operation in place at the gas power plant at Mongstad by 2015, but in 2013 the project was cancelled.

According to IEA (2013), the largest challenge for CCS deployment is the integration of component technologies into large scale projects. IEA (2013) further holds that a key action is to introduce financial support mechanisms for early deployment of CCS. There are two business models to spur CCS: One option is to provide support to power plant investors by covering a part of the additional investment cost of CCS. This is the route the Norwegian government followed. The alternative model is to focus on the CCS technology suppliers by supporting their research, development and/or demonstration constructions.

To our knowledge, the literature has not yet compared the pros and cons of the two routes. Thus, our first research question is to what extent promotion of CCS in Europe should be through subsidising development and production of CCS technologies – an upstream subsidy – or by subsidising the purchasers of CCS technologies – a downstream subsidy.

The CCS technology can be applied both to gas power and to coal power. These two technologies are likely substitutes in demand. Our second research question is therefore to what extent the EU should give priority to one of the CCS technologies. We study the research questions both theoretically within a stylized game theoretic model and numerically by using a well known economic model of the European energy market. In the analyses we take into account that competition between CCS technology suppliers likely is imperfect as there are only a few potential suppliers in the world.

Based on standard economic theory one may wonder whether the distribution between an upstream and downstream subsidy is of any importance: In a closed economy, it is of no importance whether a (positive or negative) tax is imposed on supply or demand, and this is the case both with competitive markets and under imperfect competition. However, this reasoning is based on the assumption that either all producers face the tax or all consumers face the tax, which may be the case in a closed economy. However, in the real world some CCS technology suppliers are based outside the EU, while some are based in the EU. Thus, if an upstream subsidy is offered, only the producers within the EU might be eligible for the subsidy. Once some agents in a group do not receive the subsidy, the equivalence between an upstream and a downstream subsidy/tax no longer holds.

The formal analysis indicates that CCS promotion in the EU is a case for green strategic trade policy. Strategic trade policy is extensively treated in the trade literature, see, for example, Brander and Spencer (1985), Neary (1994), and Leahy and Neary (1997; 1999). This literature typically assumes that there is production of a homogenous good in two countries but consumption in another country, imperfect competition and no externality. We depart form this literature by assuming there is consumption only in one of the producing countries, the one referred to as the EU because we believe that over the next years the will only be a market for CCS within the EU. The main research question is whether an upstream subsidy or a downstream subsidy should be used by the EU to improve its welfare.

Taking into account the standard welfare components, that is, the EU producer surplus, its consumer surplus and the tax revenue of the EU, and under the assumption of no externality, we show that with one good it is optimal to offer an upstream subsidy to the EU producers, but no downstream subsidy. Both subsidies increase the use of the technology/production, which is desirable due to imperfect competition in the market. However, by prioritizing an upstream subsidy to the EU producers, production and profits are shifted from the non-EU producers to the EU producers. In contrast, a downstream subsidy stimulates production also from the non-EU producers, which, *ceteris paribus*, shifts profits from the EU producers to the non-EU producers. With the optimal upstream subsidy the EU producers are stimulated to increase their production by so much that they voluntarily choose their competitive quantities. Hence, price will be equal to the constant unit cost of production and there will be no production from the non-EU producers.

We then solve the model with two goods. Then the EU government may offer four subsidies: one upstream subsidy to good (technology) 1, another upstream subsidy to good 2, one downstream subsidy to stimulate purchase of good 1 and another downstream subsidy to promote good 2. In our model the reason to subsidise is to shift profits from non-EU producers to EU producers, and to increase the supply of goods in general, thereby benefiting also the consumers. We find that the optimal design of subsidies is identical in the cases of one and two goods.

While the theory models in Section 2 give rules of thumb of how to design upstream and downstream subsidies, we apply a numerical model of the Western European energy markets – LIBEMOD - to illustrate the magnitudes of the optimal subsidies and their impacts on the energy markets. Although there exist several numerical studies of strategic trade policy,[1] to our knowledge no study has yet used a comprehensive model like LIBEMOD, which has a detailed treatment of the electricity sector.

In LIBEMOD, electricity can be produced by a number of electricity technologies, including conventional fossil-fuel based plants, CCS plants using either natural gas or coal, and renewables. While costs of investment and operating costs are higher for CCS plants than for

[1] See for instance Baldwin and Krugman (1988), Venables (1994) and Greaker and Rosendahl (2008)

conventional fossil-fuel based plants, the CCS technologies remove most of the carbon from the fossil fuels that have been combusted. For a given set of parameters, for example, efficiencies of electricity plants and costs of investment in electricity plants, as well as a set of policy instruments, for example, a uniform carbon tax, LIBEMOD simulates the equilibrium of a future year. This set up is, however, not suitable to examine the impact of upstream and downstream subsidies: Whereas the (unit) cost of a CCS plant is a parameter in LIBEMOD, we want this cost, which is the price of a CCS plant, to be endogenous. In order to establish a model with endogenous price formation of CCS plants, we develop a three stage procedure that integrates Cournot competition with a CGE model with competitive markets, see Section 3.

According to the numerical simulations, if the CO2 tax in 2030 is USD 90 and only downstream subsidies are used, CCS coal power plants should receive a 25% investment subsidy (in 2030) while CCS gas power plant should receive no subsidy. On the other hand, if only upstream subsidies are used, suppliers of CCS technology should receive a 95% coal power construction cost subsidy and a 45% gas power construction cost subsidy. Note that the numerical simulations confirm that upstream subsidies should be preferred over downstream subsidies.

The numerical simulations encompass two effects that are not included in the theoretical models. First, the welfare effect of reduced CO2 emissions through increased use of CCS is taken into account. Because coal has a higher emission coefficient than gas, *ceteris paribus*, it is more welfare improving to replace conventional coal power with CCS coal power than to replace conventional gas power with CCS gas power. Second, Western Europe is a major importer of natural gas and coal. Policies that increase the price on imported gas and coal therefore have a negative terms-of-trade effect. In LIBEMOD, increased demand for natural gas in Western Europe tends to increase the price of gas significantly, whereas the effect of increased demand for coal on the price of coal is moderate. The latter reflects that coal is traded in a global market (whereas natural gas is traded in a European market), and the supply elasticities of coal are large (whereas in LIBEMOD major gas extracting countries have steep marginal cost functions). The terms-of-trade effect reinforces why CCS coal power should receive a higher upstream subsidy than CCS gas power.

2. UPSTREAM VS. DOWNSTREAM CCS SUBSIDIES

In this section we examine whether it is optimal to stimulate production from a new technology through an upstream or a downstream subsidy. We assume there is no externality in the economy; we will later return to the case of externality.

2.1 One good

We consider an economy where there is production of a homogeneous good in two countries. Production of the good does not cause any externality. Let $X_{d,i}$ be production of the good in the domestic country by producer *i*, $i = 1,...,n$ and let $X_{f,j}$ be production of the good in the foreign country by producer *j*, $j = 1,...,m$.

The good is only demanded in the domestic country, and demand is given by

$$p = A - a(\sum_{i=1}^{n} X_{d,i} + \sum_{j=1}^{m} X_{f,j}). \tag{1}$$

Here, *p* is the price of the good and A and *a* are (positive) parameters.

