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Abstract

Knowing that carbon capture and storage (CCS) could play an important role in reducing CO_2 emissions, it is important to have a good understanding of this role and the importance of environmental policies to support carbon capture and geological storage from bioenergies (BECCS). To date CCS technologies are not deployed on a commercial level, and policy instruments should be used to provide incentives to firms to use these technologies to reduce pollution. The aim of this paper is to compare the cost-efficiency of several incentive-based instruments (a fossil fuel tax, an emissions tax, a cap and trade system that recognize negative emissions, and a subsidy on captured emissions) needed to spur the adoption of CCS of the emissions from fossil fuel as well as from biomass, using a dynamic general equilibrium model. The study shows that BECCS will be deployed only if a specific subsidy per unit of biomass emissions captured with a CCS technology is available. We show also that the two most cost-efficient instruments for achieving a given emissions reduction target are a specific subsidy that rewards captured emissions and a carbon tax whose revenues are recycled to subsidize BECCS.

Keywords: Bioenergies with carbon capture and storage, dynamic computable general equilibrium model, policy instruments efficiency.

Résumé

La capture et le stockage du carbone (CCS) à un rôle important à jouer dans la réduction des émissions de CO_2. Elle peut s'appliquer aux énergies fossiles et aux bioénergies (BECCS). A l'heure actuelle, ces technologies ne sont pas encore au stade de la commercialisation. Il existe donc une nécessité de mettre en place des incitations économiques claires et crédibles pour faciliter leur développement. L'objectif de ce papier est de comparer l'efficacité-économique de plusieurs instruments économiques (une taxe fossile, une taxe sur les émissions, un système de permis négociable qui reconnait les émissions négatives et une subvention à la capture des émissions) capables de stimuler le CCS et le BECCS. Cette analyse est conduite grâce à un modèle dynamique d'équilibre général calculable. Les résultats montrent que la technologie BECCS, compte tenu de sa singularité, sera développée uniquement si une subvention à la capture des émissions issues de la biomasse est mise en place. De plus, les deux instruments les plus efficace-économiquement pour atteindre un niveau donné de réduction d'émissions sont la subvention à la capture des émissions et la taxe carbone dont les revenus sont recyclés sous forme de subvention au BECCS.

Mots-clés : Capture et Stockage du Carbone, bioénergies, modèle d'équilibre général calculable, efficacité-économique, incitation-économique.

1. Introduction

Most of the global warming observed over the last 50 years is due to an increase in the concentrations of greenhouse gases (GHG) in the atmosphere. In order to identify strategies to mitigate climate change, we need to consider combining several technologies in different sectors. CO_2 capture and storage technologies (CCS) have received increased attention due to their large estimated potential to reduce CO_2 emissions (MIT, 2007; IEA, 2008; IPCC, 2005). The process consists of separation of CO_2 from industrial sources and transporting it to permanent storage in secure locations such as deep saline aquifers and depleted oil and gas fields (for a CCS technical review, see IPCC, 2005).

Bioenergy with CCS (BECCS) is an emerging technology that is beginning to attract attention. Environmental and economic studies focus on its application in the electricity and heating sectors (Carpentieri *et al.,* 2005; Rhodes 2007; Uddin and Barreto 2007) and the biofuel sector (Kheshgi and Prince, 2005; Lindfeldt and Westermark, 2008, 2009; Laude *et al.,* 2010; Mathews, 2008; Möllersten *et al.,* 2003). Considering that CO_2 from biomass is neutral, BECCS can contribute to a net removal of atmospheric CO_2. Indeed, biomass absorbs CO_2 from the atmosphere through the process of photosynthesis and releases it during combustion. If the released CO_2 is captured and stored permanently in geological storage sites, and if the biomass is grown sustainably, then we would have a situation of "negative CO_2 emissions". According to Obersteiner *et al* (2001), this option offers the dual benefit of providing low-carbon energy products and removing carbon from the natural carbon cycle. Moreover, BECCS could have an important role in the future energy mix. It has the potential to reduce the mitigation costs of achieving low atmospheric CO_2 concentration targets (Azar *et al.*, 2010; Katofsky *et al.*, 2010; Luckow *et al.,* 2010; van den Broek *et al.*, 2011).

A major issue related to the deployment of BECCS is its economic viability. To become significant, economic incentives will be needed. It seems important to mention that, since CO_2 from biomass transformation is considered neutral, traditional environmental policy instruments, such as environmental taxes, are not appropriate for this technology. Also, in the Kyoto framework, CO_2 emissions are accounted for in different ways, depending on their origin (e.g. biomass vs. fossil fuel). The regulation providing guidance for GHG accounting does not consider BECCS as eligible for the first commitment period of the protocol (2008-2012) (Grönkvist *et al.,* 2006). Thus, there are currently no incentives for firms to capture CO_2 from biomass. In our view, there should be a reward for every ton of carbon avoided by means of CCS - whatever its origin (biomass or fossil); we discuss policies that support BECCS directly. To avoid catastrophic climate change and keep temperature increases to levels of a maximum of 2°C, CCS for both biomass and fossil fuel will need to be part of the mitigation portfolio. It remains therefore to determine the policy instruments that could be used to provide adequate incentives for CCS and BECCS. We need also to determine what would be the cost of achieving emissions reductions using these instruments. The literature on BECCS focuses mainly on cost evaluations and environmental potential and tends to neglect the issue of different ways of promoting it.

The main objective of this paper is to compare - qualitatively and quantitatively - the efficiency of several environmental policy instruments, using a computable general equilibrium model. These instruments are: a fossil fuel tax, a carbon tax, a cap-and-trade system and two types of subsidies (for CCS and BECCS). We compare the instruments according to two criteria: their effectiveness on technology adoption and their cost-effectiveness in terms of welfare. We investigate the appropriateness of the instruments to encourage CCS and BECCS and their achievement of the environmental objective at least cost. It is important to understand the economic costs related to achieving a specific emissions reduction target.

The cost-effectiveness of emissions control instruments has been studied quite thoroughly in the literature on environmental policy (for a review, see Goulder and Parry, 2008). To minimize the cost of pollution reduction, the instrument needs to equalize marginal abatement across all polluters. It requires a common price for all polluters, which equates the marginal benefits and the costs of reducing emissions (Baumol, 1972). Economists favour "market-based instruments", such as emissions taxes, tradable emissions permits and emissions reduction subsidies, over "command and control instruments" (emissions standards and technology mandates). The latter are usually uniform across sources and therefore lead to higher abatement costs. This paper focuses on market-based instruments and assesses their cost-effectiveness to reduce emissions, and their ability to promote deployment of CCS and BECCS technology.

The methodology employed in our analysis is a dynamic general equilibrium model which includes CCS and BECCS technologies. This type of model has become the standard for assessing economy-wide impacts of environmental and technological policies.

This approach offers a comprehensive representation of price dependent market interactions based on Walrasian equilibrium theory. Our analysis draws on the literature.

Several top down models simulate CCS technology (Edenhofer *et al.,* 2005; Gerlagh, 2006; Grimaud *et al.,* 2009; Keller *et al.,* 2008; Otto and Reilly, 2008), but none of them tries to include BECCS. Gerlagh and van der Zwaan (2006) compare policy instruments (fossil fuel tax, carbon tax, renewable subsidy and a carbon intensity portfolio) in relation to the adoption of CCS using their DEMETER model. They show that a carbon intensity portfolio (recycling the carbon tax to subsidize renewable energies) is the most cost-efficient instrument to reduce the costs of addressing climate change. However, most studies use optimization models, which suggest equivalence between the social optimum and the decentralized equilibrium and limit the realism of the models (Beaumais and Schubert, 1996). We choose, therefore, to study the equilibrium in a decentralized economy because this allows us to examine how the economy reacts to environmental policy tools via pricing.

