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Social Acceptance and Optimal Pollution: CCS or Tax?

Pierre-André Jouvet[1] and Marie Renner[2]

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Keywords: Carbon Capture and Storage; Pollution; Tax; Social acceptance; Social optimum.

1. EconomiX, Université Paris Ouest, France and Climate Economics Chair, France
pierre-andre.jouvet@chaireeconomieduclimat.org

2. EconomiX, Université Paris Ouest, France, EDF R&D, Clamart, France, and Climate Economics Chair, France
marie.renner@chaireeconomieduclimat.org

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Abstract

The two main hurdles to a widespread carbon capture and storage (CCS) deployment are: cost and social acceptance issues. Assessing accurately social preferences is thus interesting to determine whether CCS is socially optimal. Unlike most academic papers that have a dichotomous approach and consider either the atmospheric pollution (first source of marginal disutility) or the underground pollution (second source), we consider the problem as a whole: CCS techniques introduce a third source of disutility due to the simultaneous presence of CO_2 in the atmosphere and in geological formations. The model and the numerical simulations show that there exist some configurations of social preferences for which CCS grants a higher social welfare provided that public authorities tax the carbon content of fossil fuels and subsidize carbon storage. CCS can even increase simultaneously the social welfare of the country with CCS and the one of the country without. From the perspective of minimizing the decarbonizing costs, we compare the case where each country defines its climate policy and when they are aggregated, in order to assess the transfers required to encourage CCS deployment.

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†EconomiX, Université Paris Ouest, France and Climate Economics Chair, France

‡EconomiX, Université Paris Ouest, France, EDF R&D, Clamart, France and Climate Economics Chair, France

1 Introduction

According to the IPCC (Intergovernmental Panel on Climate Change) (2005) [12], to limit the long-term global temperature increase to 2℃ (COP 15) it is necessary to halve CO_2 equivalent emissions by 2050. But if current trends persist, CO_2 emissions will almost double by 2050 due to a 85% global energy demand rise. And this would put the world on the path toward a 6℃ rise in average global temperature (IEA (2012) [18]). Thus, the current concentration of greenhouse gas (GHG) emissions in the atmosphere combined with the climate system physical inertia requires a swift action and not to foreclose any technical options to reach the 2℃ climatic goal. Technical options to be combined are: (1) a massive development of clean energies *ie* Renewable Energy Sources (RES) and nuclear, (2) improvements of energy efficiency, (3) fuel switching (coal to gas), (4) Carbon Capture and Storage techniques (CCS). CCS are a suite of geo-engineering techniques designed to intercept the CO_2 contained in industrial flue gases from large point sources (fossil fuel plants, blast furnaces, cement manufacturing) before it enters the atmosphere, to transport it (by trucks, ships, pipelines) and then to inject it into a suitable storage facility (depleted oil and gas fields and deep saline aquifers). International organizations like the International Energy Agency (IEA), Zero Emission Platform (ZEP), IPCC, European Commission (Roadmap 2050) very often present CCS as the only current mitigation technology that would allow industrial sectors (such as iron and steel, cement and fossil fuel power plant) to meet deep emission reduction targets. For instance, in its 2013 Technology Roadmap [19] analysis, the IEA develops a 2DS scenario in which CCS could account for up to 14% of cumulative CO_2 reductions by 2050 (17 % in 2050).

Many empirical studies deal with CCS through integrated assessment models (namely McFarland et al. (2003) [16], Edmonds et al. (2004) [7], Kurosawa (2004) [14]), or stylized models (Moslerner and Requate (2007) [17]) that generally give the determinants of an optimal climate policy with CCS and conclude that an early CCS use would substantially reduce the social cost of climate change.

The theoretical economic review on CCS is less abundant. Grimaud and Rougé (2013) [9] study the effects of the availability of CCS techniques on the optimal use of polluting exhaustible resources and on optimal climate policies within an endogenous growth model. Ayong Le Kama et al. (2010) [3] develop a model to emphasize the main driving forces that should de-

termine the optimal CCS policy by considering the storage rate instead of the storage flow. Lafforgue et al. (2008) [15] determine the optimal path of a CCS policy in a model of energy substitutions when carbon emissions can be stored into several reservoirs of finite size. Amigues et al. (2012) [2] assess the optimal timing of CCS policies by characterizing the optimal path of energy price, energy consumption, carbon emissions and atmospheric abatement for several kinds of CCS cost functions.
But none of these papers have focused on social acceptance regarding carbon storage. However, besides its cost, the main issue of CCS relies on carbon storage on a national site (particularly on-shore). It echoes to the famous NIMBY (Not In My Back Yard) problematic. As proof, it can be referred to the fail of a carbon storage pilot on the Kona coast (Hawaii) because of environmental organizations (De Figuereido et al. (2003) [6]), or fierce controversies in Germany and Poland with the CCS Directive (2009/31/CE Directive) implementation in national law. This social ambivalence seems paradoxical: latest public opinion surveys have shown a growing awareness of an urgent action to reduce GHG emissions, whereas a growing opposition to clean energies - nuclear power plants, RES... - can be observed. And CCS power plants are not different. This CCS social acceptance issue can mostly be explained by:

- Low levels of awareness or understanding of CCS, Ha-Duong et al.[10]. The literature review indicates that respondents better understand CCS when climate issues are explained (legitimacy of this technical option) and that an additional information can increase social acceptance (Tokushige et al. (2007) [21]).