We assume that for all producers, *c* is the constant unit cost of production where $c < A$. In the domestic country all producers receive an upstream subsidy s $(0 \leq s < 1)$.[2] Hence, for these producers the net cost of production is $c(1-s)$. The upstream subsidy is offered by the domestic government, which also offers a downstream subsidy η $(0 \leq \eta < 1)$ to all buyers of the good. Thus whereas p is the price paid by the buyers of the good, ω is the price received by the producers where

$$\omega(1-\eta) = p. \tag{2}$$

Using (1) and (2), the profit of a domestic producer is given by

$$\Pi_{d,i} = [\frac{A - a(\sum_{i=1}^{n} X_{d,i} + \sum_{j=1}^{m} X_{f,j})}{1-\eta} - c(1-s)]X_{d,i}. \tag{3}$$

Similarly, the profit of a foreign producer is

[2] Below we disregard the non-interesting cases of subsidy rates equal to one.

$$\Pi_{f,j} = [\frac{A - a(\sum_{i=1}^{n} X_{d,i} + \sum_{j=1}^{m} X_{f,j})}{1-\eta} - c]X_{f,j}. \tag{4}$$

Maximizing profit of each producer and imposing that in equilibrium all domestic producers supply the same quantity ($X_{d,i} = X_d$) and also all foreign producers supply the same quantity ($X_{f,j} = X_f$), we have

$$X_d = \frac{c}{a(1+n+m)}[l + ((m+1)s - 1)(1-\eta)] \tag{5}$$

$$X_f = \frac{c}{a(1+n+m)}[l - (ns+1)(1-\eta)] \tag{6}$$

where $l = \frac{A}{c} > 1$. From (5) and (6) we find that a higher upstream subsidy s increases domestic production but lowers foreign production. Further, a higher downstream subsidy η has an ambiguous effect on domestic production, whereas foreign production will increase:

$$\frac{dX_d}{d\eta} = \frac{-c((m+1)s-1)}{a(1+n+m)} \tag{7}$$

$$\frac{dX_f}{d\eta} = \frac{c(ns+1)}{a(1+n+m)} > 0 \tag{8}$$

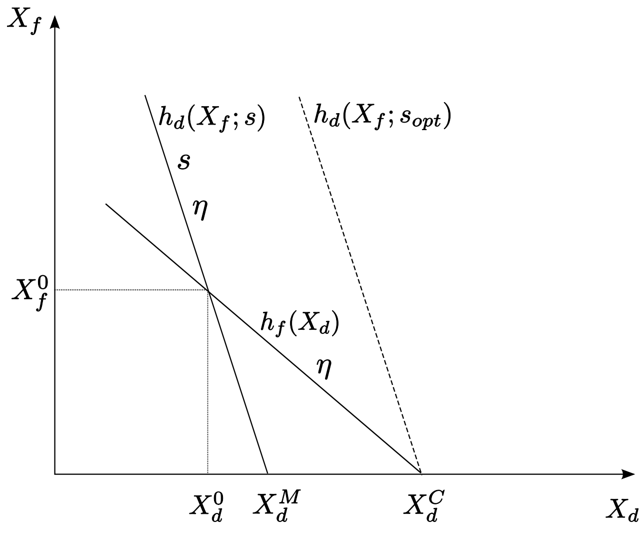
From (7) we see that provided the upstream subsidy is "low", that is, $(m+1)s < 1$, for example, $s = 0$, then a higher downstream subsidy will for sure increase also domestic production (see discussion below).

In order to gain intuition of why an upstream subsidy works differently than a downstream subsidy, it is expedient to consider the best-response curves for the domestic producer and the foreign producer in the special case of one producer in each country, see Figure 1. Because each producer has quantity as his decision variable (Cournot competition), it is well known that the response curves of the domestic producer, $h_d(X_f; s)$, and the foreign producer, $h_f(X_d)$, are downward sloping. Note that a higher upstream subsidy s shifts the response curve of the domestic producers outwards, whereas it has no impact on the response curve of the foreign producer simply because this subsidy does not enter the first-order condition of the foreign producer. Under our assumptions, which satisfy the standard "stability" condition of Cournot competition, a higher upstream subsidy will increase domestic production and lower foreign production, but the decrease in foreign production is moderate (the slope of each response curve is -0.5) so that total production increases.

Because the downstream subsidy η enters the first-order condition of both producers (through the demand function), a higher downstream subsidy shifts both response curves outwards; the shifts are $\frac{dX_d}{d\eta} = \frac{c(1-s)}{2a} > 0$ and $\frac{dX_f}{d\eta} = \frac{c}{2a} > 0$. Thus the shift is greatest for the foreign firm. As seen from Figure 1, the larger the shift of a response curve, the higher is the increase in own production. Hence, the foreign firm will increase its equilibrium production when the downstream subsidy is increased, see (8).

Why is the shift largest for the foreign firm? One way to explain this fact is to consider the first-order conditions, which, for the domestic producer, can be written as (when $n = m = 1$) $A - a(2X_d + X_f) = c(1-s)(1-\eta)$. An increase in η will decrease the right-hand side of the equation, and for given X_f, X_d has to increase in order to lower the left hand side of the equation. The change on the right-hand side of the equation is larger the larger is $c(1-s)$. The foreign producer has a corresponding expression where $s = 0$. Hence, a change in η will cause a larger change on the right-hand side of the first-order condition of the foreign producer than of the domestic producer. This explains why the shift in the response curve is largest for the foreign producer.

Figure 1 The Cournot equilibrium with one good and two producers



Let V_d be the maximized profit of a domestic producer. Using (3), (5) and (6) we find:

$$V_d = \frac{c^2}{a(1-\eta)(1+n+m)^2}[l+((m+1)s-1)(1-\eta)]^2. \quad (9)$$

From (9) we see that a higher upstream subsidy s raises the maximized profit of a domestic producer, whereas a higher downstream subsidy η in general has an ambiguous effect on the maximized profit of a domestic producer; this reflects, of course, that one partial effect of a higher downstream subsidy is increased production from the foreign producers, which lowers the price of the good.

To illustrate that the sign of $\frac{dV_d}{d\eta}$ is ambiguous, consider the subsidies $s=0$ and $s=\frac{1}{m}$. For these subsidies we always have $\frac{dV_d}{d\eta}>0$. Next, define the subsidy $\bar{s}=\frac{l+1}{m+1}+\varepsilon$ where ε is small and $l<m$ to ensure that $\bar{s}<1$. Then for $\eta=0$, $\frac{dV_d}{d\eta}>0$ if $\varepsilon<0$ and $\frac{dV_d}{d\eta}<0$ if $\varepsilon>0$. Proposition 1 summarizes the discussion above:

Proposition 1. The maximized profit of a domestic producer is higher the higher is the upstream subsidy, whereas the effect of a higher downstream subsidy on the maximized profit of a domestic producer is in general ambiguous.

According to Proposition 1, a higher upstream subsidy will always benefit the domestic producers. Because a higher upstream subsidy decreases the equilibrium price (total production increases) whereas production of the foreign producer falls, profits of each foreign producers will decrease. Proposition 1 suggests that the government in the domestic country should choose a high upstream subsidy but a low downstream subsidy to shift profits from the foreign producers to the domestic producers. But how high should the upstream subsidy be and how low is the optimal downstream subsidy; is the latter zero? In order to answer this question we have to specify the other welfare components of the domestic country, that is, consumer surplus and the tax revenue of the domestic government.