Our study suggests that the only instrument that creates adequate incentives for BECCS deployment is a subsidy per unit of captured emissions from biomass (a BECCS subsidy). To develop both CCS and BECCS, there are three options. First, a specific subsidy per unit of captured emissions; second, a carbon tax and a BECCS subsidy combined (two-part instrument); third, a cap and trade system that rewards negative emissions.

If we follow the second criteria of cost-effectiveness, results show that a specific subsidy is the most welfare improving instrument, but has the disadvantage of encouraging the use of fossil fuel. An interesting result is that it is less costly to use a carbon tax and to recycle its revenues to subsidize BECCS than to create a two-part instrument or a cap and trade system that recognizes negative emissions.

The paper is organized as follows: In the second section, we conduct a descriptive analysis of the efficiency of policy instruments for developing CCS and BECCS. Section 3 presents the theoretical model and provides a description of a decentralized economy. Section 4 explains how the model is calibrated and presents the environmental policy scenario. Section 5 presents the different simulations and results, and offers some conclusions.

2. The influence of policy instruments on CCS and BECCS adoption

This section presents the instruments and their impact on the first criteria of CCS and BECCS adoption.

2.1. Overview of the instruments studied

Market based instruments provide incentives to reduce emissions through pricing, but leave the final decision about the amount of emissions reduction, to the polluters. The instruments create markets for CO_2 emissions externalities. The emissions price represents an opportunity cost which in its turn affects the production approach of profit maximizing firms. In this paper, we distinguish four types of market based instruments.

- A fossil fuel tax (τ^F): The regulator levies a tax on the use of the fossil resource.
- A carbon tax (τ^C): The regulator levies a tax per unit of carbon released into the atmosphere: this is a tax on the pollution stream.
- A cap-and-trade system. A limit is imposed on the total quantity of emissions allowances. The cost of emitting each unit of CO_2 emissions is the current market price denoted (p^C).
- A CCS subsidy $(s^{ccs};\ s^{bccs})$: The regulator levies a subsidy on carbon emissions abatement based on CCS and BECCS technologies.

2.2 The impact of the instruments on CCS and BECCS adoption

We examine the impact of the instruments described on the first criteria highlighted in the introduction - CCS and BECCS adoption.

- Fossil fuel tax versus carbon tax

If the use of fossil fuel as an input is directly related to the amount of the emissions, and if no abatement technology is available, then an input tax is an efficient instrument for emissions reduction. In the literature, carbon emissions are often linked to the fossil resource through a simple linear function: reducing emissions means extracting less fossil fuel. In this case, taxing either the carbon emissions or the fossil resource are almost equivalent. It is also an interesting option when monitoring emissions directly is difficult

(Goulder and Parry, 2008). Therefore it would seem a good proxy for the amount of pollution to be regulated. However, in this paper we consider the availability of CCS to capture the emissions before their release to the atmosphere. The implications of a fossil fuel tax are straightforward: it will provide an incentive to substitute the fossil fuel resource for a clean resource, but it will give no incentive to start using CCS. Therefore, we need a tax on emissions (a carbon tax).

- Carbon tax limit

A carbon tax raises the cost of carbon emissions and increases the competitiveness of carbon neutral technologies. It will be profitable for a firm to reduce emissions as long as the marginal abatement cost is less than the value of the tax rate per unit of emissions. However, a traditional carbon tax will not offer any incentives to start using BECCS since, as long as biomass is produced in a sustainable manner, the CO_2 produced in the combustion/transformation will be assumed to be neutral, (IPCC, 2005). Biomass emissions are part of the natural carbon cycle: plant photosynthesis absorbs the carbon dioxide, and when the plant is burned or transformed (biofuels production) it gives back the carbon to the atmosphere and it is reabsorbed by other plants. The cycle is in balance. When a firm only uses biomass in its production process, the introduction of a CCS technology will lead to negative emissions, which need to be acknowledged and rewarded. A possible solution might be the introduction of a two-part instrument.

- A two-part instrument

If government decides to implement a carbon tax, the carbon tax needs to be modified so that it contributes to BECCS deployment. Therefore, we include a two-part instrument, which is a combination of an emissions tax (τ^C) and a subsidy (s^{bccs}) on every unit of biomass emissions captured with CCS (negative tax). The firm has to pay (will receive) the tax (subsidy) for its positive (negative) effective emissions. This results in two possible scenarios. If the effective emissions (the emissions remaining after CO_2 removal) are still positive, the firm will pay tax for each unit of emissions left. In this case, BECCS would help to reduce emissions. If the effective emissions are negative (more CO_2 is retrieved from the atmosphere than is emitted), the firm will receive a subsidy (a credit) for each unit of negative emissions equal to the amount of the carbon tax.

Azar *et al.* (2006) point out that as long as global effective emissions are positive the carbon tax will generate net revenues for the public sector. However, if global negative emissions are to be achieved the public sector will have to subsidize the removal of carbon from the atmosphere and will no longer benefit from carbon tax revenues.

- A cap-and-trade system

We have discussed why captured biomass emissions are not rewarded within the current European trading system. However, to ensure the viability of this project, negative carbon emissions from BECCS should be integrated into new GHG accounting protocols. A cap-and-trade system could be designed similar to the two-part instrument mentioned above. As long as effective emissions are positive, firms will have to buy carbon permits and if effective emissions are negative, the firm will receive additional revenue from the sale of permits (allocated freely) in the market.

- Subsidies

Environmental subsidies can take different forms. The most common are investment subsidies and emissions reduction subsidies. Investment subsidies are appropriate for CCS demonstration projects. They lower the cost of investment and facilitate the financing of projects (Finon, 2009). However, an emissions reduction subsidy would seem more appropriate since it gives visibility and stability to the operator's revenues in the long term. The subsidy we consider here is for emissions abated using CCS technology. If the subsidy is designed such that it makes no distinction between fossil fuel and biomass emissions it is a suitable instrument for developing both CCS and BECCS.

These instruments will be included in the numerical model in order to compare them against the second criteria, which is cost-effectiveness.

3. Model setup

The model we use is an aggregate general equilibrium model. It is appropriate for dealing with economic and global stock pollution problems arising from the use of fossil fuels.