- The existence of storage risks (leaks), identified and recognized, but whose control has not been proved yet due to the lack of large scale pilots.

If none article has focused on CCS and social acceptance, variants of this problem have been studied by Ayong Le Kama and Fodha (2010) [3], Moslerner and Requate (2007) [17] and Crettez and Jouvet (2010)[5]. Ayong Le Kama and Fodha deal with the optimal nuclear waste storage policy under uncertainty and use only one stock variable. Moslerner and Requate use two stock variables and study the problem of the optimal emissions of pollutants when there may exist complementary or substitutability in emission costs. The disutility of the various pollution stocks enter in a separable way in the

objective function. Crettez and Jouvet´s paper differs from this approach because even if there is only one source of pollutant emissions, stocks of pollutants can be complementary or substitutable.
In this paper, we adopt a static approach to determine, from the social point of view, simultaneously the amount of production as well as the optimal allocation of pollution (for instance CO_2) between the atmosphere and underground storage sites. We determine the tax levels associated with the optimal allocation and we compare two cases: (1) when CCS techniques are unused/used as a climate mitigation option and (2) when CCS techniques are not/are considered as a local pollution. In order to assess the sensitivity of tax and social welfare levels to social acceptance parameters, we specify the model and run some numerical simulations. We show that usually, the social welfare is higher when CCS techniques are used.
The sketch of the model is the following. We consider an economy with only one good which is produced by using fossil fuels. Its production decreases the environmental quality due to the release of carbon flows in the atmosphere. We assume that the social planner can capture and store a fraction of these carbon flows in appropriate deep geological formations. We determine the optimal consumption level of the polluting input and the optimal volume of pollutant emissions to be stored. Then, we derive the decentralized equilibrium outcome and determine the optimal tax levels required to implement the social optimum. We first consider the case where there is just one country/region that determines if CCS is socially optimal. Then, in the perspective of minimizing the cost of the ecological transition, we introduce the geographical dimension. Indeed, it can be less costly and thus more interesting to develop CCS in China (lower capital and labor costs) rather than in OECD countries. Thus we consider CCS as a local pollution and two countries, one with CCS techniques, one without. The two countries determine their social welfare (separately or aggregately) by taking into account the global pollution and their respective social preferences. The comparison of the cases where countries are or not aggregated typically allows us to assess the transfers (monetary, technological) that OECD countries should operate to encourage China to develop CCS.
This paper is organized as follows. Section 2 describes the model and its main assumptions. Section 3 studies the social optimum and then derives the decentralized equilibrium outcome to characterize the tax levels implementing the social optimum, for the two cases detailed above. Section 4 specifies the model and provides some numerical simulations in order to compare produc-

tion, tax and social welfare levels between the case without and with CCS techniques, and when CCS is seen as a local pollution. The last section concludes.

2 The model

We consider the producers of a good (for instance, energy). To produce this good, producers use a well-behaved production function (increasing, concave and homogeneous of degree one) $F : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ with an unique input E (for instance oil, gas or coal). Moreover, this function satisfies the Inada conditions: $\lim_{E\rightarrow 0} F_E(E) = +\infty$, $\lim_{E\rightarrow\infty} F_E(E) = 0$ and $F(0) = 0$. The unit cost of the input is denoted by q (in terms of the produced good).
A representative firm maximizes its profit, π:

$$\max_E \pi = F(E) - qE \tag{1}$$

With perfect competition, the factor price q is given and is equal to the marginal productivity:

$$F_E(E) = q \tag{2}$$

We assume that pollutant emissions are a joint product of the flow of the input used in the production, E. We consider that only a fraction of E may contribute to the atmospheric pollution stock (greenhouse gases, for instance CO_2 accumulation), $A(E)$. With the function $A(.)$ we accept that the effect of flow E on the stock of pollution is not to be necessarily one to one. We assume that $A_E(E) \geq 0$ and $A_{EE}(E) \geq 0$[1].
Each agent derives its utility from the consumption of goods, $C = F(E) - qE$ and is negatively affected by the pollution, $A(E)$. Households preferences are represented by a utility function U(C,A(E)):

$$U(C, A(E)) = F(E) - qE - \theta_1 A(E) \tag{3}$$

where $\theta_1 > 0$ is a preference parameter that represents the marginal disutility caused by the atmospheric emissions of pollutants.
Introducing CCS techniques implies that the effect of the flow E on the atmospheric pollution stock can be reduced. We denote by Z the quantity of