Consumer surplus is given by

$$S = \int_0^q (A-ax)dx - q(A-aq). \quad (10)$$

where q is total quantity produced by the domestic and foreign producers. Next, total payment of subsidies from the domestic government is

$$T = \eta(\frac{p}{1-\eta}q) + scnX_d. \quad (11)$$

Total welfare of the domestic country is thus:

$$W = nV_d + S - T. \qquad (12)$$

We now maximize total welfare of the domestic country with respect to the upstream subsidy s and the downstream subsidy η. The resulting optimal subsidies are summarized in the following proposition:[3]

Proposition 2: For the domestic country, the optimal downstream subsidy is zero whereas the optimal upstream subsidy is $s = \frac{1}{n}(\frac{A}{c} - 1)$.

Proposition 2 gives a simple policy rule: The domestic government should offer a subsidy only to the domestic producers of the good. The subsidy should be higher the higher the choke price is relative to the unit cost of production ($\frac{A}{c}$). Further, the subsidy rate should be lower the more domestic producers, and total payment of subsidies to the domestic producers should be $(A-c)X_d$, that is, independent of the number of domestic producers (each of these has a constant unit cost of production). By offering the optimal subsidy to the domestic producers the equilibrium price will be c, and thus there will be no production from the foreign producers. The domestic government should therefore offer a subsidy that stimulates domestic production by so much that domestic producers sell the same quantity as they would have done had they been price takers and received no subsidy, that is, the optimal subsidy neutralizes the imperfect competition effect. We thus have:

Proposition 3: In equilibrium price will be equal to the constant unit cost of production. There will be no production from the non-EU producers. The EU producers supply their competitive level of production.

We now illustrate the solution in Figure 1. The two response curves are drawn for a set of subsides. For given subsidies X_d^M is the monopoly quantity of the (single) domestic producer; this is the optimal response of the domestic producer given no production from the foreign producer. Note that $(X_d^M, 0)$ is not an equilibrium because the two response curves do not intersect at this point.

If the domestic producer offers X_d^C, the optimal response of the foreign producer is no production, see Figure 1. An optimal response of no production requires that price is equal to

[3] All optimization problems in this paper were solved by Maple, see http:/www.maplesoft.com/support/help/

the unit cost of production, that is, X_d^C is the quantity that will make price equal to *c*. How can the government make the domestic producer to offer exactly X_d^C?

As explained above, the response curve of the domestic producer shifts outwards when the domestic government increases the upstream subsidy. With the optimal upstream subsidy the response curve of the domestic producer crosses the response curve of the foreign producer at $(X_d^C, 0)$. Hence, this is an equilibrium in which the domestic producer receives the optimal subsidy and freely chooses the competitive quantity X_d^C, although this producer is de facto a monopolist.

2.2 Two substitute goods

The results above are derived under a number of simplifying assumptions. For example, we have assumed a linear demand function and a common constant unit cost of production (all producers are identical). Another simplification is that there is production of one good only. As discussed in the Introduction however, there may be supply of two types of CCS plants; one using natural gas and another using coal. We now extend the analysis to two products, assuming that these are supplied by all producers.

Let $X_{cd,i}$ be production of coal-based CCS plants by the domestic producer *i*, and let $X_{gd,i}$ be production of gas-based CCS plants by this domestic producer. The corresponding variables for the foreign producer *j* is $X_{cf,j}$ and $X_{gf,j}$. Let $X_c = \sum_{i=1}^{n} X_{cd,i} + \sum_{j=1}^{m} X_{cf,j}$ and $X_g = \sum_{i=1}^{n} X_{gd,i} + \sum_{j=1}^{m} X_{gf,j}$ be total quantity of acquired CCS coal and CCS gas respectively. Both coal-fired and gas-fired CCS plants produce electricity, and hence generate utility for those purchasing these facilities. We let the derived utility be represented by

$$U(X_c, X_d) = A_c X_c + A_g X_g - \frac{a_c}{2} X_c X_c - \frac{a_g}{2} X_g X_g - b X_c X_g. \tag{13}$$

Assuming purchasers of CCS are price takers, and choosing units such that the marginal utility of money is normalized to 1, demand for each type of CCS technology is

$$\begin{aligned} p_c &= A_c - a_c\left(\sum_{i=1}^{n} X_{cd,i} + \sum_{j=1}^{m} X_{cf,j}\right) - b\left(\sum_{i=1}^{n} X_{gd,i} + \sum_{j=1}^{m} X_{gf,j}\right) \\ p_g &= A_g - a_g\left(\sum_{i=1}^{n} X_{gd,i} + \sum_{j=1}^{m} X_{gf,j}\right) - b\left(\sum_{i=1}^{n} X_{cd,i} + \sum_{j=1}^{m} X_{cf,j}\right). \end{aligned} \tag{14}$$

In (14) the parameter $b > 0$ reflects the cross-price effect of increased sales; if a producer sells more units of coal-based CCS, the price of this technology will fall. This will shift demand for gas-based CCS inwards, which, cet. par., tends to decrease the price of gas-based CCS.[4]

Turning to production, let c_k be the common unit cost of production of a CCS plant that uses fuel *k* to produce electricity. Here, *k* can be either coal (*c*) or gas (g). Further, let s_k and η_k be the upstream and downstream subsidy rates to technology *k*, respectively. Profits of a domestic producer are now

$$\Pi_{d,i} = [\frac{p_c}{1-\eta_c} - c_c(1-s_c)]X_{cd,i} + [\frac{p_g}{1-\eta_g} - c_g(1-s_g)]X_{gd,i} \qquad (15)$$

whereas profits of a foreign producer are:

$$\Pi_{f,j} = [\frac{p_c}{1-\eta_c} - c_c]X_{cf,j} + [\frac{p_g}{1-\eta_g} - c_g]X_{gf,j} \qquad (16)$$

Like above, we assume that all producers maximize profits and that all domestic (foreign) producers supply the same quantity in equilibrium. We define the maximized profit of a domestic producer (V_d) and the tax revenue of the domestic country (*T*) similarly as in the case of one product. Consumer surplus (*S*) is now defined as the difference between gross utility and purchasing costs; $U(X_c, X_d) - p_c X_c - p_d X_d$. With two goods the domestic government maximizes domestic welfare $W = nV_d + S - T$ with respect to the four subsidy rates s_k and η_k under the restrictions that each subsidy rate is non-negative and lower than one.

To find the equilibrium using Maple, we proceeded in four steps:

i) First we maximized domestic welfare *W* with respect to the four subsidy rates without taking into account that these should be below zero and one, that is, we seek an interior solution. Maple did not find any interior solution, that is, the solution has to be at the boundary.

   Below we restrict ourselves to an economic meaningful problem, that is, we assume that costs are not fully covered by the government ($c_k < 1$) and that the purchasers of the CCS technology have to pay a strictly positive price ($\eta_k < 1$).

