Promoting CCS in Europe: A Case for Green Strategic Trade Policy?

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ABSTRACT

According to IEA (2018), there is a huge gap between the first-best social optimal utilization of Carbon Capture and Storage (CCS) technologies to lower global CO_2 emissions and the current, negligible diffusion of this technology. This calls for a financial support mechanism for CCS. We study to what extent promotion of CCS in Europe should be through subsidizing 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 new approach that integrates strategic trade policy with an economic model of the European energy markets. The theory model suggests that upstream subsidies should clearly be preferred, and this is confirmed by the numerical simulations. For the European power market, the numerical simulations suggest that subsidies to CCS coal power should exceed subsidies to CCS gas power.

Keywords: Carbon capture and storage (CCS), Electricity, Strategic trade policy, Upstream subsidy, Downstream subsidy, Profit shifting, Cournot

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1. INTRODUCTION

According to IEA (2018), there is a huge gap between the first-best social optimal utilization of Carbon Capture and Storage (CCS) technologies to lower global CO_2 emissions and the current, negligible diffusion of this technology. For example, in the Sustainable Development Scenario developed in IEA (2018), which is a cost-efficient path consistent with the Paris agreement, the global carbon capture capacity in the power sector should be 1500 $MtCO_2$ by 2040—the current capacity is only 2.4 $MtCO_2$. Likewise, whereas the global carbon capture capacity in manufacturing and energy transformation sectors should be 1600 $MtCO_2$ by 2040, the current capacity is 28 $MtCO_2$.

A number of factors may explain this big mismatch, for example, the price of carbon may be by far too low; costs of renewables may have decreased more rapidly than expected (which tends to push down the carbon price); there might be market imperfections in the CCS value chain of capture, transport and storage that slow down the speed in CCS development; policy makers may be wary of popular concerns about the safety of carbon storage and that CCS is just a way to prolong

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the fossil-fuel age; and there might be substantial policy uncertainty with respect to whether countries will take sufficient actions to reach the 2 degrees target. Because of impediments, IEA (2013) argues that a key action to kick off innovation and diffusion of CCS is to introduce financial CCS support mechanisms.

There are two business models to spur CCS. One option is to support purchasers of CCS technologies by covering a part of the additional investment cost of CCS. The alternative model is to focus on the CCS technology suppliers by supporting their research, development and production costs. 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 should be through subsidising development and production of CCS technologies—an upstream subsidy—or by subsidising the purchasers of CCS technologies—a downstream subsidy.

In the electricity sector, the CCS technology can be applied both to coal power and gas power. These two technologies are likely substitutes in demand. Our second research question is therefore to what extent policy makers should give priority to one of the CCS technologies, that is, whether the subsidy to CCS coal power should exceed the subsidy to CCS gas power.

We study the two research questions both theoretically within a stylized game theoretic model and numerically by using an economic energy market model that is innovatively integrated with strategic trade policy. In the analyses, we take into account that competition between CCS technology suppliers is imperfect as there is only a few potential suppliers in the world; some of these are located in the EU, others are situated in other regions. While there may be supply of CCS power plants both from EU and non-EU actors, we believe that over time the only significant market for CCS may be in the EU. So far, only the EU has set very ambitious climate targets. In particular, emissions from the electricity sectors are supposed to be reduced by around 95 percent (relative to 1990) by 2050, see European Commission (2011). Therefore, we assume that in the EU there will be both demand for, and supply of, CCS power plants, and we focus on how the EU should design its CCS policy by taking into account the EU suppliers of CCS power plants, the EU purchasers of CCS power plants, as well as how non-EU suppliers will respond to the EU CCS policy.

Why should public bodies offer subsidies to stimulate deployment of CCS technologies; would not an appropriate carbon tax do the job? As is well known, in an economy where CO_2 emissions are the only imperfection, efficiency is obtained by imposing a price on emissions equal to the social cost of carbon. In our model, there is, however, an additional source of imperfection, namely market power in the supply of CCS power stations. In order to maximize welfare, additional instruments are therefore required. While this is the case both from a global and an EU perspective, the choice of instruments differs. From a global perspective, instruments should be imposed in order to correct fully for market power in the CCS value chain. In contrast, from an EU perspective also the distribution of profits between the EU and the non-EU producers is of importance. Therefore, for the EU the question is to find instruments that obtain efficiency among the EU producers and also shift profits from the non-EU to the EU producers; the latter is discussed in the literature on strategic trade policy, see, for example, Brander and Spencer (1985), Neary (1994), and Leahy and Neary (1997; 1999).

The strategic trade literature typically assumes that there is production of a homogenous good in two countries, imperfect competition and no externality. In addition, the homogenous good is consumed in a third country. We depart from this literature by assuming there is consumption in one of the producing countries only; below, this country is referred to as the EU (see the discussion above on the EU climate policy).

Using a Cournot-type of model with one homogenous good, we show in Section 2.1 that the EU can maximize its welfare by offering an upstream subsidy to its producers. The EU should, however, not offer a downstream subsidy.[1] Both an upstream and a downstream subsidy increases the use of the technology, which is desirable because of 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, and hence does not shift production and profits from non-EU producers to the EU producers. The EU should offer an upstream subsidy that stimulates the EU producers to increase their production by so much that they voluntarily choose their competitive quantities. This requires that the output price is equal to the unit cost of production and therefore there will be no production from the non-EU producers.

We then solve the model with two goods (Section 2.2). In this case, the EU 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. Note that we use subsidy *rates*, that is percentages, not subsidies specified as a value per unit of production. Hence, upstream subsidy rates are percentages of the cost of producing CCS power plants, whereas downstream subsidy rates are percentages of the purchaser price of CCS power plants. Below, we use “subsidy rate” and “subsidy” interchangeably.

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 consumers. We find that also with two goods, only upstream subsidies should be offered, and each optimal upstream subsidy should reflect the social value of the good. Hence, the good with the highest social value should receive the greatest upstream subsidy. Finally, the combination of (upstream) subsidies should lower the price by so much that production is not profitable for non-EU producers, thereby shifting profits from non-EU to EU producers. To the best of our knowledge, these results are new to the literature.

While the theory models in Section 2 give rules of thumb on how to design upstream and downstream subsidies, we develop a numerical framework of the European energy markets to illustrate the magnitude of subsidies that maximizes EU welfare. Although there exist several numerical studies of strategic trade policy, see, for instance, Baldwin and Krugman (1988), Venables (1994) and Greaker and Rosendahl (2008), to our knowledge no study has yet used a comprehensive numerical framework of the energy sector to identify the magnitude of strategic trade policy instruments.

At the core of our numerical framework is a numerical model of the European energy markets; LIBEMOD. Here, electricity can be produced by a number of technologies, including conventional fossil-fuel based power plants, CCS power plants using either natural gas or coal, and renewables. While costs of investment and operating costs are higher for CCS plants than for 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, costs and efficiencies of 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 cost of investment of a CCS power plant is a parameter in LIBEMOD, we want this cost, which is the price of a CCS power plant, to be endogenous. In order to establish a model with endogenous price formation of CCS power plants, we

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[1] It is well known that in a closed economy, it is of no importance whether a subsidy is offered to supply or demand, and this is the case both with competitive markets and under imperfect competition. However, once some agents in a group do not receive the subsidy, for example, because only “domestic” producers receive an upstream subsidy, the equivalence between an upstream and a downstream subsidy no longer holds.

develop a three-stage procedure that integrates Cournot competition with the large-scale numerical LIBEMOD model, which has competitive markets, see Section 3.

Application of the numerical framework requires a Reference scenario where it is profitable to invest in CCS. To make investors choose CCS power plants instead of conventional fossil-fuel based stations, the carbon price has to be significant. This was not the case in 2020 with a CO_2 price below 30 euro, see, for example, EMBER (2020), and might neither be the case in 2030, see PRIMES (2019) and Aune and Golombek (2021). In this study we therefore analyze a more distant year than 2030, namely 2050. For this year, the GHG emissions target of the EU is a reduction of at least 80 percent (relative to 1990), which requires a high CO_2 price. In our study, the CO_2 price is set exogenously. In the Reference scenario, we assume a uniform carbon price at €100/tCO_2. This is in line with the assumption in IPCC (2019) of a CO_2 price at $100, which is supposed to be consistent with the 1.5 degree target.

The Reference scenario is analyzed in Section 4.1. These simulations encompass two effects that are not included in the theoretical models. First, the welfare effect of reduced CO_2 emissions through increased use of CCS is taken into account. Second, the terms-of-trade effect of increased imports of fossil fuels is also covered by our numerical framework.

The simulations confirm the prediction of the theory model that the upstream subsidy rate should exceed the downstream subsidy rate. When we impose that there is one common upstream subsidy rate to CCS coal power and CCS gas power, and one common downstream subsidy rate to CCS coal power and CCS gas power, it is optimal for the EU to set a high upstream subsidy rate, but no downstream subsidy. We also find that subsidies to CCS coal power should exceed subsidies to CCS gas power. If, for example, only upstream subsidies are offered in the Reference scenario, the upstream subsidy rate to CCS coal power should be as close to 100 percent as possible, whereas there should be no upstream subsidy to CCS gas power. In Section 4.2 we test the robustness of our results with respect to the magnitude of the CO_2 tax, design of subsidies, number of CCS suppliers, and cost of producing CCS power plants. We find that none of the main results from the Reference scenario change.

Our study is related to two strands of the CCS literature. First, we contribute to the literature on deployment of CCS electricity, see Abadie and Chamorro (2008) for a combined theoretical and empirical investigation of the Spanish electricity market; Golombek et al. (2011) on how investment in alternative CCS electricity technologies (coal-based vs. gas-based, and retrofitted vs. greenfield) depends on the price of CO_2 emissions in the European electricity market; Lohwasser and Madlener (2012), which uses the bottom-up electricity model HECTOR for the European electricity sector; Lund and Mathiesen (2012) for the Danish energy system; Viebahn et al. (2012) for the German electricity sector, in particular, on the competition between low-emissions and zero-emissions electricity technologies; Pettinau et al. (2013) for the Italian electricity sector; Spiecker et al. (2014) on the German electricity sector, including location of CCS electricity plants; Viskovic et al. (2014) for the electricity markets in South East Europe; Oei et al. (2016) on investment in CCS in the European power (and manufacturing) sector towards 2050 under alternative assumptions on the price for CO_2 emissions;[2] and Fan et al. (2019) for the Chinese electricity market.

Our contribution to this strand of the literature is to study how upstream- and downstream CCS subsidies impact deployment of CCS electricity in the European electricity market, using the

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[2] Oei et al. (2016) finds that the power sector starts deployment of CCS if the CO2 price exceeds 100 euro/tCO2.

detailed energy market model LIBEMOD.[3] To the best of our knowledge, no study has done something similar.

Second, we contribute to the literature on how to overcome challenges for CCS to capture significant market shares, see Gibbins and Chalmers (2008) on how to facilitate widespread commercial deployment of CCS; Otto and Reilly (2008) on how deployment of the CCS technology depends on environmental policy and directed technology progress; Herzog (2011) on economic and regulatory challenges for CCS; von Hirschhausen (2012) on why the discrepancy between the announced CCS market shares and actual deployment of CCS is due to the low number of CCS demonstration projects; Scott (2013) on CCS demonstration project funding; and Yao et al. (2018) on alternative business models for large-scale deployment of CCS.[4]

Here, our contribution is to derive theoretically how the two types of CCS subsidies—upstream and downstream—have impact on supply of, and demand for, CCS technologies, as well as on profits and social welfare. We use LIBEMOD to illustrate these effects, where also terms-of-trade effects and cost of CO_2 emissions are taken into account. In particular, we identify the combination of CCS subsidies that maximizes welfare of the region that offers CCS subsidies. To this end, we develop a procedure that integrates imperfect competition with our large-scale numerical LIBEMOD model with competitive markets to endogenize the link between CCS subsidies and the price of CCS power plants.