[1] The stock of pollution increases with the flow of emission and this effect increases with accumulation. The convexity of A has a climatic justification [13].

the emission flow which is captured and then stored underground between 700 and 5 000 m (depleted oil and gas fields or deep saline aquifers).
The storage creates a new, and then a second, stock of pollutants which is underground, $S(Z)$ with $S_Z(Z) \geq 0$ [2]. The effect of the storage on the atmospheric pollution stock implies $A(E,Z)$ with $A_Z(E,Z) < 0$. This second stock affects agent preferences in two ways. First, the underground storage, by creating a new stock of pollution, induces a new direct disutility, $\theta_2 S(Z)$ where $\theta_2 > 0$ is a preference parameter. It represents the marginal disutility caused by the storage. Second, pollutants are now both in the atmosphere and underground. This double stock induces a new effect: $G(A(E,Z), S(Z))$. With $G(.)$, unlike most academic papers that have a dichotomous approach and consider either the atmospheric or the underground pollution, we consider the problem as a whole: CCS introduces a third source of disutility due to the simultaneous presence of CO_2 in the atmosphere and in geological formations. It means that each stock of pollutants affects the marginal disutility of the other one. The effect can be of two kinds. On the one hand, an increase in the stock of pollutant may increase the marginal disutility of the other (the pollutants would be complementary); on the other hand, the effect could be negative. That is to say, an increase in the stock of one pollutant could lead to a decrease in the marginal disutility of the second one.
Furthermore, we also assume that the use of CCS techniques is costly, $\Phi(Z)$. This cost is measured in terms of production through a symmetrical function: $\Phi : \mathbb{R} \to \mathbb{R}_+$, which is increasing, convex and smooth (moreover, $\Phi(0) = \Phi_Z(0) = 0$), then the profit function becomes:

$$\max_E \pi = F(E) - qE - \Phi(Z) \tag{4}$$

In this case, household preferences are represented by:

$$U(C, A(E,Z), S(Z)) = F(E) - qE - \Phi(Z) - \theta_1 A(E,Z) - \theta_2 S(Z) - G(A(E,Z), S(Z)) \tag{5}$$

[2]The underground stock of pollution increases with the flow of pollutant emissions.

3 Social optimum without and with CCS

In this section, we consider that a social benevolent planner corrects environmental externalities without and with CCS techniques. Then we decentralize the studied economy and determine the optimal carbon tax level(s) required to implement the social optimum.

3.1 Social optimum without CCS and decentralization with a tax on input

In this case, only the atmospheric stock of pollution is considered to compute the social optimum. The central planner objective function is:

$$\max_{E} U(C, A(E)) = F(E) - qE - \theta_1 A(E) \tag{6}$$

The first order condition (FOC) is:

$$F_E(E^*) - q - \theta_1 A_E(E^*) = 0 \tag{7}$$

The FOC is a standard condition for the optimal solution. It states that the marginal utility loss caused by an additional pollution should be equal to the marginal utility gain due to an additional consumption.
If environmental externalities are internalized thanks to a tax, τ, applied on the flow of the input used in the production, E, from (1), a representative firm maximizes its profit:

$$\max_{E} \pi^{\tau} = F(E) - qE - \tau E \tag{8}$$

We obtain the following condition:

$$F_E(E) - q - \tau = 0 \tag{9}$$

Comparing (7) and (9), the optimal tax is defined by:

$$\tau = \theta_1 A_E(E^*) \tag{10}$$

The optimal taxation is equal to the effect of the pollution accumulation on agents' utility.
It is straightforward that τ increases with E.

3.2 Social optimum with CCS and decentralization

In this case, the social planner corrects environmental externalities by considering damages done to the environment and by using CCS techniques. It might be considered as a second best social optimum because of the introduction of a second source of externality. The objective function is:

$$\max_{(E,Z)} U(C, A(E,Z), S(Z)) = F(E) - qE - \Phi(Z) - \theta_1 A(E,Z) - \theta_2 S(Z) - G(A(E,Z), S(Z)) \quad (11)$$

The corresponding optimality conditions are:

$$F_E(E^{CCS}) - q - \theta_1 A_E - G_A A_E = 0 \quad (12)$$

and

$$-\Phi_Z(Z^*) - \theta_1 A_{Z^*} - \theta_2 S_{Z^*} - G_A A_{Z^*} - G_S S_{Z^*} \leq 0; = 0\, if\; Z > 0 \quad (13)$$