[4] The utility function (13) requires that the cross-price effect does not differ between the two products. In Section 4 we estimate these demand functions and find that the difference between the *b* parameter for coal and the *b* parameter for gas is tiny and not significantly different from zero.

ii) Second, we imposed the restrictions that each subsidy rate is non-negative and strictly less than one and specified the problem using the Kuhn-Tucker formulation. Maple was not able to solve this problem. This reflects that the problem is very complex.

iii) Third, we used the Kuhn-Tucker formulation to find the solution under the restrictions that a) each subsidy rate is non-negative and strictly less than one, and b) one downstream subsidy is exogenously set to zero. The resulting solution is characterized by the other down-stream subsidy being zero, whereas the upstream subsidy is given by $s_k^* = \frac{A_k - c_k}{c_k n} = \frac{1}{n}(\frac{A_k}{c_k} - 1)$, that is, has exactly the same structure as in the case of one good, see Proposition 2. Because this is the solution independent of which downstream subsidy is set to zero, the solution of the problem specified in ii) must be characterized by zero down-stream subsidies and upstream subsidies equal to s_k^*.

iv) Finally, to check whether there is more than one solution we solved the maximization problem under the restrictions that a) both downstream subsidies are zero, and b) upstream subsidies are non-negative and strictly less than one. This produced the same solution is the one in iii). Hence, there is only one optimal solution.

Note that the optimal upstream subsidies are independent of the cross-price effect *b*. This reflects that the demand functions in (14) are linear. With the optimal upstream subsidies s_k^*, price will be equal to the unit cost of production and hence like in the case of one good there will be no foreign production. The difference between the optimal upstream subsidy to CCS coal and CCS gas is

$$s_c^* - s_g^* = \frac{A_c c_g - A_g c_c}{n c_c c_g} \tag{17}$$

As seen from (17) the optimal CCS subsidy to coal should be highest if, *ceteris paribus*, CCS coal has the highest choke price or the lowest unit cost of production. Hence, the higher the social value of the good, the higher is the optimal subsidy.

The results from the two goods model are summarized in Proposition 4:

Proposition 4: If there is production of two goods, the optimal downstream subsidies are zero whereas the optimal upstream subsidies imply prices equal to the unit cost of production. The upstream subsidy of a good should be higher the higher the choke price and the lower the unit cost of production.

3. STRATEGIC TRADE POLICY IN LIBEMOD

3.1 Description of LIBEMOD

LIBEMOD is an economic simulation model of the Western European energy industry, see Aune et al. (2008) for a detailed documentation, data sources and calibration strategy. Its main focus is on the electricity and natural gas markets in Western Europe, but it also covers global markets for coal and oil. The model distinguishes between model countries – each of 16 Western European countries – and exogenous countries/regions, the latter group contains all countries in the world outside Western Europe.

In each model country there is investment in energy infrastructure, extraction of fossil fuels and production of energy, trade in energy and consumption of energy. LIBEMOD has seven energy goods - coking coal, steam coal, lignite, natural gas, oil, biomass and electricity. While all markets are competitive, the number of countries participating in energy trade varies. Natural gas and electricity are traded between model countries, and also a few exogenous countries, for example, Russia, trade in these two markets. Coking coal, steam coal and oil are traded in global markets, whereas lignite and biomass are traded in domestic markets only. Trade in natural gas and electricity requires gas pipes/electricity lines between pair of countries. At each point in time, the capacities of these pipes/lines are given, but they can be expanded through investment.

There are four groups of users of energy; power producers, households (including services), industry and transport. The first group represents intermediate demand; thermal power producers demand a fuel as an input in production of electricity. This fuel could be steam coal, lignite, natural gas, oil or biomass. The three latter groups represent end-user demand, which is modelled by nested CES utility functions with five levels. While demand from transport is restricted to oil, the other end-user sectors typically demand several of the seven energy goods.

LIBEMOD offers a detailed description of production of electricity. In general, there are a number of technologies available for production of electricity: steam coal power, lignite power, gas power, oil power, reservoir hydro power, pumped storage power, nuclear, waste power, biomass power and wind power, as well as CCS power technologies (see next subsection). Moreover, there is a distinction between “old” and “new” power plants. An old plant had pre-existing capacities in the data year 2000, and for this group of plants capacities cannot be expanded (per assumption).

There are four types of costs in electricity production: fuel costs (not relevant for hydro), maintenance costs (related to the share of the installed capacity that is maintained), start-up costs (related to additional capacity started in a time period) and investment costs. An electricity producer maximizes profits subject to technical constraints and capacities. This leads to operating rules, as well as a decision rule for optimal investment, see Aune et al. (2008). LIBEMOD determines all energy quantities – investment, production, trade and consumption – and all energy good prices (for all fossil fuels, electricity and biomass), both producer prices and end-user prices. In addition, the model calculates emissions of carbon by sectors and countries.

In this study we simulate possible equilibria for the year 2030. The simulations are based on assumptions about a number of factors, for example, future efficiency in conventional electricity plants, future supply curves for fossil fuels and economic growth. These are mainly taken from IMF and OECD projections (e.g., Consensus Economics, 2007); for a more detailed data description, see Aune et al. (2008).[5]

3.2 Modeling CCS

Golombek et al. (2011) draws a distinction between (i) retrofitting CCS to existing plants, that is, adding a capture facility without significantly changing the rest of the power plant, and (ii) acquiring a new plant where CCS is an integrated part of the technological solution, henceforth referred to as a greenfield CCS plant. One of the results in Golombek et al. (2011) is that very little retrofitting will occur. We have therefore chosen to include only two CCS technologies in this study: Greenfield gas power with CCS and greenfield coal power with CCS. Our CCS data are taken from Golombek et al. (2011), which builds on a variety of studies collected by the IPCC special report on "Carbon Dioxide Capture and Storage", see Metz et al. (2005). Relative to conventional fossil fuel plants, CCS plants have a higher cost of investment (due to the carbon capture facilities) and a lower efficiency (because part of the produced electricity is used to remove carbon).

Table 1 gives an overview of our CCS cost assumptions. The numbers in Table 1 are hypothetical because they build on engineering studies, not on actual experience. Compared to other studies, they are in the low-to-middle range, that is, these estimates should be interpreted as the costs of well-developed, commercialized CCS plants rather than the first-of-a-kind plant.

Table 1. Overview of CCS costs

	Coal Greenfield	Gas Greenfield
Reduction in net power output	10 %	15 %
Reduction in CO_2 emissions per MWH	89 %	88 %
Cost of capacity mill $/GW	198	121
COE*without CCS	49.4**	44.8
Incremental COE* increase due to CCS	18.3	18.7
COE* with CCS	67.7	63.5
Abatement cost ($/T$CO_2$ avoided)***	27.4	58.8
Abatement cost ($/T$CO_2$ avoided – with transport/storage)***	35.6	67.4

Source: Golombek et al. (2011).

*COE – average cost of energy.

**All values are measured as $/MWH (2007 USD) unless otherwise noted.

***Engineering figures (no equilibrium effects). Fuel prices taken from the LIBEMOD calibration equilibrium.

[5] The version of LIBEMOD used in the present paper differs somewhat from the one documented in Aune et al. (2008). The main differences are i) electricity is traded in two periods over the 24-hour cycle (six periods in Aune et al. (2008)), and ii) we use a more aggregated representation of coal markets.

Note that whereas average cost of electricity with CCS are higher for coal than for gas, abatement costs are lower for coal than for gas. Note also that the cost share of CCS transport and storage is moderate; this reflects an assumption of substantial volumes of removed carbon, thereby benefitting from economies of scale.

3.3 Implementing a market for CCS technologies in LIBEMOD

The (unit) investment cost of a CCS power plant (coal or gas) is a parameter in LIBEMOD. We want this cost, which is the price of a CCS plant, to be endogenous. In order to simulate a model with endogenous price formation of CCS plants, we develop a new approach which to our knowledge has not been used before.