2. UPSTREAM VS. DOWNSTREAM CCS SUBSIDIES

In this section we examine whether it is welfare optimal to stimulate production from a new technology through an upstream or a downstream subsidy. We first examine an economy with one good. Next, we consider the case with two goods. Our point of departure is the Cournot model with n domestic producers and m foreign producers competing in the domestic market.[5]

2.1 One good

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

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[3] Studies on deployment of CCS electricity in Europe can be seen as part of the broader literature on the potential market share of CCS in the global energy system, see, for example, Kitous et al. (2010) applying the energy model POLES for 2050; Magne et al. (2010) using the MERGE model; Leimbach et al. (2010) using the hybrid model REMINDER-R; Labriet et al. (2012) applying stochastic programming with the TIAM-World model; and van Vuuren et al. (2019) using the IMAGE modeling framework.

[4] Other contributions to the CCS literature include Szolgayova et al. (2008) on how climate policy instruments under uncertainty impact the electricity sector, in particular, investment in CCS technology; Torvanger and Meadowcroft (2011) on political economy factors influencing the choice of government to offer support to low-emissions technologies like CCS; Kraeusel and Möst (2012) on factors influencing the social acceptance of CCS in Germany; Nykvist (2013) on the importance of pilot projects and funding opportunities; Massol et al. (2015) on the importance of tariff structure for pipeline transport of carbon, in particular, a comparison of a common European regulatory framework with national regulations; and Zhao and Liu (2019) on the conflict of interest between the government and a coal-fired power plant located in China, studied as an evolutionary game.

[5] This set-up bears some resemblance to the reciprocal dumping model of Brander and Krugman (1983), but without trade costs and with only one market.

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

$$p = A - aX. \tag{1}$$

Here, p is the price of the good, $X = \sum_{i=1}^{n} X_{di} + \sum_{j=1}^{m} X_{fj}$ is total production, 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 $(0 \le s < 1)$. 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 $(0 \le \eta < 1)$ to all buyers of the good. Thus whereas p is the price paid by the buyers of the good, ω $(\ge p)$ is the price received by the producers where

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

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

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

Similarly, the profit of a foreign producer is

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

We assume there is Cournot competition, that is, each producer maximizes her profit with respect to her quantity. Because of symmetry, we impose that in equilibrium all domestic producers supply the same quantity ($X_{di} = X_d$), and also all foreign producers supply the same quantity ($X_{fj} = X_f$). We then 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 eq. (5) and eq. (6) we find that a higher upstream subsidy s increases domestic production but lowers foreign production. It is straight forward to show that total production ($nX_d + mX_f$) is increasing in the upstream subsidy s:

$$\frac{d(nX_d + mX_f)}{ds} = \frac{cn(1-\eta)}{a(1+n+m)} > 0 \tag{7}$$

Next, a higher downstream subsidy η has an ambiguous effect on domestic production, whereas foreign production and total production will increase:

$$\frac{dX_d}{d\eta} = \frac{-c((m+1)s-1)}{a(1+n+m)} \tag{8}$$

$$\frac{dX_f}{d\eta}=\frac{c(ns+1)}{a(1+n+m)}>0 \tag{9}$$

$$\frac{d(nX_d+mX_f)}{d\eta}=\frac{c(m+n(1-s))}{a(1+n+m)}>0 \tag{10}$$

From (8) 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.

In the empirical part of the paper, see the discussion on energy prices in Section 4, we compare whether a downstream subsidy has a higher impact on total production (on thus the price) than an upstream subsidy. Using eqs. (5) to (9), we find, like in Section 4, that this is the case:

$$[\frac{d(nX_d+mX_f)}{d\eta}]_{s=0}-[\frac{d(nX_d+mX_f)}{ds}]_{\eta=0}=\frac{m}{a(1+n+m)}>0 \tag{11}$$

Here, the first term shows the effect on total production of a marginal increase in the downstream subsidy η when there is no upstream subsidy $(s=0)$, whereas the second term shows the effect on total production of a marginal increase in the upstream subsidy s when there is no downstream subsidy $(\eta=0)$. According to eq. (11), this difference is positive, which reflects that all purchasers of the good benefit from the downstream subsidy, whereas only the domestic producers enjoy the upstream subsidy.

We now discuss how a higher subsidy impacts profits of the domestic producers. Let V_d be the maximized profit of a domestic producer. Using eqs. (3), (5) and (6) we find:

$$V_d=\frac{c^2}{a(1-\eta)(1+n+m)^2}[l+((m+1)s-1)(1-\eta)]^2. \tag{12}$$

From (12) 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. The latter reflects that one partial effect of a higher downstream subsidy is increased production from the foreign producers, see (9), which tends to lower 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 $\overline{s}=\frac{l+1}{m+1}+\varepsilon$ where ε is small and $l<m$ to ensure that $\overline{s}<1$. 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 (s), whereas the effect of a higher downstream subsidy* (η) *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 from a foreign producer falls, see discussion above, profit of each foreign producer 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 should the downstream subsidy be?

In order to answer these questions 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

$$S = \int_0^X (A - aq)dq - X(A - aX) \qquad (13)$$

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

$$T = \eta \frac{p}{1-\eta} X + scnX_d. \qquad (14)$$

The first term shows government payments of downstream subsidies. For all units purchased by the clients (X), the government subsidizes each unit by $\eta\omega = \eta \frac{p}{1-\eta}$. The second term shows government payments of upstream subsidies: for all units produced by the domestic producers (nX_d), the government subsidizes a share (s) of the unit cost of production (c).

Total welfare of the domestic country is thus:

$$W = nV_d + S - T. \qquad (15)$$

We now maximize total welfare of the domestic country with respect to the upstream subsidy s and the downstream subsidy η. The resulting subsidies that are optimal for the domestic country are summarized in the following proposition:[6]

> *Proposition 2: If there is production of one good, for the domestic country the welfare optimal downstream subsidy is zero, whereas the welfare optimal upstream subsidy is* $s^{opt} = \frac{1}{n}(\frac{A}{c} - 1)$.
>
> Note that $s < 1$ requires that $\frac{A}{c} < n + 1$.

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, A / c, which is a measure of the social value of the product. Further, the subsidy rate should be lower the more domestic producers (n), and total payment of subsidies to the domestic producers should be $(A - c)X_d$, which is decreasing in the number of domestic producers, see (5).

Using eqs. (1) and (5) as well as the upstream subsidy s^{opt}, we find that 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: If the subsidy that maximizes domestic welfare is offered, then the resulting equilibrium price will be equal to the constant unit cost of production. There will be*

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

no production from the foreign producers, whereas the domestic producers supply their competitive level of production.

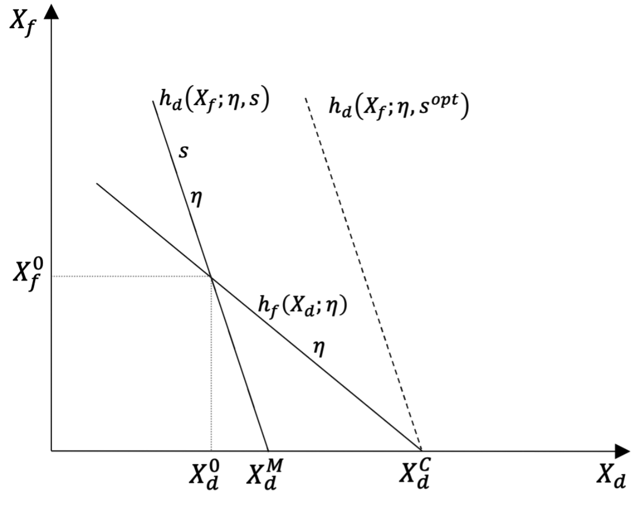
In order to gain intuition of why an upstream subsidy works differently than a downstream subsidy, we illustrate the special case of one producer in each country $(n = m = 1)$, see Figure 1. Here, the two downward sloping curves are the best-response curves for the two producers. For the domestic producers, we find this curve by maximizing profit of the domestic producer, see (3), with respect to production of this producer (X_d) taking the level of the other producer (X_f) as given. Solving the resulting first-order condition with respect to production of the domestic producer, we find:

$$X_d = \frac{-aX_f + A - c(1-s)(1-\eta)}{2a} = h_d(X_f; s, \eta) \tag{16}$$

where $h_d(X_f; s, \eta)$ is the best-response curve of the domestic producer. It shows, for each possible level of production of the foreign producer, the level of production of the domestic producer that maximizes her profit. From (16) we find that slope of the response curve, dX_d / dX_f, is -0.5, which reflects the assumption of a linear demand function. We find the best-response curve of the foreign producer, $h_f(X_d; \eta)$, in the same way as we derived the response curve $h_d(X_f; s, \eta)$. The two functions have the same properties, except that the best-response curve of the foreign producer is of course independent of the upstream subsidy rate s as this subsidy is restricted to the domestic producer (and hence does not enter the first-order condition of the foreign producer).

Figure 1 shows the two response curves. A higher upstream subsidy s shifts the response curve of the domestic producers outwards $(\frac{\partial h_d(X_f; s, \eta)}{\partial s} > 0)$, whereas it has no impact on the response curve of the foreign producer (see last paragraph). In contrast, a higher downstream subsidy η shifts both response curves outwards $(\frac{\partial h_d(X_f; s, \eta)}{\partial \eta} > 0, \frac{\partial h_f(X_d; \eta)}{\partial \eta} > 0)$. For given values of the two subsidy rates, say, they are both set to zero initially, the non-cooperative equilibrium of the (Cournot) game is found where the two response curves intersect. In Figure 1, the equilibrium quantities of the domestic and foreign producer (when $s = \eta = 0$) are X_d^0 and X_f^0, respectively.

Figure 1: The non-cooperative equilibrium with one good and two producers



According to the response curve of the domestic producer, if, hypothetically, there is no supply from the foreign producer, the profit-maximizing quantity of the domestic producer is X_d^M, see Figure 1. Hence, X_d^M is the monopoly quantity of the domestic producer. Note that $(X_d^M,0)$ is not an equilibrium because the two response curves do not intersect at this point.

If, hypothetically, the domestic producer sells X_d^C, see Figure 1, then, using the best-response curve of the foreign producer, this actor will not produce anything. To avoid foreign production, the price has to be equal to the unit cost of production. Thus, X_d^C is the quantity that will make price equal to c. How can the government trigger the domestic producer to offer exactly X_d^C, that is, how can the government choose its instruments so that $(X_d^C,0)$ becomes an equilibrium?

As explained above, the response curve of the domestic producer shifts outwards when the domestic government increases the upstream subsidy s. If the government offers the upstream subsidy s^{opt}, then $h_d(X_f;s^{opt},\eta)$ is the new response curve of the domestic producer. This response curve 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 subsidy s^{opt} 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 linear demand functions 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, there may be supply of two types of CCS power plants; one using natural gas and another using coal. We now extend the analysis to two products; good c ("CCS coal power plants") and good g ("CCS gas power plants"). We assume both goods are supplied by all producers.