3.1 Model structure

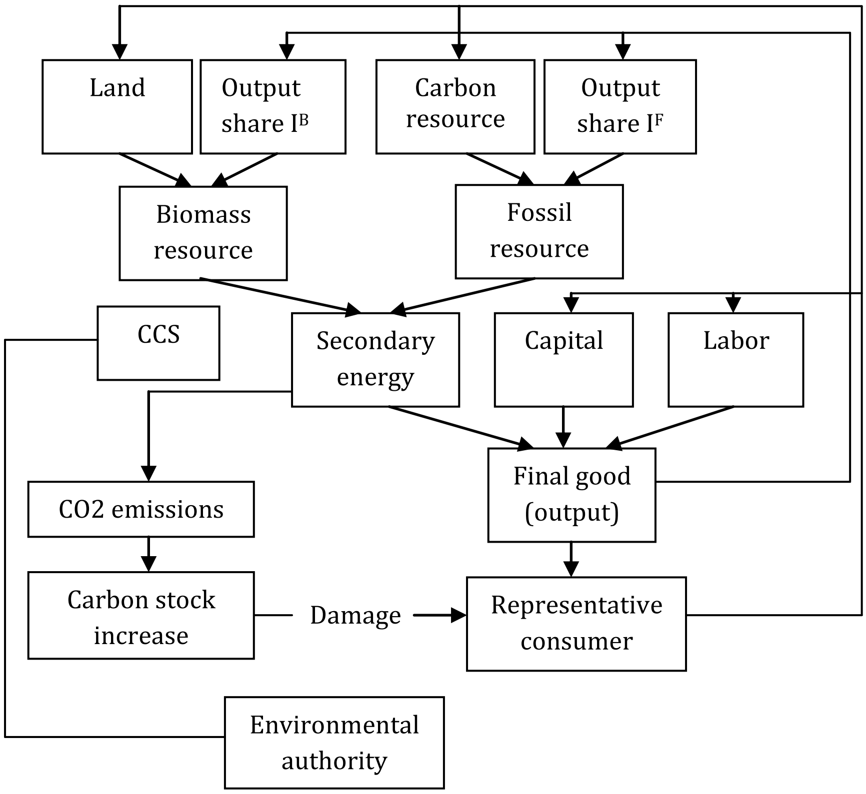
The model distinguishes one representative consumer and four representative producers $j=C, E, F, B$. $j=C$ for the final good or consumption good producer, $j=E$ for the secondary energy producer, $j=F$ for the fossil fuel producer and $j=B$ for the biomass producer. There is a representative consumer who consumes the final good which is secondary energy, capital and labour. The secondary energy is produced from biomass and from fossil fuel. Fossil fuel is produced from a non-renewable resource (exogenous in our model) and from a share of the final output. Biomass is produced from land which is exogenous and a share of the final output. The representative consumer owns the land, the fossil resource and the capital in the economy.

The economic part of the model is linked to the climate part by the CO_2 emissions generated by the use of fossil fuel in the secondary energy sector. The flow of emissions accumulates in the atmosphere and increases the atmospheric carbon stock. This stock causes environmental damage that has a negative effect on social welfare.

We assume that all sectors are perfectly competitive and that agents are rational. Each producer maximizes its inter-temporal profit under its technological constraint and the consumer maximizes its inter-temporal utility function under its budget constraint. A Walrasian general equilibrium prevails when the supply and demand of each good and input are equalized across all markets.

The unique market failure involved in the model is the pollution in the secondary energy sector. We assume that there is an environmental authority that chooses one of the economic instruments described in section 2, to internalize the pollution externality. The secondary energy sector can reduce its pollution by using more biomass in its production process, or by decarbonizing its production using CCS technology. We assume also that the environmental authority is the owner of the CCS installation. Therefore, the energy producer will have to pay to the authority the cost of using CCS. The model is depicted in figure 1.

Figure 1: The model framework



3.2 The decentralized economy

3.2.1 The final good sector

The final good also called final output Y_t^C, is produced from two endogenous inputs - the secondary energy Y_t^E and the capital $\mathrm{K_t}$ – and one exogenous input - labour L_t (corresponding to the population level) which is assumed to be constant. The production function is increasing and concave with constant return to scale and is denoted

$$Y_t^c = \mathrm{A}_1 Q(K_t, L_t, Y_t^E) = \mathrm{A}_1 \mathrm{K}_t^{\vartheta} \mathrm{L}_t^{\varphi} \, {Y_t^E}^{1-\vartheta-\varphi} \quad , \vartheta, \varphi \in (0,1),$$

where A_1 is a scaling parameter and ϑ and φ are respectively capital and labour elasticities in final good production.

This final output is used for consumption, for fossil fuel production, for biomass production, for investment in physical capital and for public expenses according to the following equation:

$$Y_t^c = C_t + I_t^F + I_t^B + \mathrm{I_t} + G_t \qquad (1)$$

where I_t is the investment in physical capital given by

$$I_t = K_{t+1} - (1-\delta)K_t \quad (2)$$

where δ is the capital depreciation rate.

We normalize to one the price of the final good. At each time t, the final good producer maximizes the following profit

$$Max_{K_t, Y_t^E, L_t} \quad \pi_t = (Y_t^C - (r_t + \delta)K_t - w_t L_t - P_t^E Y_t^E)$$

where P_t^E, w_t and r_t are respectively the energy price, the real wage and the interest rate. From the first-order conditions, we obtain the following optimal factor demands:

$$\frac{\partial \pi}{\partial K_t} = 0 \rightarrow K_t = \frac{\vartheta Y_t^c}{r_t + \delta} \quad (3)$$

$$\frac{\partial \pi}{\partial L_t} = 0 \rightarrow L_t = \frac{\varphi Y_t^c}{w_t} \quad (4)$$

$$\frac{\partial \pi}{\partial Y_t^E} = 0 \rightarrow Y_t^E = \frac{(1-\vartheta-\varphi) Y_t^c}{P_t^E} \quad (5)$$

3.2.2 The secondary energy sector and the environmental damage

The secondary energy Y_t^E is produced from two imperfect substitutes: a polluting fossil resource Y_t^F and a non-polluting biomass resource Y_t^B according to the following technology:

$$Y_t^E = E(Y_t^B, Y_t^F) = A_2(a(Y_t^F)^{(\sigma-1)/\sigma} + (1-a)(Y_t^B)^{(\sigma-1)/\sigma})^{\sigma/(\sigma-1)}$$

where a is a preference parameter for fossil fuel and σ is the substitution elasticity between fossil fuel and biomass $1 < \sigma < \infty$.

This section is organized in three subsections. In the first subsection we present the environmental consequences of the use of fossil fuel; in the second we specify CCS and BECCS technologies; and in the third we examine the energy producer profit maximization under the instruments mentioned in section 2.

Emissions flows, carbon stock and climatic damage

The use of fossil fuel in this sector generates a pollutant flow noted E_t^F. Let ε^F be the exogenous carbon content of the fossil resource so that, in the absence of environmental regulation, the instantaneous carbon flow or emissions released by the secondary energy sector into the atmosphere would be:

$E_t^F = \varepsilon^F Y_t^F$

The biomass conversion to the secondary energy good also leads to CO_2 emissions such as $E_t^B = \varepsilon^B Y_t^B$, where ε^B is the exogenous carbon content of biomass. However, we assume that the biomass is grown in a sustainable manner; this means that these emissions have no impact on the carbon stock (S_t). The amount of CO_2 released during the biomass transformation (E_t^B) is exactly compensated by the amount of CO_2 that previously was captured during photosynthesis (ph), such that:

$S_t = S_{t-1} - ph_{t-1} + E_t^B$

$ph_{t-1} = E_t^B$ and S_t is the carbon stock.

Therefore, the atmospheric carbon stock is increased only by CO_2 emissions from fossil fuel use in the secondary energy sector. The dynamic equation of the atmospheric carbon stock evolution is:

$$S_{t+1} = E_t^F + \overline{\mathrm{E}} + (1-\zeta)S_t \qquad (6)$$

where ζ is the instantaneous rate for natural absorption, $0 < \zeta < 1$ and is constant (Kolstad and Krautkraemer, 1993). This parameter corresponds to the oceans' absorption of fossil emissions. As our model only considers emissions related to the use of fossil energy in the secondary energy sector, we introduce an exogenous variable $\overline{\mathrm{E}}$ for emissions from other polluting sectors such as industry, agriculture and residential.

The increase in atmospheric carbon concentration due to fossil fuel emission streams is used in the model as an "indicator" of anthropogenic climate change. The environmental damage is a standard increasing and convex function of the stock of pollution: $D(S_t) = \mathrm{S_t} + 0.5\mathrm{bS_t}^2$, b is a scale parameter.