First, we run the LIBEMOD model to find demand for CCS plants: We specify costs of investment for CCS technologies, and also a carbon policy (here a uniform carbon tax), and run the model for a future year (2030). Then we change the cost assumptions (but keep the uniform carbon tax), and run the model for the same year. This procedure is repeated numerous times (2597). For each model run we find how much of each CCS technology that is purchased. From the set of model runs we can therefore estimate demand for CCS technologies (coal or gas) as a function of costs of CCS investments (given the uniform carbon tax).

Second, we combine this demand block, extended by downstream subsidies, together with a supply block that specifies production of CCS technologies under Cournot competition and upstream subsidies; this corresponds to the model in Section 2.2. In the model there are both EU and non-EU producers of CCS technologies, but only the first group receives upstream subsidies. This model, henceforth referred to as the CCS model, determines, for a given set of subsidies, the price of each CCS technology. By running the CCS model under alternative assumptions about the upstream and downstream subsidies, we find the corresponding prices for CCS technologies.

Third, each vector of CCS prices from the CCS model is then imposed in LIBEMOD as parameter values for costs of investment in CCS technologies. We then run the LIBEMOD model for each vector of parameter values for costs of investment in CCS technologies. Hence, by combining the CCS model and LIBEMOD we find, for each set of upstream and downstream subsidies, the corresponding equilibrium in the energy markets in Western Europe, including how much of each CCS technology that has been purchased. Because we can calculate welfare of different groups in LIBEMOD, we can identify which combination of upstream and downstream CCS subsidies that maximizes the welfare of Western Europe.

Why did we develop this procedure instead of simply extending the LIBEMOD model by a CCS production model block with imperfect (Cournot) competition? The answer is that in order to find the equilibrium under Cournot competition it is necessary to specify the first-order conditions of profit maximization, which requires differentiation of the demand functions. However, as specified above in LIBEMOD end-user demand is represented by nested CES utility functions, and these cannot be differentiated. We use nested CES utility functions to ensure a consistent representation of demand within a multi-good model.

4. RESULTS FROM THE LIBEMOD SIMULATIONS

4.1 Deriving demand functions for CCS

We examine the European power market in the future year 2030 under the assumption that the CCS technology is supplied by three European ("domestic") firms and two non-European ("foreign") firms.[6] In the simulation we fix the CO2 price at $90, which is consistent with the 2^{o}C target according to IEA (2008). The dataset was then used to estimate the following demand functions:

$$\sum_{i=1}^{n} X_{cd,i} + \sum_{j=1}^{m} X_{cf,j} = \alpha_c - \gamma_c p_c + \psi_g p_g$$

$$\sum_{i=1}^{n} X_{gd,i} + \sum_{j=1}^{m} X_{gf,j} = \alpha_g - \gamma_g p_g + \psi_c p_c \qquad (23)$$

where $\alpha_k, \gamma_k, \psi_k$, k= c,g, are parameters to be estimated, and where the terms on the left hand side of (23) are total installed CCS capacity (GW). As specified above, we have 2597 observations. The estimation produced a very good fit; the R-square for CCS coal and CCS gas is 99.8% and 96.7 % respectively. For all parameters the t-values exceed 100. Hence, the estimated demand system provides a very good representation of the derived demand for CCS from LIBEMOD.

The estimates were used to derive the inverted demand functions, that is, the price of a good as a function of quantities, see (13). The derived parameter values are shown in Table 2. In general, the derived cross-price parameter differs between coal and gas, but because the difference is tiny and not significantly different from zero, we use a common *b*-value.

[6] For instance; Alstom (France), Siemens (Germany), Aker Solutions (Norway), Mitsubishi (Japan) and General Electric (US).

Table 2. Demand parameter for CCS coal and CCS gas

Parameter	CCS Coal	CCS gas
Choke price (A)	487	406
Slope (a)	1,33	2,66
Cross-price effect (b)	0,47	0,47

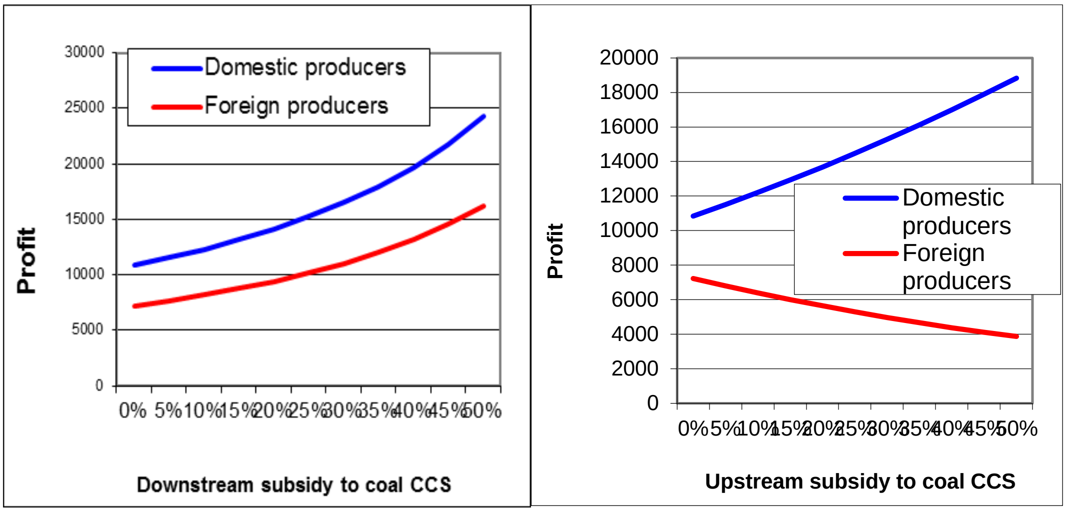
Note that the slope in the demand function is greater for gas than for coal ($a_g > a_c$) and the choke price is higher for coal than for gas ($A_c > A_g$). Even if coal has a higher investment cost (see Table 1), some simple calculations show that the potential consumer surplus is much higher for coal. This suggests, *ceteris paribus*, that coal CCS should be prioritized with respect to subsidizing. (See also discussion in Section 2.2).

4.2 Market effects

The two types of subsidies – downstream and upstream - have different effects on the competition between the CCS technology firms.[7] Below we present two figures which show the effect on total profits of the domestic and foreign CCS technology producers when there are no downstream subsidies to CCS gas, but either a downstream subsidy to CCS coal or an upstream subsidy to CCS coal.

[7] Like in Section 2 all firms produce both CCS coal and CCS gas. Note that there are three domestic firms and two foreign firms. This suggests that, ceteris paribus, total foreign profit is lower than total domestic profit.