Let X_{cdi} be production of good c by the domestic (d) producer i, and let X_{gdi} be production of good g by this domestic producer. The corresponding variables for the foreign (f) producer j are X_{cfj} and X_{gfj}. Let $X_c=\sum_{i=1}^{n}X_{cdi}+\sum_{j=1}^{m}X_{cfj}$ and $X_g=\sum_{i=1}^{n}X_{gdi}+\sum_{j=1}^{m}X_{gfj}$ be total quantity of good c and good g, respectively. We let the derived utility of consuming these goods be represented by

$$U(X_c,X_g)=A_cX_c+A_gX_g-\frac{a_c}{2}(X_c)^2-\frac{a_g}{2}(X_g)^2-bX_cX_g \tag{17}$$

where A_c, A_g, a_c, a_g and b are (positive) parameters.

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

$$\begin{aligned}p_c&=A_c-a_cX_c-bX_g\\ p_g&=A_g-a_gX_g-bX_c.\end{aligned} \tag{18}$$

(18) is an inverse demand system, which can be transformed to a standard demand system. In order to obtain negative own-price elasticities and positive cross-price elasticities in the standard demand system, we have to impose $a_c/2>b>0$ and $a_g/2>b$.

Turning to production, let c_k be the common unit cost of production of good k, $k=c,g$. Further, let s_k and η_k be the upstream and downstream subsidy rates of good k, respectively. Profits of a domestic producer are now

$$\Pi_{di}=[\frac{p_c}{1-\eta_c}-c_c(1-s_c)]X_{cdi}+[\frac{p_g}{1-\eta_g}-c_g(1-s_g)]X_{gdi} \tag{19}$$

whereas profits of a foreign producer are:

$$\Pi_{fj} = [\frac{p_c}{1-\eta_c} - c_c]X_{cfj} + [\frac{p_g}{1-\eta_g} - c_g]X_{gfj} \tag{20}$$

Like above, we assume that all producers maximize profits. 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; $U(X_c, X_d) - p_c X_c - p_d X_d$. 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. We find that $s_k^{opt} = \frac{1}{n}(\frac{A_k}{c_k} - 1)$, which has the same structure as in the case of one good, see Proposition 2. For technical details about the derivation, see Appendix A. Note that the upstream subsidies that maximizes welfare of the domestic country are independent of the cross-price effect b. This reflects that the demand functions in (18) are linear.

With the upstream subsidies s_k^{opt}, each 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. Furthermore, the subsidy to good c should exceed the subsidy to good g ($s_c^{opt} > s_g^{opt}$) if and only if $\frac{A_c}{c_c} > \frac{A_g}{c_g}$. Hence, the good with the highest social value, measured by $\frac{A_k}{c_k}$, should receive the highest subsidy.

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

> *Proposition 4: If there is production of two goods, for the domestic country 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. MODELING STRATEGIC TRADE POLICY

In this Section, we develop a framework to study numerically the effect of downstream and upstream subsidies, that is, the impact of strategic trade policy, on the European energy market when there is market imperfection in supply of CCS power plants. Our empirical strategy is to combine a multi-good, multi-period, numerical equilibrium model of competitive *energy* markets, LIBEMOD, with a numerical version of the Cournot model in Section 2.2 that specifies four subsidies (upstream vs. downstream subsidy, subsidy to CCS coal power plants vs. subsidy to CCS gas power plants). The link between the two models is the prices of CCS power plants: In LIBEMOD, these are exogenous cost of investment parameters, whereas in the Cournot model, prices of CCS plants are endogenous variables. From our framework we find the impact of alternative values of the four CCS subsidies on the energy markets, and thus on welfare.

3.1 The numerical model LIBEMOD

LIBEMOD is an economic simulation model of the European energy sector, see LIBEMOD (2015) for a detailed documentation, including information about data sources and calibration strategy. For applications of the model, see Aune et al. (2015) and Aune and Golombek (2021); the latter study also offers a documentation of the model. LIBEMOD covers competitive electricity, natural gas and biomass markets in Europe, as well as competitive global markets for coal, oil and biofuels. The model distinguishes between model countries—each of 30 European countries—and "other" countries/regions; the latter group contains all other countries in the world.

In each model country there is investment in energy infrastructure, extraction of fossil fuels, production of energy, energy transport, and consumption of eight energy goods—coking coal, steam coal, lignite, natural gas, oil, biomass, biofuel, and electricity. All model countries participate in energy trade of the eight energy goods. Natural gas and electricity trade requires gas pipes/electricity lines between pair of countries.[7] At each point in time, the capacities of these pipes/lines are given, but they can be expanded through investment. For fossil fuels, there are annual markets, whereas for electricity the year is divided between the summer and the winter season, and each season consists of two periods, day and night.[8]

There are five groups of users of energy; electricity producers, households, services and public sector, industry, and transport. The first group represents intermediate demand; thermal power producers demand a fuel as an input to produce electricity.[9] This fuel could be steam coal, lignite, natural gas, oil or biomass. In the end-user sectors, demand for various energy carriers is derived from nested CES utility functions. In LIBEMOD, there is one CES utility function for each of the four end-user sectors in each of the 30 model countries, see Aune et al. (2008) section 2.4 for details.

LIBEMOD offers a detailed description of production of electricity. Power stations are either "old" or "new". An old plant has pre-existing capacities, and for this group of plants capacities cannot be expanded (per assumption).[10] In contrast, capacities of new plants are of course endogenous in the model, determined by profitability. In LIBEMOD, 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, run-of-river power, nuclear, waste power, biomass power, wind power, solar, and CCS power technologies. The latter group consists of pre-existing (old) gas-fired and coal-fired power plants that have been retrofitted by a capture technology, and new gas-fired and new coal-fired plants with integrated capture facilities ("greenfield CCS plants").

In LIBEMOD, there are four types of costs in electricity production: fuel costs (not relevant for hydro, wind and solar), 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, for example, that maintained power capacity cannot exceed installed power capacity. This leads to operational rules, as well as a decision rule for optimal investment, see Aune et al. (2008), and Aune and Golombek (2021).

The modeling of renewable electricity is similar to the modeling of conventional technologies, but key characteristics of the renewable technologies are taken into account. For wind power and solar, sites within a country differ with respect to what share of the installed capacity that will be used during a standard (weather) year. Furthermore, it is assumed that sites are developed in descending order, i.e., the best site is first developed, but there are constraints for how much capacity that can be installed in a grid cell, see Aune and Golombek (2021) for details. For reservoir hydro, which has a reservoir to store water, it is imposed that the reservoir filling at the end of a season

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[7] In LIBEMOD, there are two types of natural gas. One type is transported by pipes and another type (LNG) is transported by ship. For end users, these goods are homogenous. Whereas pipes are used for transport between European countries, as well as to import natural gas from Russia and Algeria, there is a world market for LNG in LIBEMOD.

[8] Time is modeled circular, that is, follows a specific sequence of periods that is repeated.

[9] In LIBEMOD, the electricity generation sector covers electricity supply as well as electricity used to produce heat.

[10] For nuclear, we use information from World Nuclear Association (2019) to phase out capacities according to approved national plans. In addition, there is standard depreciation of all pre-existing capacities.

cannot exceed the reservoir capacity. In addition, total use of water should not exceed total supply of water, that is, total production of reservoir hydropower in a season plus the amount of water in the reservoir at the end of this season should not exceed the amount of water in the reservoir at the end of the previous season plus the seasonal inflow of water.

Turning to CCS power stations, Golombek et al. (2011) finds that very little retrofitting of power plants will occur. The reason is high costs of retrofitting, which is still the case because of negligible R&D on this technology. In this study, we have therefore chosen to include only green-field CCS power plants. Table 1 shows our CCS cost assumptions for 2050 (our scenario year). Because no CCS power stations have to date been installed in Europe, we cannot use historical data to calibrate the CCS block of the numerical model. Instead, we use information on expected future costs and efficiency of CCS power stations from the New Policy Scenario in IEA (2016).[11] This source has capital costs, O&M costs and efficiency for new CCS power plants in 2030 and 2040, and we use these to calculate the LIBEMOD 2050 parameters.[12]

Table 1: CCS parameters

	Capital costs ($2015 per kW)			O&M costs ($2015 per kW)			Efficiency (%)		
	2030 IEA	2040 IEA	2050 LIBEMOD	2030 IEA	2040 IEA	2050* LIBEMOD	2030 IEA	2040 IEA	2050 LIBEMOD
Coal CSS	5000	4800	4608	180	170	160	39	40	41
Gas CCS	2800	2650	2508	90	80	70	53	54	55

Source for IEA numbers: IEA (2016).

*O&M costs can be split into a variable part (3 $€_{2009}$ per MWh for coal CCS and gas CCS), see ZEP (2011), and a residual fixed part (113 and 39 $€_{2009}$ per kW for CCS coal power and CCS gas power, respectively). The fixed O&M cost is based on a capacity utilization rate of 70%, which for years has been the standard assumption in IEA studies.

Whereas capital costs and O&M costs in Table 1 are measured in $\$_{2015}$ per kW, we have transformed the 2050 figures to $€_{2009}$ per kW because in LIBEMOD, values are measured in $€_{2009}$. In addition, we have split the O&M cost into variable and fixed cost of O&M. Drawing on ZEP (2011), we set the variable O&M cost to 3 $€_{2009}$ per MWh for both CCS coal power and CCS gas power. We find the fixed O&M cost as the difference between total and variable O&M cost, assuming an annual capacity utilization rate of CCS power plants of 70 percent. The resulting fixed O&M cost is 113 and 39 $€_{2009}$ per kW for CCS coal power and CCS gas power, respectively.

LIBEMOD is a static model that determines all energy quantities—investment, production, trade and consumption—and all energy good prices—for all fossil fuels, electricity and bioenergy—both producer prices and end-user prices, as well as emissions of CO_2 by sectors and countries, for a future year, here 2050. By changing parameter values, alternative 2050 equilibria are calculated.

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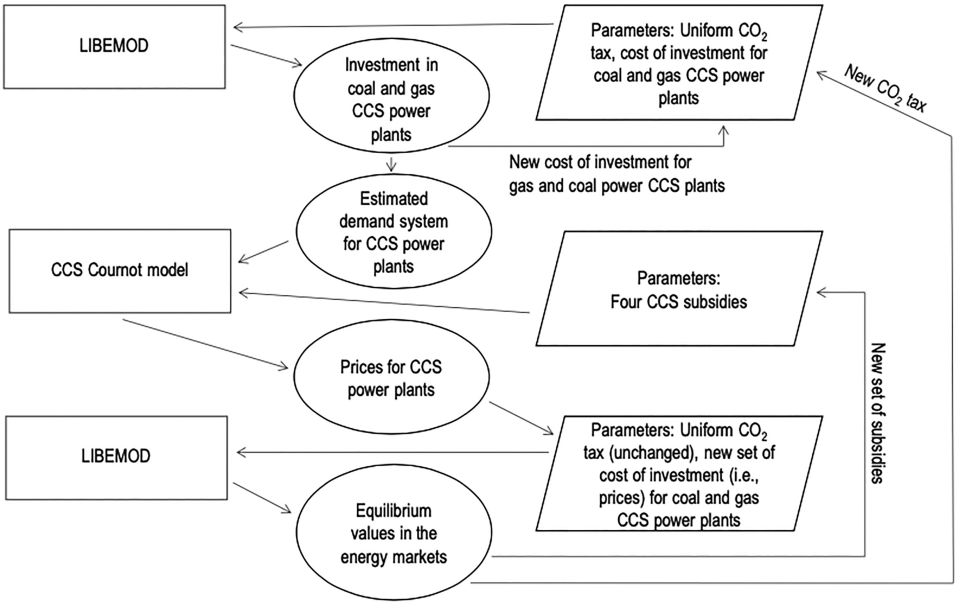
[11] For alternative sources of cost estimates, see Rubin (2012), which reviews and compares alternative methods, metrics and assumptions for estimating costs of CCS electricity; Voll et al. (2012) for a review of CCS electricity studies; Rubin et al. (2015) on fossil-fuel based CCS electricity; Kjärstad et al. (2016) on transport of carbon by either pipes or ship; and Feron et al. (2019) on the potential to increase CO_2 capture rates for power technologies.