CCS and BECCS specifications

To correct for market failure due to CO_2 pollution and to promote CCS technology, the environmental authority can use one of the instruments referred to in section 2. One possible firm strategy would be to decarbonize production using a CCS technology.

Let μ_t^F and μ_t^B be respectively the part of fossil and biomass emission flows that is captured and stored with CCS, so that the effective carbon stock, would be:

$$S_{t+1} = \left(1 - \mu_t^F\right)E_t^F - \mu_t^B E_t^B + \overline{E} + (1-\zeta)S_t \quad (7)$$

To date, geologist experts cannot be certain that a part of the CO_2 stored in geological formations will not leak back into the atmosphere and increase the atmospheric carbon concentration. In this paper, however, we assume that leakages cannot occur.

CCS and BECCS processes are described through cost functions, which are quadratic functions depending on the share of CO_2 that is captured and stored (Gerlagh and van der Zwan, 2006). We use $z_F\left(\mu_t^F E_t^F\right) = \left(1/2k_1 {\mu_t^F}^2\right) E_t^F$ to denote the CCS cost function and $z_B\left(\mu_t^B E_t^B\right) = \left(1/2k_2 {\mu_t^B}^2\right) E_t^B$ to denote the BECCS cost function. k_1, k_2 are convexity parameters.

Profit maximisation when environmental instruments are provided

We use P_t^E, P_t^B and P_t^F to denote the prices of secondary energy, biomass and fossil fuel respectively. At each time t, the energy producer chooses $Y_t^F, Y_t^B, \mu_t^F, \mu_t^B$ which maximizes its profit.

Each instrument can be studied independently.

τ_t^F is a fossil fuel tax, τ_t^c is a carbon tax, s_t^{ccs} is a CCS subsidy and s_t^{bccs} is a BECCS subsidy. The energy producer profit is:

$$\pi = P_t^E Y_t^E - P_t^B Y_t^B - \left(1 + \tau_t^F\right) P_t^F Y_t^F - \tau_t^c\left(1 - \mu_t^F\right)E_t^F + s_t^{bccs}\mu_t^B E_t^B + s_t^{ccs}\mu_t^F E_t^F - z_B\left(\mu_t^B E_t^B\right) - z_F\left(\mu_t^F E_t^F\right).$$

Including all market-based instruments, the first-order conditions give us the optimal factor demands

$$\frac{\partial \pi}{\partial Y_t^F} = 0 \rightarrow Y_t^F = {A_2}^{\sigma-1} Y_t^E \left(\frac{a P_t^E}{(1+\tau_t^F)P_t^F - s_t^{ccs}\mu_t^F \varepsilon^F + \tau_t^c(1-\mu_t^F)\varepsilon^F + 0.5k_1 {\mu_t^F}^2 \varepsilon^F}\right)^{\sigma} \quad (8)$$

$$\frac{\partial \pi}{\partial Y_t^B} = 0 \rightarrow Y_t^B = {A_2}^{\sigma-1} Y_t^E \left(\frac{(1-a) P_t^E}{P_t^B - s_t^{bccs}\mu_t^B \varepsilon^B + 0.5k_2 {\mu_t^B}^2 \varepsilon^B}\right)^{\sigma} \quad (9)$$

$$\frac{\partial \pi}{\partial \mu_t^F} = 0 \rightarrow \mu_t^F = \frac{s_t^{ccs} + \tau_t^c}{k_1} \quad (10)$$

$$\frac{\partial \pi}{\partial \mu_t^B} = 0 \rightarrow \mu_t^B = \frac{s_t^{bccs}}{k_2} \quad (11)$$

Equation (10) shows that the firm will capture its emissions only when a specific CCS subsidy or a carbon tax is implemented. BECCS will be developed when a subsidy is provided (equation 11). Equation (9) shows that BECCS subsidy will also motivate the firm to use more biomass with a CCS process. Equation (8) shows that the carbon tax will not be an incentive for the firm to use less fossil fuel as long as $\mu_t^F < 1$. However, the CCS subsidy creates incentives to use more fossil fuel in the production process if CCS is implemented. The two-part instrument consists of the carbon tax and the BECCS subsidy combined (same rates). The first order conditions will be identical if a cap and trade system that recognizes negative emissions is developed. The rate of τ_t^c will be equal to the rate of s_t^{bccs} which will be equal to the permit price P_t^C.

3.2.3 The primary energy sector: The biomass and fossil fuel sectors

The biomass Y_t^B is obtained from land T_t which is assumed exogenous and from a share of the final output I_t^B. The production function is denoted:

$$Y_t^B = A_3 B(I_t^B, T_t) = A_3 {I_t^B}^{\alpha} {T_t}^{1-\alpha}$$

At each time t, the biomass producer maximizes its profit:

$$Max_{I^B,T} \ \pi = Y_t^B P_t^B - I_t^B - P_t^T T_t$$

where P_t^B and P_t^T are respectively the biomass and the land prices at time t.

This leads to the following first conditions

$$\frac{\partial \pi}{\partial I_t^B} = 0 \ \rightarrow I_t^B = \alpha Y_t^B P_t^B \quad (12)$$

$$\frac{\partial \pi}{\partial T_t} = 0 \ \rightarrow T_t = \frac{(1-\alpha) Y_t^B P_t^B}{P_t^T} \quad (13)$$

The fossil fuel Y_t^F is produced according to the following production function: $Y_t^F = A_4 F(R_t, I_t^F) = A_4 {I_t^F}^{\gamma} {R_t}^{1-\gamma}$

where I_t^F is the amount of final output which is devoted to the production of fossil fuel and R_t is the exogenous carbon resource.

At each time t, the fossil fuel producer maximizes its profit

$$Max_{I^F,R} \ \pi = Y_t^F P_t^F - I_t^F - P_t^R T_t$$

where P_t^F and P_t^R are respectively the fossil fuel and the resource prices at time t.

This leads to the following first conditions

$$\frac{\partial\pi}{\partial \mathrm{I}_t^F} = 0 \quad \rightarrow \mathrm{I}_t^F = \gamma Y_t^F P_t^F \tag{14}$$

$$\frac{\partial\pi}{\partial \mathrm{R}_t} = 0 \quad \rightarrow \mathrm{R}_t = \frac{(1-\gamma)Y_t^F P_t^F}{P_t^R} \tag{15}$$

3.2.4 The consumers and the public sector

$\mathrm{U(C_t)}$ is the instantaneous utility function that depends only on consumption $\mathrm{C_t}$. ρ is the pure rate of time preferences. We can write $\mathrm{U(C_t)} = \frac{1}{1-\theta}\mathrm{C_t}^{1-\theta}$ where the constant intertemporal elasticity of substitution for consumption is θ.