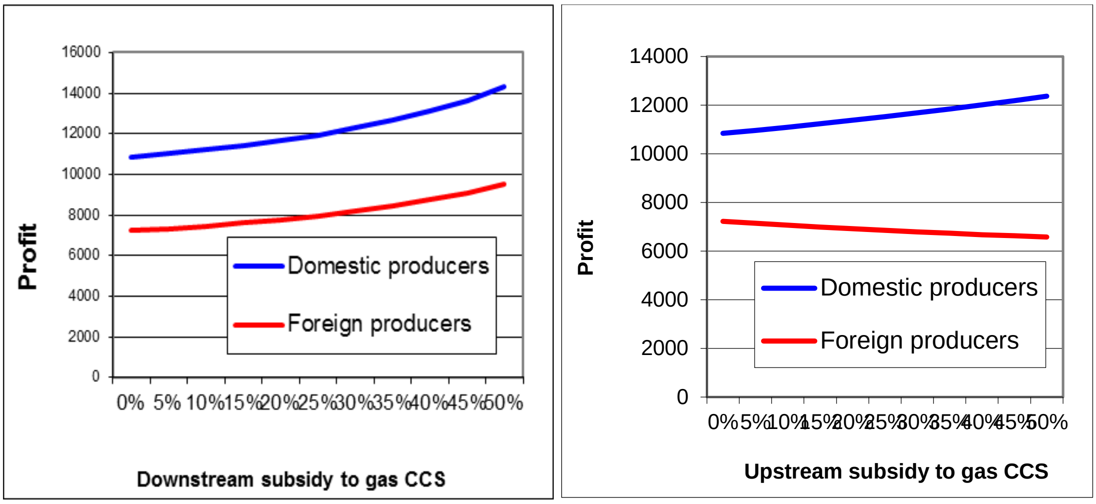
Figure 2. Upstream profits CCS Coal.



In Figure 2, initially there are no subsidies. We then introduce a downstream subsidy to CCS coal, see panel to the left. A higher downstream subsidy to coal yields increased total profits both to the domestic (EU) and to the foreign (non-EU) firms. The latter increase is not a gain to the EU. In the panel to the right we introduce an upstream subsidy to CCS coal (only EU CCS coal producers receive this subsidy) and increase this subsidy from zero. Then profit is shifted from the foreign firms to the domestic firms, and EU welfare increases.

As we can see from the next figure, the picture is very much the same for subsidies to CCS gas:

Figure 3. Upstream profits CCS gas.

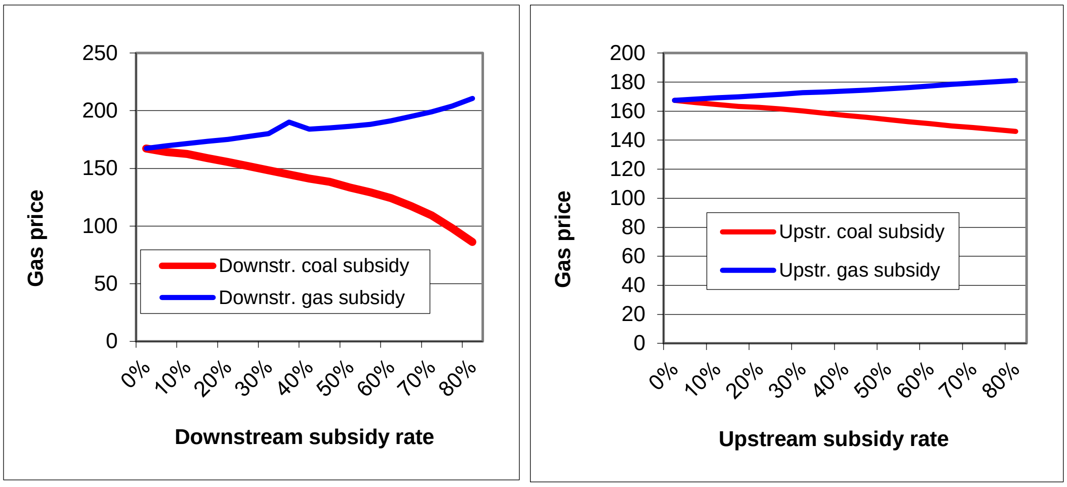


In Figure 3 we vary the subsidy rates for CCS gas from 0 to 50%, and look at the effect on upstream profits. If we compare the scale on the Y-axis in Figure 2 and 3, we see that a CCS gas subsidy affects profits less than a CCS coal subsidy. This has to do with the smaller market potential for CCS gas (see the discussion of the demand functions in the subsection above).

The shift in profits is not the whole story because profits of the CCS technology firms only make up a part of EU welfare. Since the power industry pays carbon taxes equal to \$90 per tonne CO2, access to cheaper abatement technology improves both the producer surplus and consumer surplus in the electricity sector. This effect is positive for both upstream and downstream CCS coal subsidies. We will return to look at welfare below.

All four types of subsidies affect the EU import price of natural gas. In Figure 3, we compare subsidies to CCS coal and CCS gas with respect to their effect on the gas price. We note that while both an upstream and a downstream subsidy to CCS coal reduce the EU import price, both and upstream and a downstream subsidy to CCS gas increases the EU import price.

Figure 4. EU Import gas price.

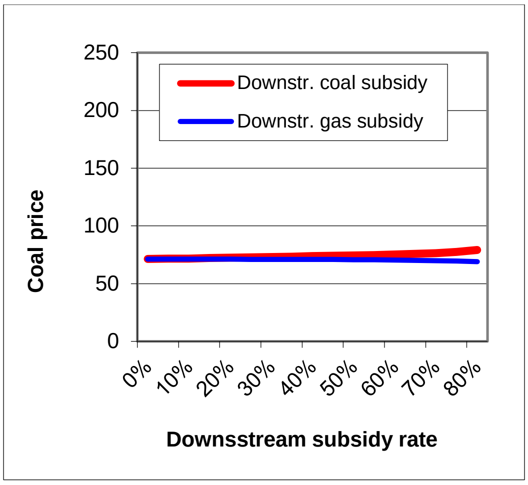


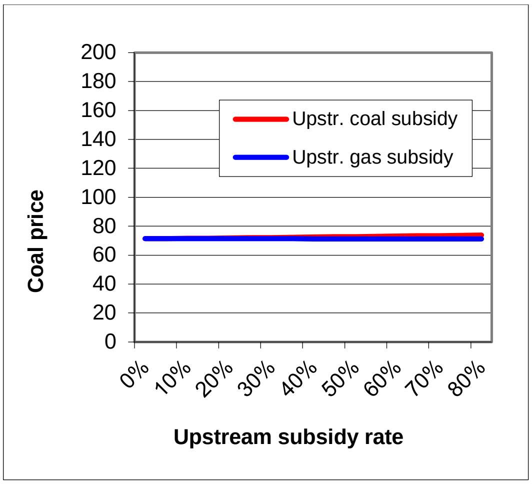
In Figure 4 we measure the import gas price on Y-axis, and we let the subsidy rate vary between 0 and 90% along the X-axis. The plot to the left looks at downstream subsidies, while the plot to the right looks at upstream subsidies. Note that we only look at one type of subsidy at the time e.g. only downstream CCS coal, only upstream CCS gas etc.

First, note that the price effect for the two types of downstream subsidies has the same sign as the price effect for the two types of upstream subsidies: A subsidy to CCS gas increases the import price, while a subsidy to CCS coal decreases the import price. Note further that the downstream subsidy yields higher price variations: In the plot to the left the import price varies between \$90 and \$210, while the plot to the right the import price varies between \$145 and \$180. The reason is that the downstream subsidy affects supply of CCS technology stronger since all suppliers are covered by this type of subsidy.

Figure 5 includes the same plots for the price of steam coal. We see that the price effects are very small compared to gas. One of the reasons is that coal supply is global while the supply of gas to the EU is regional.

Figure 5. EU steam coal price.