[12] We assume that the percentage change in capital costs between 2030 and 2040 applies also for the change from 2040 to 2050. Moreover, the absolute change in O&M costs between 2030 and 2040 is assumed to apply also for the change between 2040 and 2050. Finally, the absolute change in efficiency (measured in percentage points) from 2030 to 2040 is assumed to be valid also for the change between 2040 and 2050, see Table 1. Under our assumptions, capital cost of CCS coal power decreases by 16 percent between 2015 and 2050, whereas the corresponding number for CCS gas power is 20 percent.

3.2 Endogenous prices for CCS plants

Cost of investment for coal and gas CCS power plants are parameters in LIBEMOD. We want these costs, which are the prices faced by CCS power plants, to be endogenous in our analysis. In order to simulate a model with endogenous price formation for CCS power plants, we develop an approach, which to our knowledge has not been used before. Figure 2 shows a flowchart of the procedure. Here, a rectangular box represents a numerical model, a parallelogram contains parameters to be used in a numerical model, whereas an oval shows output from a numerical model.

Figure 2: Procedure to examine impacts of CCS subsidies



First, we choose a uniform CO_2 tax and also values for cost of investment for coal and gas CCS power plants; this is represented in Figure 2 by the parallelogram with the text "Parameters: Uniform CO_2 tax, cost of investment for coal and gas CCS power plants". We use these parameters to run the LIBEMOD model for the year 2050, see the top rectangular box, to find purchase of (i.e., investment in) each type of CCS power plant; this is represented by the top oval in Figure 2 with the text "Investment in coal and gas CCS power plants". Then we change the assumptions for cost of investment for CCS power plants (but keep the CO_2 tax)—this is represented by the arrow with the text "New cost of investment for coal and gas CCS power plants"—and run the LIBEMOD model again. We used 51 values for each of the two cost parameters (CCS coal power and CCS gas power plants), thereby producing a full sample of 2601 model runs.[13]

From the set of model runs, we estimate demand for coal-fired CCS power plants, X_c, and demand for gas-fired CCS power plants, X_g, as functions of investment cost of CCS coal power and CCS gas power plants, p_c and p_g (for a given CO_2 tax):

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[13] For each type of CCS power plant, capital cost, which is transformed to annualized cost of investment under the assumption of a 5 percent real rate of interest and 30 years of lifetime, is varied from 25 percent of the value in Table 1 to 150 percent of the value in Table 1, with step length of 2.5 percentage points. This leads to 51 steps for each type of CCS power plant.

$$\begin{aligned} X_c &= \alpha_c - \gamma_c p_c + \psi_g p_g \\ X_g &= \alpha_g - \gamma_g p_g + \psi_c p_c \end{aligned} \tag{21}$$

Note that as opposed to the inverse demand system (18), the cross price parameter ψ differs between the two demand functions. This is because the LIBEMOD model captures more effects than the simple theory model in Section 2. In particular, in LIBEMOD all energy prices are endogenous. If the cost of CCS power plants are changed, that is, the purchaser prices p_c and p_g are changed, then the equilibrium prices of the energy carriers coal and gas change. While both the coal and the gas markets are competitive in LIBEMOD, demand and supply elasticities in these markets differ. In particular, supply of coal is much more price elastic than supply of gas. Hence, if the purchaser prices of coal power and gas power CCS plants are altered by the same amount, the changes in coal and gas prices will differ, which is why the estimated cross price parameter (ψ) differs between the two demand functions. In Figure 2, the estimation is represented by the oval with the text "Estimated demand system for CCS power plants".

The OLS estimated demand parameters are shown in Table 2. We have estimated the parameters when (i) data from all model runs are used, and when (ii) equilibria with no purchase of a CCS plant have been removed. Below we use the parameters from the latter case because here we obtain a better fit (measured by the adjusted R square). Note that all parameters are significant at the 1 percent test level, and the adjusted R square is at least 0.91. This clearly suggests that the estimated demand systems provide a good approximation of the demand for CCS coal power and CCS gas power plants in LIBEMOD.

Table 2: OLS estimates of demand parameters for CCS coal power and CCS gas power plants

	CCS Coal Plants			CCS Gas Plants	
	Full sample (1)	Drop 0 obs (2)		Full sample (3)	Drop 0 obs (4)
Tax=50	N=2601	N=1887		N=2601	N=1097
Const.: α_c	450.01***	514.88***	Const.: α_g	103.67***	197.60***
P_c: γ_c	1.46***	1.91***	P_g: γ_g	0.76***	2.45***
P_g: ψ_g	0.04*	0.05***	P_c: ψ_c	0.06***	0.16***
Adj.R^2	0.93	1.00	Adj.R^2	0.61	0.91
Tax=100	N=2601	N=2354		N=2601	N=2600
Const.: α_c	359.78***	365.30***	Const.: α_g	193.49***	193.48***
P_c: γ_c	1.29***	1.41***	P_g: γ_g	1.20***	1.20***
P_g: ψ_g	0.46***	0.58***	P_c: ψ_c	0.45***	0.45***
Adj.R^2	0.95	0.98	Adj.R^2	0.92	0.92
Tax=200	N=2601	N=1772		N=2601	N=2601
Const.: α_c	177.06***	210.99***	Const.: α_g	263.61***	263.61***
P_c: γ_c	0.71***	1.13***	P_g: γ_g	0.71***	0.71***
P_g: ψ_g	0.30***	0.53***	P_c: ψ_c	0.29***	0.29***
Adj.R^2	0.81	0.95	Adj.R^2	0.91	0.91

Significance codes: * 10% level, ** 5% level, and *** 1% level.

Next, we set up a numerical model which is similar to the theory model in Section 2.2; this is represented by the rectangular box with the text "CCS Cournot model". Here, demand is represented by the system (21), that is, the two goods in the model are CCS coal power plants and CCS gas power plants. Like in Section 2.2, there is an exogenous number of identical domestic producers and an exogenous number of identical foreign producers. All producers supply both types of CCS power plants and there is Cournot competition between all producers.

Like in Section 2.2, there are four CCS subsidies: an upstream subsidy to produce CCS coal power plants, an upstream subsidy to produce CCS gas power plants, a downstream subsidy to purchase CCS coal power plants, and a downstream subsidy to purchase CCS gas power plants; this is represented by the parallelogram with the text "Parameters: Four CCS subsidies". We assume, like in the theory model, that only domestic producers receive upstream subsidies. Henceforth, domestic producers are referred to as EU producers, whereas foreign producers are referred to as non-EU producers.

We run the numerical Cournot model for some specific values of the four CCS subsidies, thereby obtaining prices for coal CCS and gas CCS power plants; this is represented in Figure 2 by the oval with the text "Prices for CCS power plants". Then we use these CCS power plant prices, which correspond to a specific vector of the four CCS subsidies, to run the LIBEMOD model. In Figure 2, the new set of parameters is represented by the bottom parallelogram. As for any other LIBEMOD run, we obtain all equilibrium quantities and prices in the European energy market, as well as CO_2 emissions, and can thus construct standard welfare measures for the EU and the world; this is represented by the oval with the text "Equilibrium values in the energy market". We then pick another vector of subsidies, find the corresponding CCS power plant prices and run the LIBEMOD model with this set of prices. This procedure is repeated several time, and in Figure 2 it is represented by the arrow with the text "New set of subsidies".

For each run, we let a subsidy rate increase by 5 percentage points from 0 percent to 95 percent. Thus for a number of combinations of the four subsidies, we obtain the price of CCS coal power plants and the price of CCS gas power plants, and the corresponding equilibrium values in the energy markets.

We follow the procedure described above for each of three CO_2 taxes, that is, we pick a CO_2 tax, use the derived demand parameters in the numerical Cournot model, and use this tax when we run the LIBEMOD model in the last stage of the procedure. We then pick another uniform CO_2 tax and run through the complete procedure again, etc; this is represented in Figure 2 by the arrow with the text "New CO_2 tax".

Our starting point for choosing CO_2 taxes is IEA (2008). Here, it is argued that a CO_2 price at \$90 is consistent with the 2 degree target. Similarly, IPCC (2019) assumes a CO_2 price at \$100, which is supposed to be consistent with the 1.5 degree target. In line with these predictions, we use a uniform CO_2 tax at €100 in the 2050 Reference scenario. In addition, we explore the effects of two alternative uniform CO_2 taxes: 50 euro/tCO_2 and 200 euro/tCO_2.

4. EFFECTS OF STRATEGIC TRADE POLICY

In this Section we will use the numerical framework in Section 3 to answer the main research questions in this paper. First, should the upstream subsidy be greater than the downstream subsidy? Second, should CCS coal power plants receive a higher subsidy than CCS gas power plants?

According to the simple theory models in Section 2, the upstream subsidy should not only be greater than the downstream subsidy, there should in fact be no downstream subsidy. Furthermore, the good with the highest social value, measured as the intercept term in the demand function of this good (i.e., the choke value) relative to the unit cost of this good, should receive the highest subsidy. Applying this rule to CCS power plants, the numbers from Tables 1 and 2 suggest that CCS coal power plants should receive the highest subsidy as its social value ratio is 42 percent higher than the social value ratio of CCS gas power plants.

Using the numerical framework developed in Section 3, we want to find the combination of subsidies that maximizes EU welfare. Note that our numerical framework captures more effects than the theory models. First, the *welfare effect of reduced CO_2 emissions* through increased use of CCS power stations 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, EU welfare also depends on *terms of trade effects* through the cost of net imports of energy (whereas in Section 2 we assumed that all input prices are fixed). Here, there are several effects, two of these are:

a) If one type of CCS plants is stimulated, say, CCS coal power plants, then the price of coal will increase. Because the EU is a net importer of coal, the EU welfare will, *cet. par.*, decrease. While this effect applies to both CCS coal power plants and CCS gas power plants, the fact that supply of coal is more price elastic than supply of natural gas suggests to subsidize CCS coal power plants more than CCS gas power plants.
b) The EU imports more natural gas than coal. Therefore, if, hypothetically, the prices of coal and natural gas increase equally much, then, *cet. par.*, costs of net imports of natural gas will increase more than costs of net imports of coal. This reinforces to subsidize CCS coal power more than CCS gas power.

To sum up, these two additional effects tend to suggest to subsidize CCS coal power more than CCS gas power.