Consumers maximize the welfare function

$$W = \sum_{\mathrm{t}=0}^{\infty} 1/(1+\rho)^t (U(\mathrm{C_t}) - \mathrm{D(S_t)})$$

subject to the following intertemporal budget constraint:

$$(r_t + \delta)K_t + w_t L_t + P_t^T T_t + P_t^R R_t + \mathrm{tr} = C_t + \mathrm{Sa_t} \tag{16}$$

Consumers own land, capital and fossil resources. $(r_t + \delta)$ is the gross rate of return on capital, which corresponds to the capital user cost to the final output producer. w_t is the real wage, P_t^T is the revenue from land rented to the biomass sector, P_t^R is the revenue from the carbon resource and tr is a transfer from government to the consumers. This revenue is used for consumption C_t and saving $\mathrm{Sa_t}$. Moreover, the gross accumulation of physical capital is the only possible saving in the economy. Therefore, we can write $\mathrm{Sa_t} = \mathrm{I_t}$. By incerting equation (2) in equation (16), the budget constraint can be rewritten:

$$K_{t+1} = (1 + \mathrm{r_t})K_t + w_t(1 + \tau^{\mathrm{w}})L_t + P_t^T T_t + P_t^R R_t + \mathrm{G} - C_t \tag{16}$$

In solving the first order conditions, we obtain the dynamic of consumption.

$$C_{t+1} = C_t(\frac{1 + \mathrm{r_{t+1}}}{1+\rho})^{1/\theta} \tag{17}$$

The public sector sets the different instruments described above and holds CCS infrastructures. Its budget constraint has to be balanced.

$$G_t = \tau^{\mathrm{c}}(1 - \mu_t^F)E_t^F + \tau_t^F P_t^F Y_t^F + z_F(\mu_t^F E_t^F) + z_B(\mu_t^B E_t^B)$$

$$-s^{bcsc}\mu_t^B E_t^B - s^{csc}\mu_t^F E_t^F - tr \tag{18}$$

All the markets are in equilibrium. Each activity's production or endowment is matched by others' uses in the economy and each activity's income (value) is balanced by others' expenditures. Therefore, neither products nor values can appear from nowhere, the Walrasian general equilibrium is satisfied.

4. Numerical specification and scenarios

4.1 Numerical specification

4.1.1 Energy consumption and emissions

The start year is 2005 as we have complete date. In 2005, atmospheric carbon concentration was 808.9GtC which correspond to 2993GtCO_2 (Nordhaus, 2008).
According to IEA (2008b), world fossil fuel consumption in 2005 was 420.558EJ. We assume that all the carbon included in one unit of energy is released in the atmosphere. World fossil fuel consumption and the linked emissions are presented in the following table.

Table 1: Fossil fuel world consumption, linked emissions and CO_2 coefficient

	Oil	Natural gas	Coal	Total
World consumption in EJ (10^{18}J)	179.222	112.935	128.431	420.558
Emissions of CO_2 in million of metric tons	11105.37	5868.45	11511.18	28485
Emission coefficient in CO_2 tons per GJ(10^9J)	0.062	0.052	0.090	0.068

By dividing the CO_2 emissions 28,485 million metric tons, by world consumption of fossil fuel of 420588 million GJ, we obtain the CO_2 emission intensity of fossil fuel. We write $\varepsilon^F=0.068$ for the CO_2 content of the fossil resource. We conclude that 1 GJ of energy delivered from fossil fuel leads on average to 0.068 tons of CO_2.
In this model, we consider only fossil fuel consumption in the secondary energy sector. CO_2 emissions are released during the process of converting primary energies into secondary energies. Therefore, we analyse the electricity and heat sectors as well as the fossil fuel transformation sector (petroleum refineries). According, to IEA (2008), fossil fuel consumption in those sectors in 2005 was 155EJ, which represents about 10.5Gt of

CO_2. The other 17.9Gt of CO_2 are considered exogenous emissions from final use sectors such as industry, transport, services, agriculture and non-energy uses.

According to IEA (2008) world biomass consumption in 2006 was around 1,186Mtoe, which represents 49.64880 EJ. The predominant use of biomass currently is for fuel for non-commercial applications, and inefficient stoves for domestic heating and cooking in developing countries where biomass contributes to 60% of the total world consumption. Biomass consumption for bioenergies, such as electricity, heat and biofuels, is equal to 12.294986880 EJ.

According to the IPCC, the carbon content of biomass is 0.111 tons of CO_2 per GJ. We write this as $\varepsilon^B = 0.111$. The emissions released during biomass transformation in bioenergies represent about 1,364 million tons of CO_2

We need also to consider the quantity of land devoted to biomass production, as well as the amount of extracted resource in 2005. Azar *et al.* (2006) assume an average yield of 200Gj per hectare per year to produce biomass. Biomass production in 2005, required some 60 million ha of land. According to IEA (2008), the quantity of extracted carbon resource was 490EJ in 2005.

4.1.2 CCS costs

The extent to which CCS technologies will contribute to GHG emissions reductions will be determined by its cost. Capture seems to be the largest part of the cost on fossil fuel CCS (70% of the total cost, IPCC, 2005). CCS costs quoted in the literature differ significantly depending on capture technology, transport distances and storage site injectivity. In the electricity sector, the cost of the CCS chain varies between 50US$ and 90US$ per ton of CO_2 avoided (IEA, 2008). We retain an average initial cost of 60US$/t$CO_2$.

Biomass based-CCS costs are more difficult to estimate because biomass plants are small scale and available data are scarce. According to the literature it seems that the resulting costs of production using CCS are relatively high compared to fossil alternatives. In the electricity sector for a 75MWe plant, it is estimated that between 65US$ and 100US$ per ton of CO_2 is avoided (IEA, 2009). We retain an average initial cost of 70US$/t$CO_2$. The model is calibrated to fit the world 2005 data

4.2 Policy Scenarios

We investigate the cost-effectiveness of the instruments presented in section 2. The emissions target is a 20% decrease in total emissions from the secondary energy sector. To take account of negative emissions from BECCS, total emissions can be written as follows:

$$\mathrm{Etot} = \left(1 - \mu_t^F\right) E_t^F - \mu_t^B E_t^B$$

In the first simulation, we compare the cost of meeting that target with the fossil fuel tax, the carbon tax, the subsidy on abated emissions from using a CCS technology, and the two-part instrument (or equivalent cap and trade system) that recognizes negative emissions from biomass.

In the second simulation, we investigate the possibility of recycling environmental tax revenues (fossil tax and carbon tax). We compare the economic impact of these taxes considering two particular schemes for recycling revenues:

- Revenues returned to consumers as lump-sum transfers.
- Revenues used to subsidize BECCS.

Simulation 1:

S1: A carbon tax (τ_t^c) is implemented to reach the emissions target. The revenue from the tax increases the public budget.

S2: A fossil fuel tax (τ_t^F) is implemented to reach the emissions target. The revenue from the tax increases the public budget.

S3: A subsidy on captured emissions is implemented. It develops CCS and BECCS $(s_t^{bccs} = s_t^{ccs})$

S4: A two-part instrument or a tradable allowance system is used to develop CCS and BECCS. The carbon tax rate is equivalent to the subsidy rate $(\tau_t^c = s_t^{bccs})$.

Simulation 2:

S5: A carbon tax (τ_t^c) is implemented. Revenue is recycled to subsidize biomass emissions captured with CCS (s_t^{bccs})

S6: A carbon tax (τ_t^c) is implemented. Revenue is returned to consumers as lump-sum transfers.

S7: A fossil fuel tax (τ_t^F) is implemented. Revenue is recycled to subsidize biomass emissions captured with CCS (s_t^{bccs})

S8: A fossil fuel tax (τ_t^F) is implemented. Revenue is returned to consumers as lump-sum transfers.

5. Simulation results

This section presents the results of the simulations.

5.1 Results from simulation 1

Table 2 summarizes the behaviour of the variables following the simulated policy shocks. We compare the long run equilibrium with the initial situation (2005). The first three rows show the changes in the environmental variables. We can compare the cost of achieving the given emissions reduction using our instrument. The dynamic response of the main variables to the shocks S1, S2, S3, S4 are presented in Appendix A.