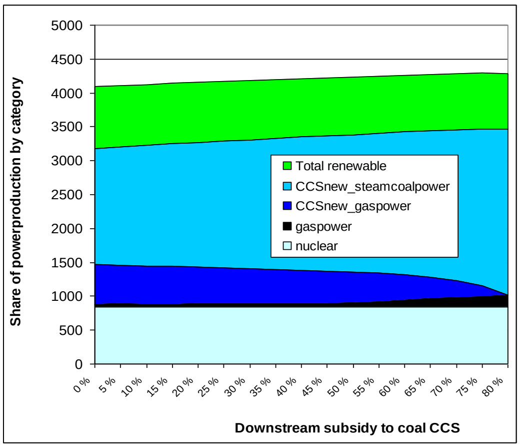


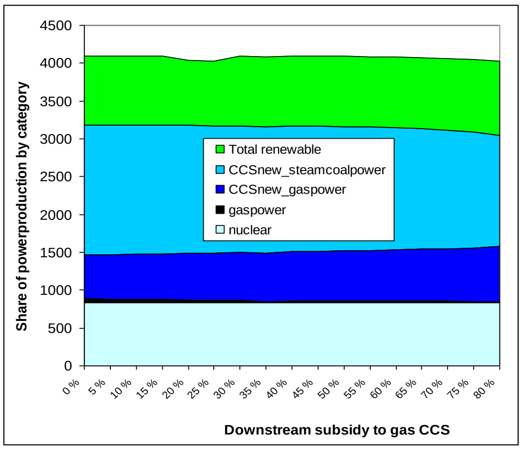


Finally, in Figure 6 and Figure 7 we look at the power mix in the EU electricity market under the four subsidy regimes. Note that in all regimes conventional coal power is closed down. This is due to the high carbon price, which makes it profitable to close down all remaining coal power plants and replace them with CCS coal power plants even without subsidies to CCS coal (see Golombek et al., 2011).

There is still some ordinary gas power. Gas power has lower emissions per unit of production, and is not as vulnerable to a high price on carbon as conventional coal. Further, in all regimes the subsidy has a lower impact on the market share of CCS gas than on the market share of CCS coal. Total electricity supply is also modestly affected in the case of subsidies to CCS gas power. The reason is the effect on the gas price. As we can see from Figure 5, we don't have the same price effect for coal.

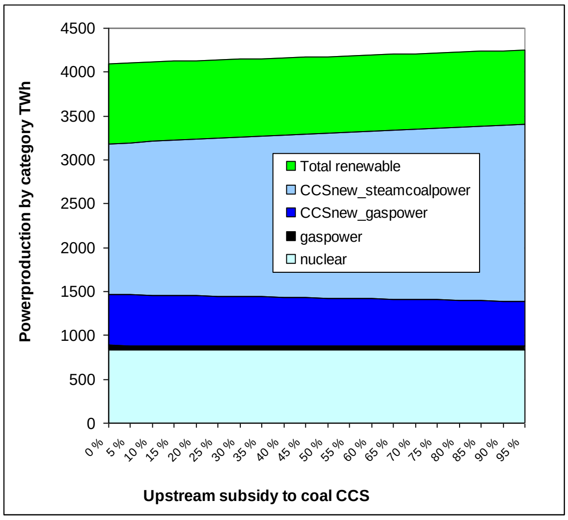
Figure 6. Power supply under different downstream subsidy regimes.

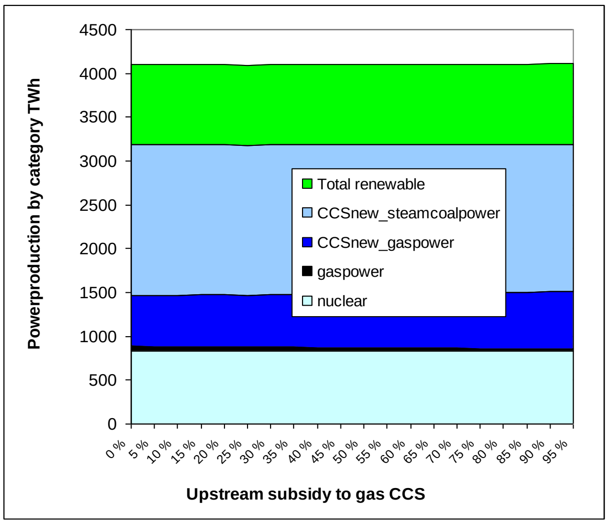




A downstream subsidy to coal CCS boosts CCS coal power and reduces CCS gas power. Since the import gas price also falls, ordinary gas power picks up for high subsidy rates. More or less, the opposite happens with a down stream subsidy to gas CCS. The picture is much the same for the upstream subsidy, but since the gas price is only moderately affected, the changes in the power mix are not so pronounced.

Figure 7. Power supply under different upstream subsidy regimes.





Note that, even it is harder to affect the total supply of CCS gas power, an upstream subsidy may be desirable in order to shift profits to domestic producers. Note also that renewables are not much affected by any of the subsidies. In the case in which the government provides an upstream subsidy to domestic CCS coal, the total market for electricity increases. If the government provides an upstream subsidy to domestic CCS gas, the total market for electricity does not increase as much since import prices of natural gas increases. Table 3 summarizes the market effects of the subsidies:

Table 3. Market effects of the four types of subsidies

	No subsidies	Downstream 50% coal 0% gas	Downstream 0% coal 50% gas	Upstream 50% coal 0% gas	Upstream 0% coal 50% gas
Total market	4099	4235	4091	4178	4105
Market share coal	42%	48%	40%	45%	41%
Market share gas	14%	11%	16%	13%	15%

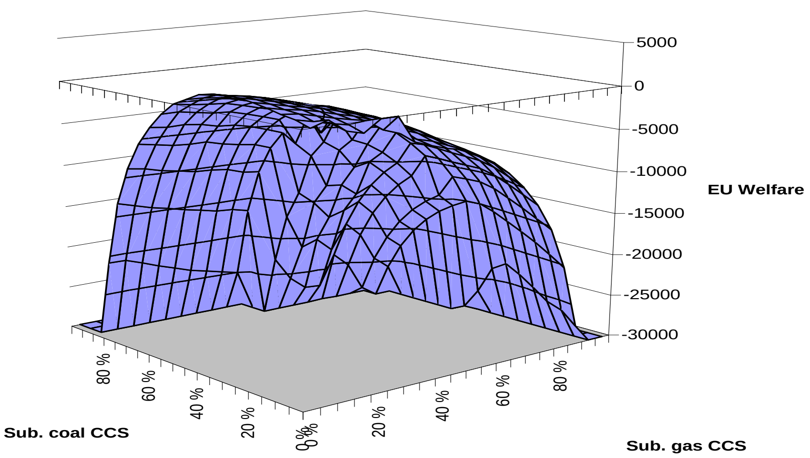
4.3 Optimal policies

Below we present results from three welfare simulations. In the first simulation, we only give a downstream subsidy, but we give the same rate to both CCS coal power and CCS gas power. EU welfare is measured on the vertical axis. The subsidy to CCS gas varies along the x-axis, while the subsidy to CCS coal varies along the y-axis.

As we can see from the figure below, some subsidizing of CCS coal power is warranted. This is due to the effect of imperfect competition in the market for CCS technology. That is, even though the subsidy shifts profit abroad, investors in CCS coal power plants pay a price closer to the cost of CCS coal capacity. As we can see from Figure 4, the total production of electricity also increases which benefits consumers.

There should be very small subsidies to CCS gas power. We also have imperfect competition in this market, but the effect on the EU import price of gas probably makes this subsidy next to undesirable.