In our Reference scenario (Section 4.1), we study effects of different combinations of downstream and upstream subsidies in 2050 under the assumption that the uniform CO_2 tax in the EU is $€_{2009}$ 100 per tCO_2. Like in the theory models, there is a fixed number of firms supplying both CCS coal power plants and CCS gas power plants. These firms are identical, but only firms located in the EU receive upstream subsidies. Based on current technology competence and expressed interest in CCS power plants, in the Reference scenario we assume there are three EU firms and two non-EU firms.[14] Because these numbers are uncertain, in Section 4.2 we examine effects of subsidies under alternative assumptions about the number of EU suppliers of CCS power plants. Here we also study welfare effect if the uniform CO_2 tax in the EU differs from 100 euro per tCO_2, as well as consider other combinations of subsidies than the ones studied in the Reference scenario.

4.1 Welfare effects

Figure 3 shows plots of EU welfare for various subsidies. Here EU welfare is defined as the sum of consumer surplus, producer surplus including the profit of the EU CCS firms, and net income of the (EU) government, aggregated over all goods and model countries in LIBEMOD. In addition, cost of CO_2 emissions of the EU is subtracted.

We distinguish between global cost of CO_2 emissions and the EU cost of CO_2 emissions. The global cost of emissions is defined as global emissions (tCO_2) times the global social cost of carbon. The global social cost of carbon represents the global cost of emitting one more unit of CO_2, which we set equal to the CO_2 tax rate. Cost of emissions of the EU is then defined as global emissions (reflecting the transboundary character of CO_2 emissions) times the EU social cost of carbon. Finally, the EU social cost of carbon is set equal to the CO_2 tax times EU's share of global GDP.

Panel a in Figure 3 shows how EU welfare depends on a downstream subsidy to CCS coal power plants (solid curve), or alternatively an upstream subsidy to CCS coal power plants (dashed curve). Similarly, panel b in Figure 3 shows how EU welfare depends on a downstream (solid curve)

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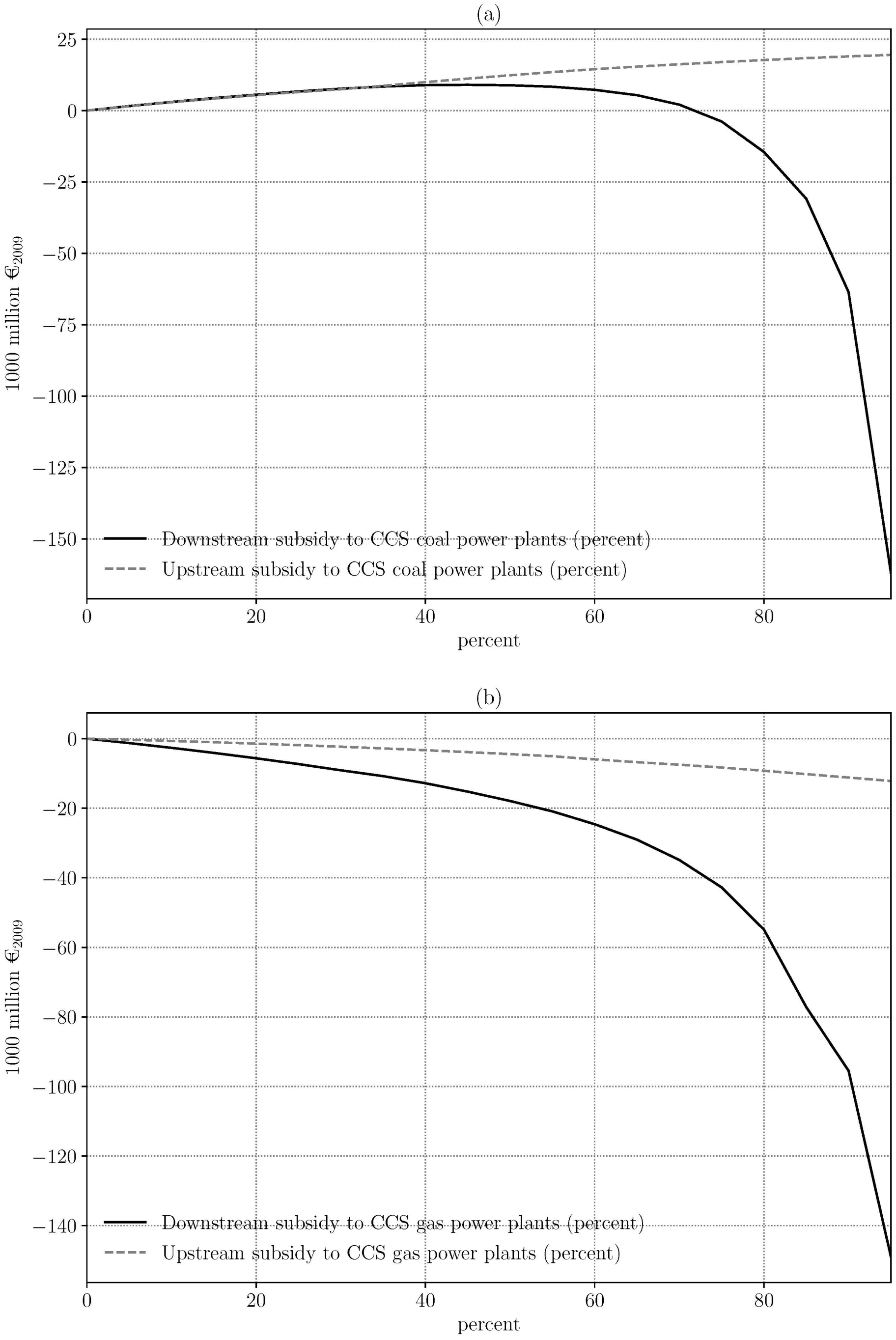
[14] These could be Aker Solutions (Norway, member of the European Economic Area), Alstom (France), Siemens (Germany), and the non-EU producers General Electric (US) and Mitsubishi (Japan).

or an upstream (dashed curve) subsidy to CCS gas power plants. First, from Panel a we note that an upstream subsidy to CCS coal power plants unambiguously increases EU welfare, and that the subsidy rate should be set to 95% (the maximum in our study). Further, as seen from Panel a, a

Figure 3: EU welfare—2D plots. CO_2 tax at €$_{2009}$ 100 per tCO_2.



Panel a: i) Downstream subsidy to CCS coal power plants, ii) upstream subsidy to CCS coal power plants
Panel b: i) Downstream subsidy to CCS gas power plants, ii) upstream subsidy to CCS gas power plants

higher downstream subsidy to CCS coal power plants first increases EU welfare slightly, but then decreases EU welfare significantly (provided there are no other subsidies). Thus, our simulations with subsidies to CCS coal power plants largely confirm our theoretical results.

Next, Panel b shows that both a higher upstream and downstream subsidy to CCS gas power plants decreases EU welfare (provided there are no other subsidies). The negative effect on EU welfare is much stronger for the downstream subsidy than for the upstream subsidy. As we will return to, the reason for the negative effects is partly that the EU must pay much more for imports if it subsidizes CCS power plants (terms of trade effect).

The 2D panels in Figure 3 show how *one* subsidy changes EU welfare, keeping the other subsidies at zero. In order to find the *combination of subsidies* that maximizes welfare, we have made 3D plots.

Panel a in Figure 4 shows how EU welfare depends on combinations of an upstream subsidy to CCS coal power plants and an upstream subsidy to CCS gas power plants. The dashed curves in Panels a and b in Figure 3 can be reproduced by fixing either the upstream subsidy to CCS gas power plants at zero, or by fixing the upstream subsidy to CCS coal power plants at zero. The black dots in Figure 4 show the maximum value of EU welfare. As seen from Panel a, EU welfare is maximized by setting the upstream subsidy to CCS coal power plants as high as possible, which in our study is 95 percent, whereas there should be no upstream subsidy to CCS gas power plants.

In Figure 4, the EU welfare without any subsidies is normalized to zero. With upstream subsidies that maximize the EU welfare, the annual increase in EU welfare (relative to no subsidies) is 20 thousand million euro_{2009}. This amount corresponds to around 0.1% of GDP in EU-30, and to 7 percent of total costs of electricity producers.

Panel b in Figure 4 shows how EU welfare depends on combinations of a downstream subsidy to CCS coal power plants and a downstream subsidy to CCS gas power plants. The maximum value of EU welfare is reached by setting the downstream subsidy to CCS coal power plant to 45 percent and offer no downstream subsidy to CCS gas power plants. Thus, as for upstream subsidies, CCS coal power should receive the highest subsidy when downstream subsidies are used.

With downstream subsidies that maximize the EU welfare, the annual increase in EU welfare (relative to no subsidies) is 9 thousand million euro_{2009}. This amount corresponds to less than 0.1% of GDP in EU-30, and to around 3 percent of total costs of electricity producers.[15]

According to our results, to maximize EU welfare the upstream subsidy for CCS coal power plants should be greater than the downstream subsidy for CCS coal power plants, that is, the upstream subsidy should exceed the downstream subsidy. This is in line with the discussion in Section 2. For CCS gas power, both the upstream and downstream subsidy should be zero.[16] In order to get a better understanding of these stark results, we will look more into some effects that are crucial for welfare.

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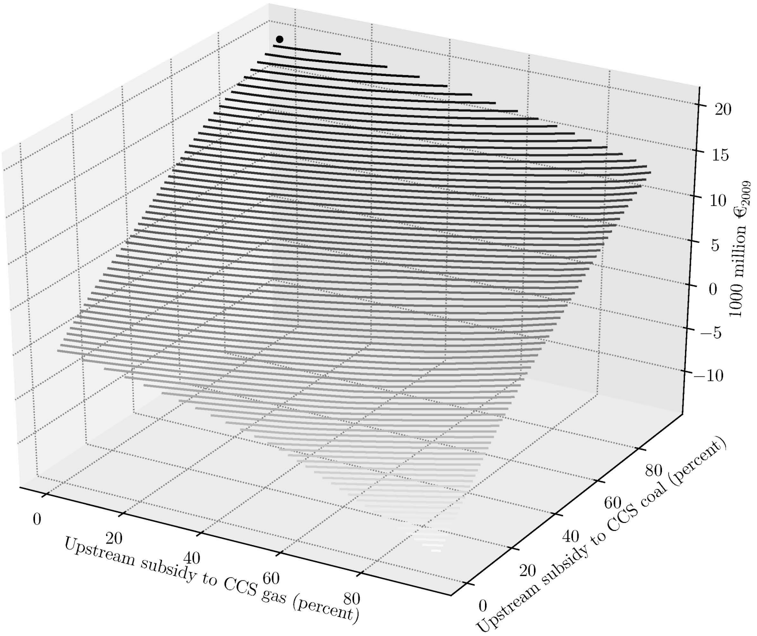
[15] The subsidies that maximize global welfare are found to be very different from the ones that maximize the EU welfare. From a global perspective, subsidies should correct for market power in the upstream market, whereas profit shifting of course is not an issue for a global analysis.