Table 2: Simulated shocks (percent change)

Shocks/Variables	S1 $\tau^C = 22.951$ *	S2 $\tau^F = 0.556$	S3 $s^{CCS} = s^{BCCS} = 61.8$	S4 $\tau^C = s^{BCCS} = 22.07$
S	-3.635	-3.634	-3.635	-3.634
D(S)	-7.136	-7.136	-7.136	-7.136
Etot	-20.319	-20.319	-20.319	-20.319
EF	-13.423	-20.319	3.994	-12.929
EB	0.952	1.538	0.001	0.976
YB	0.952	1.538	0.001	0.976
YF	-13.423	-20.319	3.994	-12.929
YE	-3.161	-4.805	1.016	-3.031
YC	-0.322	-0.493	0.102	-0.309
I	-0.322	-0.493	0.102	-0.309
Sa	-0.322	-0.493	0.102	-0.309
K	-0.322	-0.493	0.102	-0.309
QF	-30.255	-43.157	10.285	-29.261
QB	2.511	3.875	-0.381	2.457
C	-0.690	-1.004	0.246	-0.664
PBTTC	1.499	2.308	-0.520	1.430
PFTTC	6.842	10.877	-1.860	6.561
PE	2.932	4.528	-0.904	2.807
PRE	-30.222	-43.161	10.259	-29.298
PT	2.513	3.876	-0.382	2.459
w	-0.322	-0.493	0.102	-0.309
r	NS**	NS	NS	NS
Bê	0.0078	-0.0105	0.0621	0.0093
UC	-0.0350	-0.0508	0.0125	-0.0336

* Carbon tax and subsidies are expressed in $/t$CO_2$ and the fossil fuel is in percentages.
These values are long term steady state values.
** NS means not significant. The interest rate value move slightly during the transition but its steady state value is the same as its initial value.

Table 3 shows the deployment of CCS and BECCS under simulations S1, S2, S3 and S4.

Table 3: BECCS and CCS deployment under S1 to S4

	S1	S2	S3	S4
MUF (%)	8%	0%	22%	8%
MUB (%)	0%	0%	16%	6%

Scenarios S3 and S4 yield appropriate incentives for CCS and BECCS. Those technologies are better developed under the specific subsidy than under the two-part instrument. As we saw in section 2, a carbon tax on its own encourages only deployment of CCS and the fossil fuel tax fails to exploit these abatement channels.

Economic impacts of the fossil fuel and carbon taxes

Both instruments have a negative impact on consumption and output. This effect is exacerbated by the fossil fuel tax. The fossil fuel tax is a tax on polluting input. Since this instrument does not focus on the externality source itself, it provides no incentives for CCS. Therefore, it is more costly than the carbon tax which focuses on emissions. This result is in line with the literature. Goulder *et al* (1998) show that to minimize the cost of reaching the environmental target, individual firms have to use the lowest cost combination of reducing pollution (input substitution, output reduction and abatement technology). Since the fossil fuel tax fails to exploit the abatement effect (end of pipe treatment in Goulder et al.'s study) it is more costly than an emissions tax.

In (S1), the carbon tax allows the secondary energy producer to reduce emissions by using more biomass (+0.9%), by reducing its production (-3%), and by using a CCS technology. However, in (S2) the level of the fossil fuel tax has to be high enough to induce sufficient input substitution and output reduction. Therefore, the price of fossil fuel increases significantly (+10.8%) as does the price of secondary energy (+4.5%). As a result, the cost in terms of economic welfare (UC: utility variation) is higher with the fossil fuel tax. Utility decreases by 0.05% in S2 compared to 0.035% in S1. In S2, the net efficiency impact of the fossil tax (Bê: environmental benefits less economic costs) is negative. The decline in CO_2 emissions is not sufficient to offset the economic cost of the instrument.

Economic impacts of the two-part instrument

Combining a subsidy for BECCS with a carbon tax leads to a smaller decrease in final output and consumption than a carbon tax alone. The tax rate is slightly lower than in S1 (22.07\$/tCO_2). As a result, the decrease in demand for fossil fuel is less significant (-12.9%). To meet the environmental target, the energy producers relies more on biomass (+0.9%), contracts its production (-0.3%), and uses CCS and BECCS technologies. The cost of the two-part instrument, therefore, is less than the cost of the carbon tax: Utility decreases by only 0.033%.

Economic impacts of the specific subsidy

With the specific subsidy, firms are rewarded for every unit of emissions they capture with CCS. We can see the superiority of this instrument in terms of welfare. It has a positive effect on the economy. It increases overall levels of secondary energy, final output and consumption. However, by supporting CCS and BECCS the subsidy also encourages the extraction and use of fossil fuel. The price of fossil fuel drops by 1.8% which leads to a rise in fossil fuel demand of almost 4%. Also, the biomass price slightly declines, but not enough to boost demand. The environmental target is reached only thanks to the abatement technology since the subsidy provides the wrong incentives in terms of the level of energy production. Environmental taxes involve net transfers from polluter to government, while subsidies lead to net transfers in the opposite direction. In our model, government spending is allocated to the final output. Considering the soft emissions reduction target the impact of transfers on *YC* is marginal. However, if we consider that subsidies are financed by a levy on household revenues the utility level does not increase in the same way as in S3 but rather slightly decreases (-0.004%) (see Appendix A: Graphs A and B, scenario S3').

We have shown that the cost of reducing emissions is significantly lower under a carbon tax than under a fossil tax. Also, the two-part instrument performs better than the carbon tax alone and supports the deployment of both CCS and BECCS. The specific subsidy has a positive impact on the economy and also allows CCS and BECCS deployment. However, its disadvantage is that it promotes fossil fuel use and leads to greater fossil fuel extraction.

Environmental taxes raise revenues that can be recycled to promote BECCS. We investigate this option in the next subsection.

5.2 Results from simulation 2:

Fossil fuel tax and carbon tax revenues are used to subsidize BECCS (S5, S7) and are returned to households as lump-sum transfers (S6, S8). These policies are revenue neutral in the sense that the gross revenue from taxes equals the revenue cost of the BECCS subsidy or the transfers to consumers. The Results are presented in Tables 4 and 5.

Table 4: Simulated shocks (percentage change)

Shocks/Variables	S5 $\tau^C = 12.283$ $s^{BCCS} = 258.086$	S6 $\tau^C = 22.951$	S7 $\tau^F = 0.227$ $s^{BCCS} = 293.578$	S8 $\tau^F = 0.556$
S	-3.635	-3.635	-3.635	-3.634
DS	-7.136	-7.136	-7.136	-7.136
Etot	-20.319	-20.319	-20.319	-20.319
EF	-7.800	-13.422	-10.470	-20.320
EB	2.784	0.950	3.663	1.538
YB	2.784	0.950	3.663	1.538
YF	-7.800	-13.422	-10.470	-20.320
YE	-0.219	-3.161	-0.388	-4.805
YC	-0.022	-0.322	-0.039	-0.493
I	-0.022	-0.322	-0.039	-0.493
Sa	-0.022	-0.322	-0.039	-0.493
K	-0.022	-0.322	-0.039	-0.493
QF	-18.375	-30.255	-24.155	-43.157
QB	7.228	2.511	9.487	3.875
C	-0.022	-0.077	-0.039	-0.152
PBTTC	-0.803	1.499	-0.983	2.308
PFTTC	2.877	6.842	3.982	10.877
PE	0.197	2.932	0.351	4.528
PRE	-18.392	-30.222	-24.122	-43.161
PT	7.226	2.513	9.489	3.876
w	-0.022	-0.322	-0.039	-0.493
r	NS	NS	NS	NS
Bê	0.0466	0.0454	0.0457	0.0418
UC	-0.0010	-0.0020	-0.0018	-0.0050

Table 5: BECCS and CCS deployment under S5 to S8

	S5	S6	S7	S8
MUF (%)	4.3%	8%	0%	0%
MUB (%)	65.4%	0%	73.4%	0%

BECCS subsidy levels are higher than in simulation 1. This matters because this will drive the level of abatement with CCS as the effort is endogenously chosen by the firm.