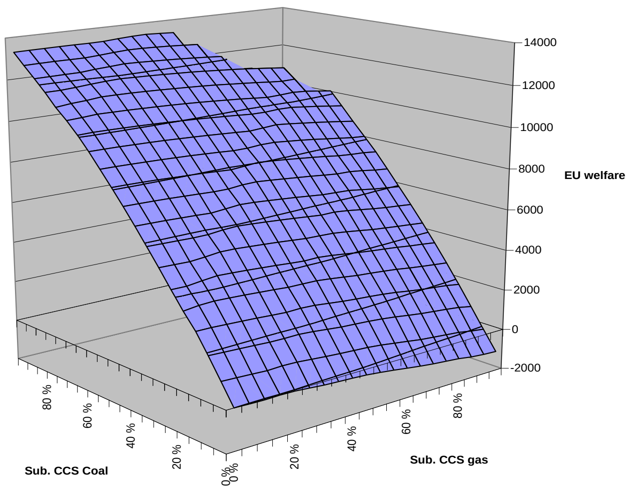
Figure 8. Welfare effects of a downstream subsidy



Note that the welfare improvements for the two kinds of subsidies are mostly negative. There is only a slight improvement around a 25% subsidy to coal CCS.

In the next figure we look at an upstream subsidy. The same subsidy rate is given to both technologies. Then the EU should provide a positive subsidy to both CCS coal power technology suppliers and CCS gas power technology suppliers.

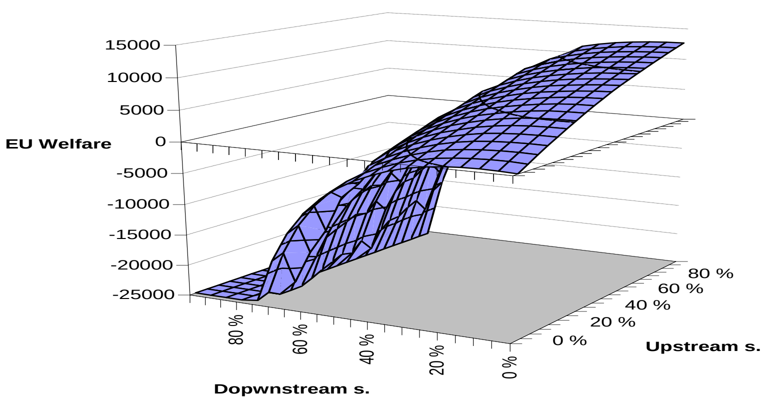
Figure 9. Welfare effects of an upstream subsidy



Again, EU welfare is measured on the vertical axis, while the subsidies to CCS gas and CCS coal are measured along the x- and y-axis, respectively. First, note the big welfare gains of upstream subsidies compared to the very limited welfare gains of downstream subsidies in Figure 6. Second, note that welfare increases much more in the case of a subsidy to CCS coal. This follows from i) that the potential demand for CCS coal is larger and ii) that a subsidy to CCS gas has a negative terms of trade effect.

Finally, in Figure 8 we look at welfare when both upstream and downstream subsidies are varied, and for each type of subsidy CCS gas and CCS coal are given the same rate.

Figure 8. Optimal combination of upstream and downstream subsidies.



EU welfare is measured on the vertical axis, while the upstream and downstream subsidies to CCS gas and CCS coal are measured along the x- and y-axis, respectively. As expected the downstream subsidy does not significantly improve welfare, and if the upstream subsidy is in use, no downstream subsidy should be given. In fact this is the optimal policy e.g. yields the highest welfare.

5. DISCUSSION AND CONCLUSION

There are several reasons to subsidize the deployment of CCS technologies. The most obvious reason is imperfect competition among technology suppliers, which causes a dead-weight loss due to above marginal cost pricing. The picture is further complicated by the existence of more CCS technologies. These technologies are substitutes, and the optimal policy for one technology is affected by the policy for the other technology. In general the government should prioritize the technology with largest potential to increase consumer surplus. In our study this happens to be CCS for coal power and not CCS for gas power.

There are two more subtle rationales for a CCS deployment subsidy. One has to do with strategic trade motives. As long as there is imperfect competition among CCS technology suppliers, the EU can gain by reserving its subsidies for the national technology champions. Thus, the EU should not subsidize downstream, for instance, by providing power suppliers with investment support. This policy is likely optimal even if foreign countries retaliate and starts to subsidize their CCS technology firms. Moreover, retaliation would imply even lower costs on CCS technology, and thus benefit consumer surplus in the EU.

Finally, the four kind of subsidies have effects in other markets which may hamper or benefit EU welfare. In our case, the effect on the import price of natural gas turned out to be crucial. Both kinds of subsides to CCS gas power technology increases the price on this input which is not desireable from an EU point of view.

One could question whether “production” subsidies to national firms are compatible with GATT law. Subsidizing pollution abatement technology firms is a rising issue within the WTO. On the one hand the subsidy code of the GATT states that a production subsidy is an actionable subsidy. On the other hand, countries could argue that it is a policy which seeks to protect the environment, and hence, is covered by the escape clauses in Article XX of the GATT. According to the WTO, supporting the deployment and diffusion of green technologies is not hindered by WTO rules (WTO 2011).

We have not treated a fifth potential rational for CCS subsidies, and that is, too weak climate policy. If carbon taxes are too low, too little abatement is carried out, and subsidies to abatement technologies may constitute a second best policy.

References

Aune, F. R., Golombek, R., Kittelsen, S. A. C., and Rosendahl, K. E. (2008), Liberalizing European Energy Markets: An Economic Analysis. Edward Elgar.

Baldwin R. E. and P.R. Krugman (1988), "Market Access and International Competition: A Simulation Study of the 16K Random Access Memories", in Empirical Methods for International Trade, edited by R.C. Feenstra, The MIT Press p. 171-198.

Brander J. and B. Spencer, Export Subsidies and International Market Share Rivalry, *J. Internat. Econom*. 18, p. 83-100 (1985).

Golombek R., M. Greaker, S. A. C. Kittelsen, O. Røgeberg and F. R. Aune (2011), Carbon capture and storage technologies in the European power market, *Energy Journal* 32, p. 209-238.

Greaker, M. and K. E. Rosendahl. 2008. Environmental policy with upstream pollution abatement technology firms, J. Environ. Econom. Management 56, pp. 246-259.

IEA (2013), "Technology Roadmap: Carbon Capture and Storage".

IEA (2008): World Energy Outloook, International Energy Agency, Paris.

Leahy D. and J. P. Neary (1997), "Public Policy Towards R&D in Oligopolistic Industries", *The American Economic Review* 87, p. 642-662.

Leahy D. and J. P. Neary (1999), "R&D spillovers and the case for industrial policy in an open economy", *Oxford Economic Papers* 51, p. 40-59.

Metz, B., O. Davidson, H. de Coninck, M. Loos, and L. Meyer. 2005. IPCC special report on carbon dioxide capture and storage. Cambridge University Press, New York, NY (United States).

Neary J. P. (1994), "Cost asymmetries in international subsidy games: Should governments help winners or losers?", *Journal of International Economics* 37, p. 197-218.

Venables A. J. (1994), "Trade Policy under Imperfect Competition: A Numerical Assessment", in Empirical Studies of Strategic Trade Policy (ed. Paul Krugman and Alasdair Smith), The University of Chicago Press.

World Trade Organization 2011. Harnessing trade for sustainable development and a green economy, Geneva, Switzerland.