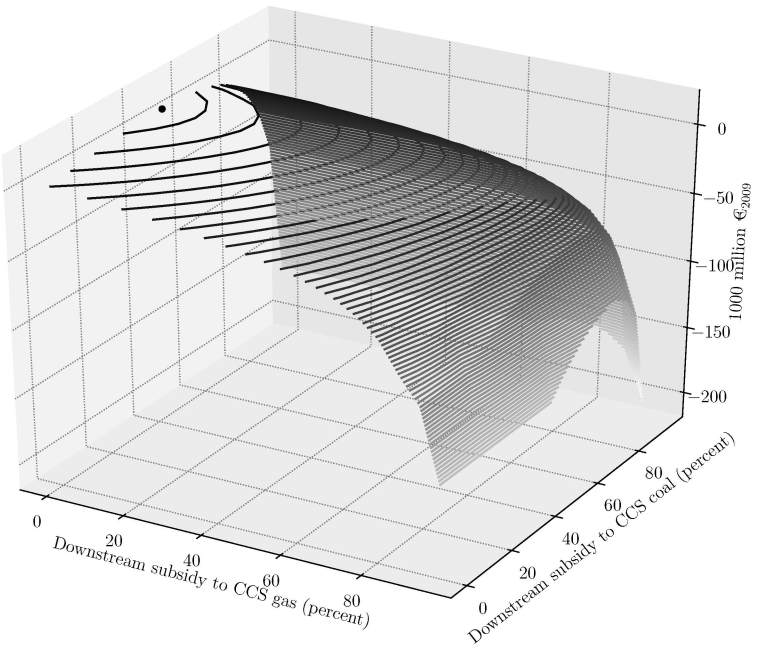
[16] Whereas we have argued in favor of an upstream CCS subsidy for coal power, one could question whether such a subsidy is compatible with GATT law. Subsidizing pollution abatement technology firms is a rising issue within the WTO. On the one hand, the subsidy code of the GATT states that a production subsidy is an actionable subsidy. On the other hand, countries could argue that they offer an upstream subsidy to protect the environment, and therefore such an instrument is covered by the escape clauses in Article XX of the GATT. According to the WTO, supporting deployment and diffusion of green technologies is not hindered by WTO rules (WTO 2011).

Figure 4: EU welfare—3D plots. CO_2 tax at €$_{2009}$ 100 per tCO_2.

(a) Upstream subsidy to CCS coal power plants combined with upstream subsidy to CCS gas power plants



(b) Downstream subsidy to CCS coal power plants combined with downstream subsidy to CCS gas power plants



Panel a: Upstream subsidy to CCS coal power plants combined with upstream subsidy to CCS gas power plants
Panel b: Downstream subsidy to CCS coal power plants combined with downstream subsidy to CCS gas power plants

Import price effects

When a subsidy is offered, say, an upstream subsidy for CCS coal power plants, demand for coal is increased, whereas demand for natural gas is decreased. Hence, equilibrium import prices of both energy carriers change. Figure 5 shows how various combinations of subsidies impact the price of coal, whereas the impact on the natural gas price is depicted in Figure 6. Each figure has two panels, and each panel shows two subsidy cases.

Panel a in Figures 5 and 6 shows the cases of i) only a downstream subsidy to CCS coal power plants (solid curve), or alternatively ii) only an upstream subsidy to CCS coal power plants (dashed curve). Both subsidies lead to a higher price of coal (see Figure 5) and a lower price of natural gas (see Figure 6), as expected.

Panel b in Figures 5 and 6 shows the cases of i) only a downstream subsidy to CCS gas power plants (solid curve), or alternatively ii) only an upstream subsidy to CCS gas power plants (dashed curve). Both subsidies lead to a higher price of natural gas (see Figure 6) and a lower the price of coal (see Figure 5), again as expected.

As seen from Panels a and b in Figures 5 and 6, a downstream subsidy always has a greater effect than a corresponding upstream subsidy. This reflects that a downstream subsidy is offered to all clients, whereas an upstream subsidy is restricted to EU producers. Note that this result is in line with the discussion in Section 2.1, see (11).

By comparing Panel a in Figure 5 with Panel b in Figure 6, we see that the change in the price of coal (due to subsidies to CCS coal power plants) is lower than the change in the price of natural gas (due to subsidies to CCS gas power plants). For example, the price of coal increases by 5 euro per toe if there is a 95 percent downstream subsidy to CCS coal power plants (Figure 5, Panel a, solid curve), whereas the price of natural gas increases by almost 60 euro per toe if there is a 95 percent downstream subsidy to CCS gas power plants (Figure 6, Panel b, solid curve). The difference reflects the demand and supply parameters in LIBEMOD, in particular, that supply of coal is more price elastic than supply of natural gas.

The energy mix

Figure 7 shows supply of electricity by technology in the EU under alternative assumptions about subsidy regime: the subsidy regimes in Figures 5 and 6 are represented in Figure 7 by four panels. Panel a shows how a downstream subsidy to CCS coal power plants impacts supply of power. Without any subsidy, the production share of conventional fossil-fuel based electricity and CCS electricity is 1% and 34%, respectively, and emissions in the electricity generation sector are 93% lower than in 1990.[17] There is a marginal increase in total electricity production as the subsidy is increased from zero to 95 percent. The main effect is a great increase in CCS coal power, which crowds out both CCS gas power and renewable electricity. Since there are almost no conventional fossil fuel plants in operation, the effect on CO_2 emissions is tiny.

Panel b shows the impact of an upstream subsidy to CCS coal power plants. It has the same type of effects as in the case of a downstream subsidy to CCS coal power plants, but the magnitudes are smaller, reflecting that all purchasers receive the downstream subsidy whereas only domestic producer receive the upstream subsidy. Again, since there is almost no conventional fossil fuel plants in operation, the effect on CO_2 emissions is very small.

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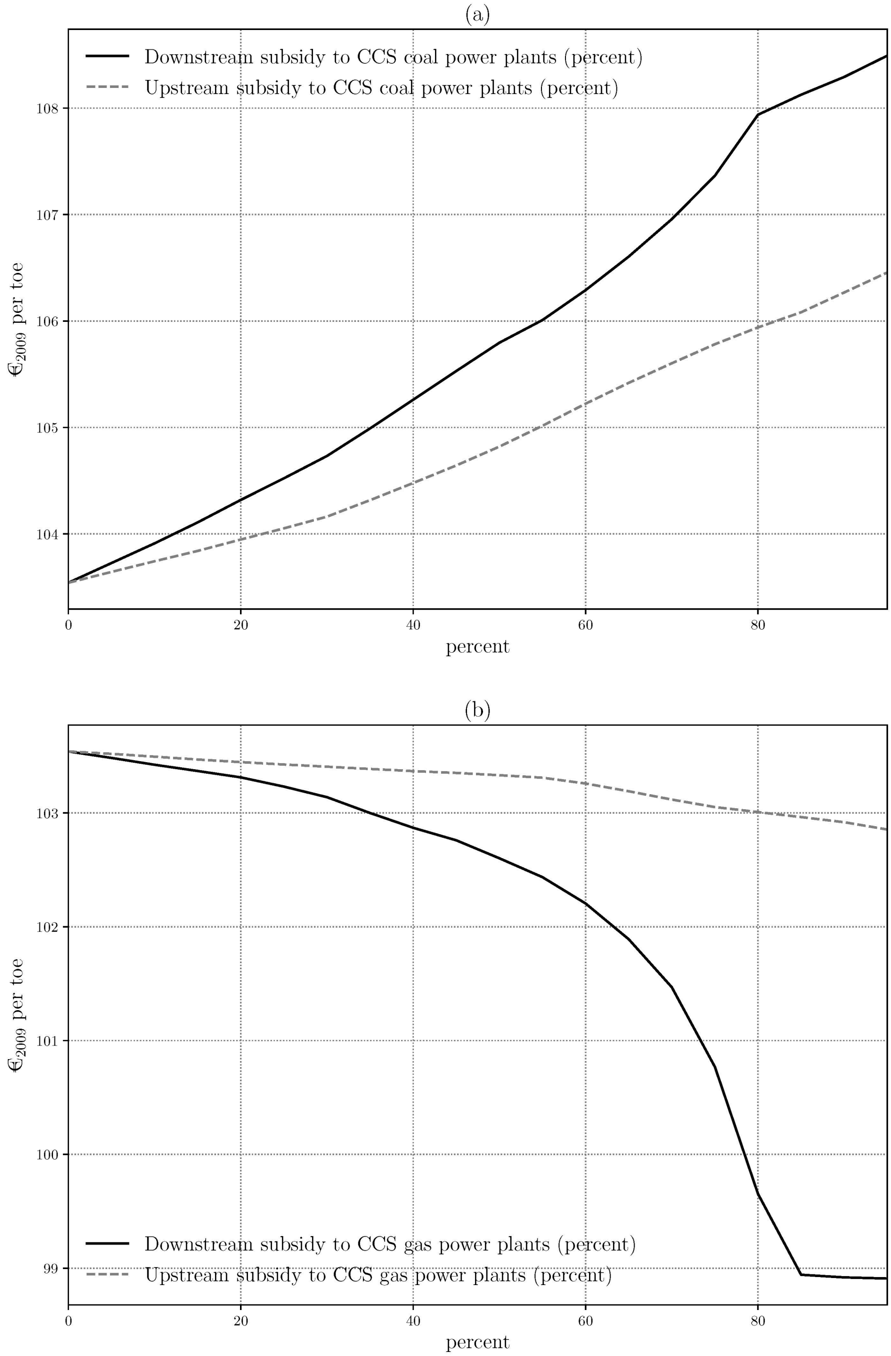
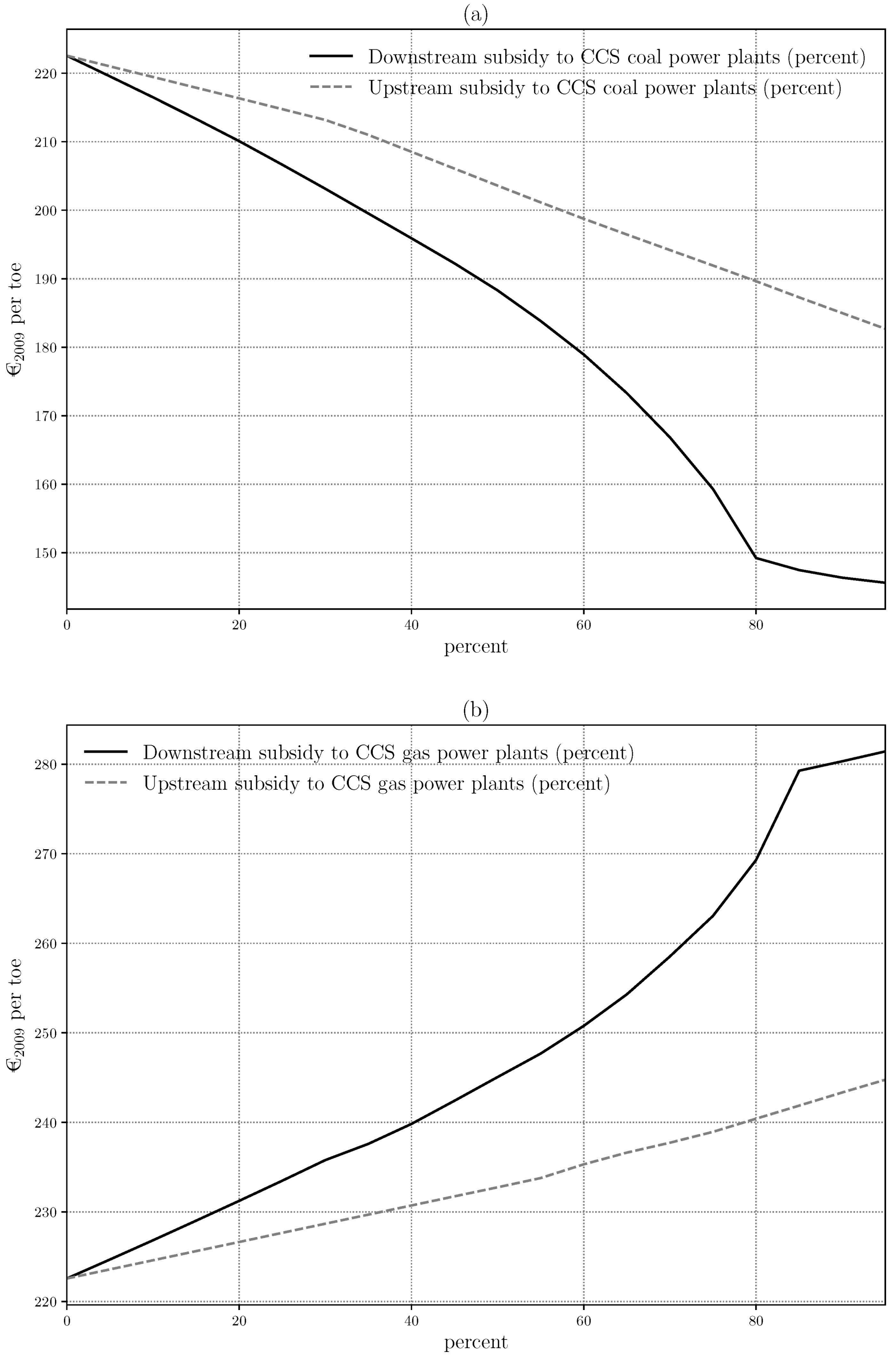
[17] Without any CCS subsidies, CCS power stations become profitable (in LIBEMOD) if the carbon tax is at least 46 euro/tCO2. Note that because of market imperfections, no pure carbon tax will ensure the social optimal magnitude of each electricity technology.