When taxes revenues are recycled to support BECCS; the share of biomass emissions captured using CCS is considerably larger than in scenario (S4) with the two-part instrument. In (S5), 65.4% of biomass emissions are captured and the percentage of fossil emissions, in contrast, is lower than in previous scenarios. In (S7), the fossil fuel tax yields important revenues that mostly finance the BECCS subsidy. The technology is developed at more than 73%.

Revenue recycling effect

Recycling tax revenues offsets a significant part of the economic cost of this instrument. The cost of meeting the environmental target is lower under scenarios S5 to S8 than under scenarios S1, S2 and S4 (see appendix B: graph A).

- Recycling revenue to consumers

The economic cost of a fossil fuel and a carbon tax with revenue returned to consumers as lump-sum transfers, is ten times less than if revenue increases government spending. In S8, the level of utility decreases by only 0.005% compared to the same scenario without revenue effect (S2) where it decreases by 0.05%. We find the same results for the carbon tax. The revenue effect in both scenarios (S6 and S8) prevents consumption for falling. Giving revenue to consumers as lump-sum transfers leads to a revenue effect but does not have an impact on the other variables. Graph E in Appendix B shows that the impact on output in the long term is the same as in S1 and S2. The increase just after the shock (2100) in (S1) and (S2) is due to an increase in public expenditure, which is affected to the output (Appendix B, Graph E). We show below that it is even less costly to recycle tax revenues to subsidize BECCS.

- Recycling revenue to BECCS subsidy

In S5, using tax revenue to finance BECCS subsidy leads to a very high subsidy rate (258$/tCO_2$). In order to meet the environmental target, the tax rate does not have to be as high as in (S1). Therefore, tax has a lower depressive impact on the economy than in (S1). With a carbon tax of 12$/tCO_2$ demand for fossil fuel slightly declines (-7.8%). Recall that in (S1), the carbon tax rate is 22$/tCO2 and fossil fuel demand decreases by 13%. Also, the BECCS subsidy encourages the use of biomass which rises by 2.7%. As a consequence output and consumption are maintained at near their initial levels. The cost of the carbon tax with revenue recycled to subsidize BECCS is less than the costs of the other taxes studied.

In S7, a fossil fuel tax of 22% yields a large revenue that can be used to subsidize BECCS up to 293$/tCO_2$. This, in turn, accelerates the deployment of BECCS. 73% of biomass emissions are captured in the long run. As CCS is not deployed for fossil fuel, the energy producer relies more on inputs substitution and BECCS to reduce its emissions. Surprisingly, it is less costly to achieve a given environmental target under S7 than under S8 or even S6. This demonstrates the role played by BECCS in reducing the cost of achieving emissions reductions.

This second simulation shows that the issue of how tax revenues are recycled is as important as the choice to tax emissions or fossil fuels. If government decides to conduct an environmental tax approach (fossil fuel or carbon taxes), we show that it is less costly to recycle fossil fuel and carbon tax revenues to support BECCS, than to return it to consumers as lump sum transfers. We show too that the most-efficient instrument, according to the criteria of CCS and BECCS adoption and welfare efficiency, is S5 (see Appendix B, Graph B).

- Recycling revenue from the two-part instrument (S4)

We propose to study a variant of scenario (S4). In S4 we study the impact of a two-part instrument that can be a combination of a carbon tax and a BECCS subsidy, or a tradable system that allows for negative emissions. The carbon tax yields revenue part of which is used to finance the BECCS subsidy (same rate). The remainder can be returned to consumers as lump-sum payments. The situation is the same if we consider fossil CO_2 permits allocated by auctions. The key difference between auctioned and grandfather permits is that grandfather permits do not raise revenues that can be returned to consumers. In S'4 revenue from tax or from the auctioned permits is returned to consumers ($\tau^C = s^{BCCS} = 22.07$). The revenue effect prevents a fall in consumption. If we compare S'4 and S4 we find that there is a smaller decrease in consumption in S'4 (-0.072%). Thus, the economic cost of S'4 is inferior to the economic cost of S4. The utility levels drops by only 0.0019%. This means that auctioned permits are less costly than grandfather permits. However, in terms of economic ranking instruments the cost of S'4 exceeds the cost of S5 and is almost equivalent to S7 (see Appendix B, Graph C).

6. Conclusion

In this paper we focused on BECCS, which has been acknowledged to be an interesting option to achieve major CO_2 emissions reductions because potentially contributes to purifying the atmosphere. While there are many advantages related to BECCS, it is necessary to create incentives for the storage of biomass emissions. This paper has reviewed a number of policy instruments that could be used to reduce CO_2 emissions cost-effectively and contribute to BECCS deployment. We established two criteria for evaluating the performance of these instruments: their ability to support CCS and BECCS deployment and their cost-effectiveness in achieving a given emissions reduction target.

The method used was a dynamic computable general equilibrium model that includes both CCS and BECCS technologies.

Based on the first criterion for CCS and BECCS adoption the study suggests that: Firstly, a tax on fossil fuel use will induce energy producer to use more biomass, it will not lead to the decarbonization of fossil fuel through CCS deployment. The implication in terms of climate change policy is direct tax on the pollution stream through a carbon tax.

Secondly, a carbon tax raises the cost of emissions and creates incentives for biomass and fossil based-CCS. However it does not create incentives for BECCS. Only a specific subsidy on captured emissions from biomass will increase the deployment of BECCS. To overcome this barrier, we proposed a two part instrument based on a combination of a carbon tax and a subsidy on biomass emissions captured with CCS. This subsidy is equal to the tax amount.

Finally, a specific subsidy to emissions reduction with a CCS technology is an adequate instrument to develop CCS and BECCS.

When we add to the analysis the second criterion, of cost-effectiveness, the results suggest that:

If CCS technologies are available, the most cost-effective instruments are those that directly price the pollution externality (carbon tax and subsidies). Fossil fuel tax is less cost effective because its fails to exploit the CCS abatement channel.

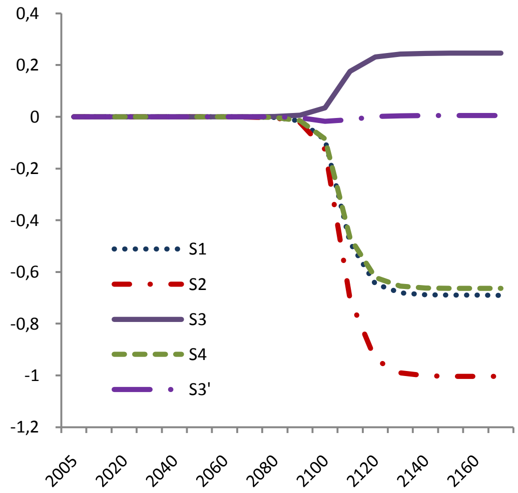
Also, the specific subsidy (S3) is the most welfare improving instrument. However, it encourages the use of fossil fuel and speeds up resource extraction compared to other instruments that reduce demand for fossil fuel.

Finally, implementing a carbon tax and recycling its revenues to BECCS subsidy (S5) is less costly in terms of welfare, than to develop the two-part instrument (S4, S'4). Revenue from the tax allows a much larger deployment of BECCS.