Figure 5: EU price of coal. CO_2 tax at €$_{2009}$ 100 per tCO_2.



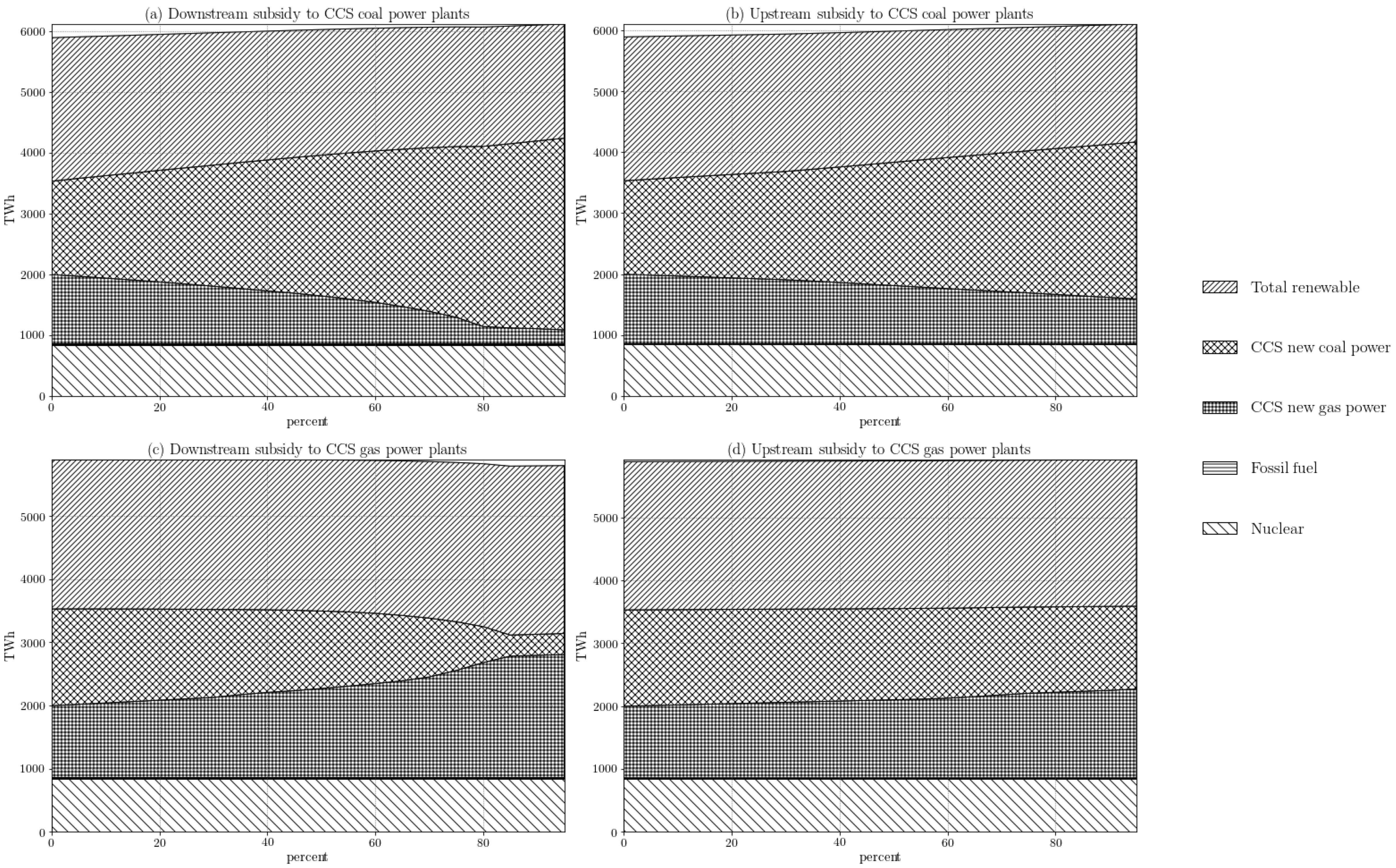
Panel a: i) Downstream subsidy to CCS coal power plants, ii) upstream subsidy to CCS coal power plants
Panel b: i) Downstream subsidy to CCS gas power plants, ii) upstream subsidy to CCS gas power plants

Figure 6: EU price of natural gas. CO_2 tax at €$_{2009}$ 100 per tCO_2.



Panel a: i) Downstream subsidy to CCS coal power plants, ii) upstream subsidy to CCS coal power plants
Panel b: i) Downstream subsidy to CCS gas power plants, ii) upstream subsidy to CCS gas power plants

Figure 7: EU Power supply. CO_2 tax at €$_{2009}$ 100 per tCO_2.



Panel a: Downstream subsidy to CCS coal power plants
Panel b: Upstream subsidy to CCS coal power plants
Panel c: Downstream subsidy to CCS gas power plants
Panel d: Upstream subsidy to CCS gas power plants

Panel c shows the effect of a downstream subsidy to CCS gas power plants. As the subsidy rate is increased, supply of CCS gas power is stimulated, and this effect is strong. Whereas total production of electricity is hardly changed, supply of CCS coal power is partly phased out, whereas there is a small increase in renewable electricity production. Once the subsidy rate reaches 85 percent, a higher subsidy has hardly any impact. With an upstream subsidy to CCS gas power plants (Panel d), CCS gas power crowds out CCS coal power, but the effect is small. As for subsidies to CCS coal power, the effect on CO_2 emissions is very small.

To sum up, our results for EU welfare are not driven by differences in emissions between the subsidy regimes.

4.2 Robustness

The analysis in Section 4.1 assumed i) a CO_2 tax at 100 euro per tCO_2, ii) either only upstream subsidies to CCS coal power and CCS gas power, or only downstream subsidies to CCS coal power and CCS gas power, iii) five CCS power plant producers of which three are located in the EU, iv) identical cost of production for EU and non-EU CCS suppliers, and v) no subsidies to actors outside the CCS sector. Below, we examine to what extent our main findings in Section 4.1 depend on these assumptions.

CO_2 tax

In the Reference scenario, the CO_2 tax is 100 euro per tCO_2. We now examine which subsidy rates that maximize EU welfare when the CO_2 tax is either 200 euro per tCO_2 or 50 euro per tCO_2. The results are shown in Table 3. Like in the Reference scenario, CCS coal power plants should be subsidised more heavily than CCS gas power plants, and the upstream subsidy should exceed the downstream subsidy. To be more specific, when only upstream subsidies are offered, the upstream subsidy to CCS coal power plants should be 95 percent (i.e., the maximum subsidy rate per construction) in all three tax regimes. Moreover, there should be no upstream subsidy to CCS gas power plants. When only downstream subsidies are used, there should be no subsidy to CCS gas power in all three tax cases, whereas the downstream subsidy to CCS coal power should be around 50 percent.

Table 3: CCS subsidies that maximize EU welfare under alternative assumptions on CO_2 tax ($euro_{2009}$ per tCO_2), type of subsidies, and number EU suppliers of CCS

	Tax 100 3 EU suppliers Reference	Tax 200 3 EU suppliers	Tax 50 3 EU suppliers	Tax 100 2 EU suppliers	Tax 100 5 EU suppliers
Upstream subsidy to CCS coal power plants combined with upstream subsidy to CCS gas power plants	Coal: 95% Gas: 0	Coal: 95% Gas: 0	Coal: 95% Gas: 0	Coal: 95% Gas: 0	Coal: 95% Gas: 0
Downstream subsidy to CCS coal power plants combined with downstream subsidy to CCS gas power plants	Coal: 45% Gas: 0	Coal: 55% Gas: 0	Coal: 45% Gas: 0	Coal: 40% Gas: 0	Coal: 55% Gas: 0
Common downstream subsidy to CCS power plants combined with common upstream subsidy to CCS power plants	Downstr: 0 Upstr: 95%	Downstr: 0 Upstr: 95%	Downstr: 25% Upstr: 35%	Downstr: 0 Upstr: 95%	Downstr: 10% Upstr: 70%
A common downstream and upstream subsidy to CCS coal power plants, and a common downstream and upstream subsidy to CCS gas power plants	Coal: 50% Gas: 0	Coal: 55% Gas: 0	Coal: 50% Gas: 0	Coal: 45% Gas: 0	Coal: 60% Gas: 0

CCS subsidies

In the Reference scenario, we identified the pair of upstream subsidies to CCS coal power and CCS gas power that maximized the EU welfare without imposing any constraints on these two rates (except that they are less than 100 percent). This was also the case with downstream subsidies to CCS coal power and CCS gas power.

We now examine two cases in which there are constraints on the magnitude of the subsidies (but we keep the assumption of a tax rate at 100 euro per tCO_2). First, assume there is one common upstream subsidy to CCS coal power and CCS gas power, and also one common downstream subsidy to CCS coal power and CCS gas power. Hence, in this case we focus solely on the upstream versus downstream dimension (not on CCS coal power versus CCS gas power). We find that for the EU, it is optimal to impose a common upstream subsidy rate at 95 percent, whereas it is optimal not to offer any downstream subsidy, see Table 3. Hence, the upstream subsidy should by far be greater than the downstream subsidy. This is in line with the theory discussion Section 2.1. Here, our simple model suggested that no downstream subsidy should be offered.

Next, assume the upstream subsidy to CCS coal power and the downstream subsidy to CCS coal power have the same rate, and also that the upstream and downstream subsidy to CCS gas power have the same rate (The two common rates may differ). Hence, in this case we focus solely on CCS coal power versus CCS gas power (not on upstream subsidy versus downstream subsidy). With this type of policy constraints, CCS coal power should receive a common subsidy at 50 percent, whereas there should be no subsidy to CCS gas power. Again, CCS coal power should receive a higher subsidy than CCS gas power.

CCS power plant suppliers in the EU

In the Reference scenario, we assume that there are three EU suppliers of CCS power plants (and two non-EU suppliers). We now examine two other cases with respect to the number of EU suppliers of CCS power stations, but keep the assumption of the Reference scenario of a CO_2 tax at 100 euro per tCO_2.

First, assume there are two CCS suppliers in the EU. We then obtain the same results as in the Reference scenario (with minor adjustments), see Table 3. Next, suppose there are five EU suppliers (as opposed to three EU suppliers in the Reference scenario). We still obtain the same type of results as in the Reference scenario: a higher upstream subsidy than a downstream subsidy, and higher subsidies to CCS coal power plants than to CCS gas power plants. The only deviation from the Reference scenario is that the downstream subsidy to CCS coal power is 5 percentage points lower (2 EU producers) or 10 percentage points higher (5 EU producers).

Cost of producing CCS power plants

In the Reference scenario, costs of producing CCS power plants are assumed to be identical for all suppliers. These costs may, however, differ between suppliers, for example, because of different production technologies or different unit cost of input factors. To illustrate the importance of cost differentials, we now assume that costs of producing CCS power plants differ between the EU and the non-EU suppliers (but costs are identical within each group of suppliers).

First, assume costs of the non-EU suppliers are ¾ of the costs of the EU suppliers. This has negligible effects on the optimal CCS subsidies, see Table 4, column “low cost of non-EU suppliers”. Also if the non-EU suppliers have higher costs than the EU suppliers, here defined as costs of the non-EU suppliers are 4/3 of costs of the EU supplies, the difference from the Reference scenario is minor. The greatest deviation from the Reference scenario is found in the case of a common downstream subsidy to CCS power plants, which is combined with a common upstream subsidy to CCS power plants. The optimal downstream subsidy is now 25% as opposed to 0 in the Reference scenario.

Table 4: Subsidies that maximize EU welfare under alternative assumptions on cost of producing CCS power stations of the non-EU suppliers, and renewable electricity subsidy

	Tax 100 3 EU suppliers Low cost of non-EU suppliers*	Tax 100 3 EU suppliers High cost of non-EU suppliers**	Tax 100 3 EU suppliers Renewable electricity subsidy
Upstream subsidy to CCS coal power plants combined with upstream subsidy to CCS gas power plants	Coal: 95% Gas: 0	Coal: 95% Gas: 0	Coal: 95% Gas: 0
Downstream subsidy to CCS coal power plants combined with downstream subsidy to CCS gas power plants	Coal: 40% Gas: 0	Coal: 45% Gas: 0	Coal: 0 Gas: 0
Common downstream subsidy to CCS power plants combined with common upstream subsidy to CCS power plants	Downstr: 0 Upstr: 95%	Downstr: 25% Upstr: 95%	Downstr: 0 Upstr: 30%
A common downstream and upstream subsidy to CCS coal power plants, and a common downstream and upstream subsidy to CCS gas power plants	Coal: 50% Gas: 0	Coal: 50% Gas: 0	Coal: 55% Gas: 0

* Cost of non-EU suppliers is ¾ of cost of EU suppliers.
** Cost of non-EU suppliers is 4/3 of cost of EU suppliers.

Renewable electricity subsidy

In the Reference scenario, only actors in the CCS sector receive subsidies in order to maximize the EU welfare. In general, public bodies may offer a number of subsidies (and/or impose a number of taxes) to achieve policy goals. For example, in the 2030 EU policy package, there are three main targets: lower greenhouse gas emissions, a higher renewable share in final energy consumption, and improved energy efficiency. Aune and Golombek (2021) examines this policy package and find that to achieve the renewable target, a subsidy of 52 euro/MWh to all renewable electricity producers will do the job. To illustrate the importance of additional subsidies, we examine optimal CCS subsidies when renewable electricity producers receive a subsidy of 52 euro/MWh.

We find that for two of the four CCS subsidy cases, the difference from the Reference scenario is minor, whereas for a third case—a common downstream subsidy and a common upstream subsidy—the difference is significant as the common upstream subsidy now should be 30% (see Table 4, third line, last column) as opposed to 95% in the Reference case (see Table 3, third line, first column). The greatest difference from the Reference scenario is found in the case of only downstream subsidies. The optimal downstream subsidy for CCS coal power plants is now 0 (see Table 4, second line, last column), whereas it is 45% in the Reference case. The difference reflects that a subsidy to renewable electricity producers stimulates electricity supply, thereby pushing down the price of electricity. Hence, demand for CCS power stations decreases and therefore the price of CCS power stations falls. As the main task of the CCS subsidies is to lower the price of CCS power stations by so much that production is not profitable for the non-EU CCS suppliers, the need for CCS subsidies is reduced when the EU also offers a renewable electricity subsidy.

5. CONCLUSION

The aim of this paper has been to examine how to design an EU support scheme for CCS power plants. Two instruments have been investigated, namely an upstream subsidy (to lower the cost of supplying CCS power technologies) and a downstream subsidy (to lower the price of purchasing CCS power technologies). Under the assumption of imperfect competition in the European CCS power market, we have explored whether the upstream subsidy should be greater than the downstream subsidy. Also, we have explored whether subsidies to different CCS electricity technologies (coal based vs. gas based) should differ.

The two research questions have been investigated both with simple theory models and within a framework where a numerical version of the theory model is soft-linked with LIBEMOD, a large-scale numerical model of the European energy markets. The link between the two models is the prices of CCS power plants: In LIBEMOD, these are exogenous cost parameters, whereas in the numerical version of the theory model prices of CCS power plants are endogenous variables.

Both the theory models and application of the numerical framework suggest that the upstream subsidy should exceed by far the downstream subsidy. The main reason is simply that an upstream subsidy shifts production and profits from non-EU CCS power station suppliers to EU suppliers, thereby increasing EU welfare. In addition, both upstream and downstream subsidies stimulate total production, thereby lowering the initial dead-weight loss due to the lack of marginal cost pricing.

Furthermore, we find that subsidies to CCS coal power plants should exceed subsidies to CCS gas power plants. The reason is partly that the pure social value of CCS coal power plants (measured as its choke price relative to its unit cost of production) exceeds the social value of CCS gas power plants. This is reinforced by the fact that coal has a higher CO_2 emission coefficient that natural gas, and hence it is more valuable to replace conventional coal power with CCS coal power than to replace conventional gas power with CCS gas power. In addition, because supply of coal is more price elastic than supply of natural gas, there is a terms-of-trade effect that rationalizes that CCS coal power plants should receive a higher subsidy than CCS gas power plants.

Several extensions of the analysis are possible. One possible extension would be to endogenize *costs* of CCS power plants. Hence, instead of assuming that these costs decrease exogenously over time in accordance with IEA (2016), see the discussion in connection with Table 1 in Section 3.1, one could specify the Cournot model as a two-stage game where R&D (to lower cost of production) is determined in stage one, whereas production is determined in stage two. Fischer et al. (2017) argue that an upstream subsidy to Cournot producers can be interpreted as an R&D subsidy to the same producers, which then indirectly would decrease production costs. Including R&D in the Cournot game would likely imply that also the downstream subsidy would reduce cost by making private R&D more profitable at the margin. Would this change our results? In our opinion the answer is “no” as the downstream subsidy would also lead to more R&D by the foreign producers, thereby improving the competitive position of this group of producers. Therefore, a downstream subsidy may not be offered by the EU.

Another extension would be to include upstream subsidies to the foreign producers, offered by the governments in the jurisdictions where these producers reside. If we introduce an exogenous upstream subsidy to the non-EU producers, the EU still has an incentive to shift profits from the non-EU producers to the EU producers, and none of the results would likely change. Alternatively, there could be a game in which governments in the EU and outside the EU set upstream subsidies simultaneously. Each government then has an incentive to offer an upstream subsidy in order to shift profits to its producers. There likely exists a Nash- equilibrium in this game with positive upstream subsidies in both regions. Although in this equilibrium the amount of profit shifting to the EU would be less or disappear entirely, the EU would still benefit from the reduced price on CCS technology as, by assumption, the major market for CCS technology is in the EU. Thus, as opposed to the strategic trade policy game described by Brander and Spencer (1985), a subsidy war on the production of CCS technology may not qualify as a Prisoners Dilemma.

A final extension would be to highlight the importance of energy storage technologies, which may be important because the share of intermittent power (solar and wind power) may increase over time to meet ambitious carbon targets. In the current analysis, we have included the storage technologies reservoir hydro and pumped storage hydro, whereas a possible extension could be hydrogen, which is not included in the current version of LIBEMOD.

Hydrogen produced from renewables (green hydrogen), and hydrogen produced from natural gas or coal combined with CCS (blue hydrogen) may be used for electricity supply, by manufacturing firms in the EU ETS sectors, and also in some of the non-ETS sectors, for example, to power vehicles. If hydrogen production is profitable and used to produce electricity, the price of electricity will be lowered, thereby making development in CCS power stations less profitable. Therefore, hydrogen may have a similar effect as a renewable support scheme, see Section 4.2, where we found that overall, the CCS subsidies that maximize EU welfare tend to decrease.

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APPENDIX A: OPTIMAL SUBSIDIES FOR THE DOMESTIC COUNTRY

We consider an economy with two goods (technologies). The goods are consumed in the domestic country only. The government in the domestic country maximizes its welfare, which is the sum of producer surplus of the domestic producers, consumer surplus and net income of the domestic government by choosing upstream and downstream subsidy rates of the two goods, under the restrictions that i) upstream subsidies are offered to the domestic producers only, ii) all subsidy rates much be non-negative and strictly less than 100%.

To find the equilibrium, we proceeded in three steps:

i) First, we maximized domestic welfare with respect to the four subsidy rates, imposing that each subsidy rate is non-negative and strictly less than one. Maple was not able to solve this problem. Hence, there is either no solution to this problem, or there is a solution but Maple is not able to find it with the specification we used. Therefore, we try to solve the problem in another way.

ii) Second, we maximized domestic welfare under the restrictions that one downstream subsidy is exogenously set to zero, say the downstream subsidy to good *c*, i.e., $\eta_c = 0$, whereas each of the three remaining subsidy rates are non-negative and strictly less than one. The resulting solution is characterized by the other down-stream subsidy being zero ($\eta_g = 0$), and the upstream subsidies are given by $s_k^{opt} = \frac{1}{n}(\frac{A_k}{c_k} - 1)$, that is, they have exactly the same structure as in the case of one good, see Proposition 2. We then repeated this procedure, but now the other downstream subsidy is exogenously set to zero, i.e., $\eta_g = 0$. Again we obtained that the endogenous value of the downstream subsidy should be zero i.e., $\eta_c = 0$, whereas the upstream subsidies are given by s_k^{opt}. Because we obtain the same solution independent of which downstream subsidy is exogenously set to zero, the solution of the problem in i) must be characterized by zero down-stream subsidies and upstream subsidies being equal to s_k^{opt}.

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