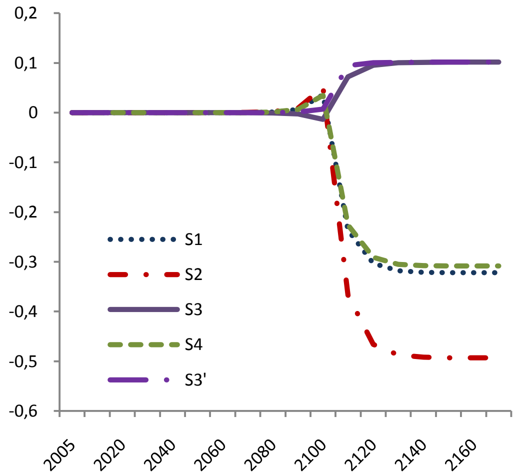
Appendix A

Simulation 1: Dynamic response of main variables to shocks S1, S2, S3 and S4

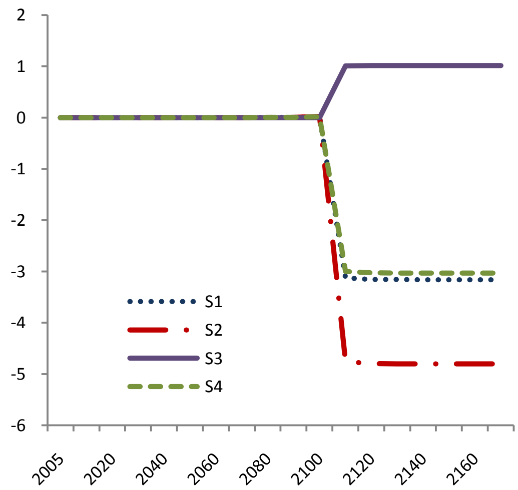
A: Consumption (C)



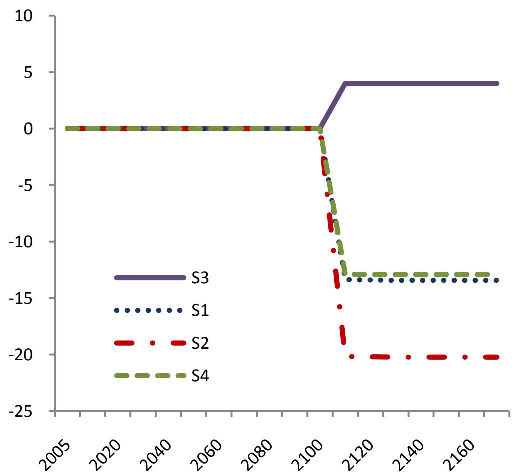
B: Output (YC)



C: Energy demand (YE)



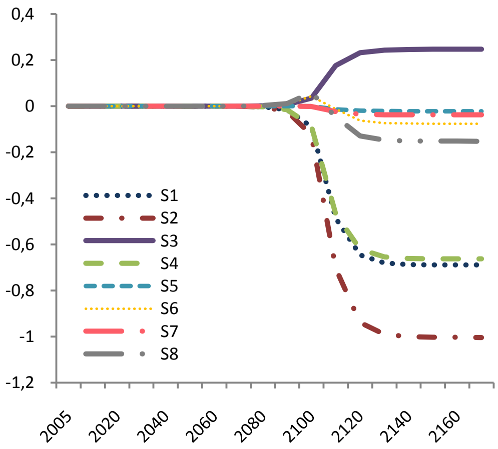
D: Fossil fuel demand (YF)



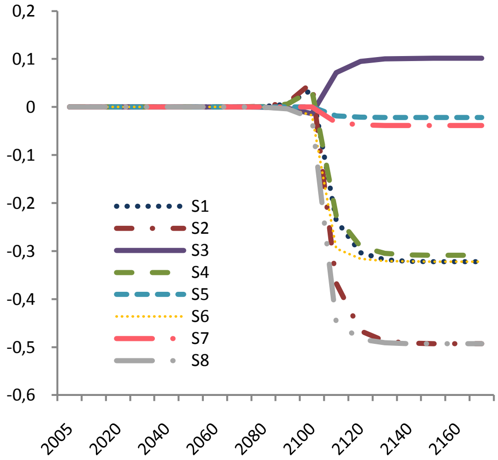
Appendix B

Dynamic response of consumption and output to all shocks

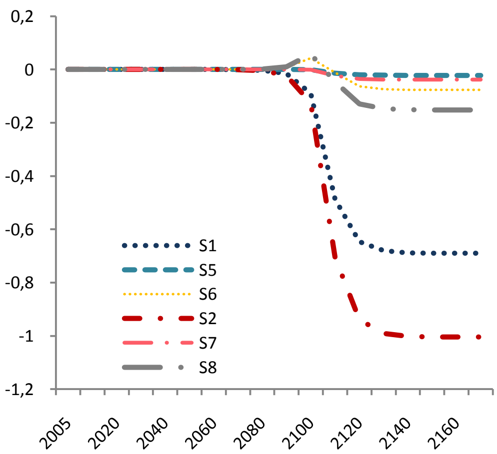
A: Consumption



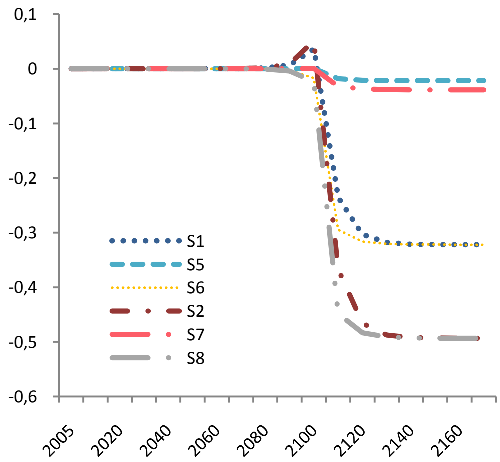
D: Output



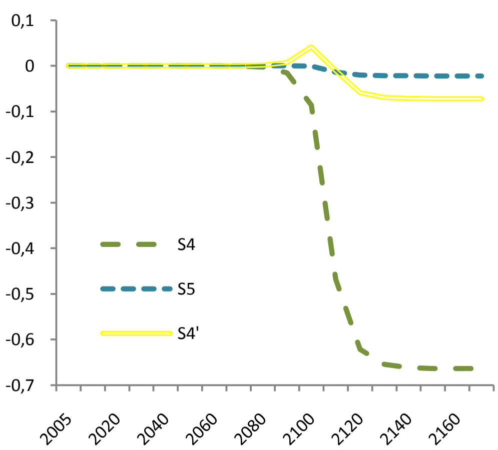
B: Environmental tax revenue recycling effects on consumption



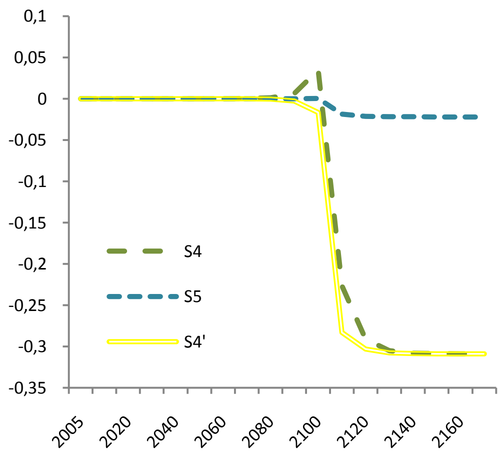
E: Environmental tax revenue recycling effects on output



C: Effect of S5, S4 and S4' on consumption



C: Effect of S5, S4 and S4' on output



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