The corner solution, $Z = 0$ is defined by:

$$F_E(E) - q - \theta_1 A_E(E, 0) = 0 \quad (14)$$

and

$$-\theta_1 A_Z(E, 0) - G_A(A(E, 0), 0) A_Z(E, 0) \leq 0 \quad (15)$$

In the corner case, the first optimality condition can be interpreted as above. The second condition shows that decreasing the first stock at the margin yields a benefit which is more than cancelled by the increase in the damage due to the second stock of pollutant.
Considering the interior solution $Z > 0$, we have:

$$-\Phi_Z(Z^*) - \theta_1 A_{Z^*} - \theta_2 S_{Z^*} - G_A A_{Z^*} - G_S S_{Z^*} = 0 \quad (16)$$

In this case, if environmental externalities are internalized thanks to a tax, ρ, on the flow of the input used in the production, E, CCS techniques and a new tax, γ, on the underground storage, from (1) a representative firm maximizes its profit:

$$\max_{E,Z} \pi^{\rho,\gamma} = F(E) - qE - \Phi(Z) - \rho E - \gamma Z \quad (17)$$

We obtain the following conditions:

$$F_E(E) - q - \rho = 0 \quad (18)$$

and

$$-\Phi_Z - \gamma = 0 \tag{19}$$

Comparing (12), (16) and (18), (19), the optimal policy is defined by:

$$\rho = \theta_1 A_E(E^{CCS}, Z^*) - G_A(A(E^{CCS}, Z^*), S(Z^*))A_E(E^{CCS}, Z^*) \tag{20}$$

and

$$\gamma = \theta_1 A_{Z^*} + \theta_2 S_{Z^*} + G_A A_{Z^*} + G_S S_{Z^*} \tag{21}$$

In order to compare production, tax and welfare levels between the case with and without CCS techniques, we need to specify the technology and the external effect of pollution.

3.3 Global and/or local pollution

Considering CCS as a local pollution effect and assuming two different regions, region S with CCS and the other region, region A without CCS, we can draw the welfare effect on introducing CCS in only one region. Assuming that technologies are identical between the two regions, from above equations, region A and S welfares are respectively given by:

$$U^A(C^A, A(E^A + E^S, Z)) = F(E^A) - qE^A - \theta_1^A A(E^A + E^S, Z) \tag{22}$$

and

$$U^S(C^S, A(.,.)) = F(E^S) - qE^S - \Phi(Z) - \theta_1^S A(.,.) - \theta_2^S S(Z) - G(A(.,.), S(Z)) \tag{23}$$

We obtain the following optimal conditions:

$$F_E(E^A) - q - \theta_1^A A_{E^A} = 0 \tag{24}$$

$$F_E(E^S) - q - (\theta_1^S + G_A)A_{E^S} = 0 \tag{25}$$

and

$$-\Phi_Z - (\theta_1^S + G_A)A_Z - (\theta_2^S + G_Z)S_Z = 0 \tag{26}$$

Optimal tax/susbidy levels for each region are equivalent to the previous results.

If we compute the total welfare, the program to be solved is:

$$\max_{(E^A, E^S, Z)} U^A(C^A, A(E^A + E^S, Z)) + U^S(C^S, A(E^A + E^S, Z)) \tag{27}$$

We obtain the following optimal conditions:

$$F_E(E^A) - q - (\theta_1^A + \theta_1^S + G_A)A_{E^A} = 0 \tag{28}$$

$$F_E(E^S) - q - (\theta_1^A + \theta_1^S + G_A)A_{E^S} = 0 \tag{29}$$

and

$$-\Phi_Z - (\theta_1^A + \theta_1^S + G_A)A_Z - (\theta_2^S + G_Z)S_Z = 0 \tag{30}$$

The comparison of the FOCs (24, 25, and 26 with 28, 29 and 30) shows that in the case where the two countries/regions are aggregated, the marginal disutility due to pollution felt in one of the two countries directly affects the other one.

In order to compare the social welfares of the two regions as well as the total welfare effect, we need to specify the technology and the external effect of pollution.

4 Numerical simulations

Let's present some numerical simulations for illustration. Note the term illustration: we do not intend to quantify tax and social welfare levels but illustrate their sensitivity/evolution to changes of the parameters featuring the disutility of the pollution stocks or, in order words, to social acceptance regarding atmospheric pollution, underground pollution or both.

4.1 Model specification and assumptions

To specify the model and get simple analytical developments, we assume that the production function is a Cobb-Douglas with an unique input E, and constant yield β with $0 < \beta < 1$. Classically, we have: $F(E) = E^{\beta}$.

When CCS techniques are not used (BAU case), we assume that the stock of atmospheric pollution is:
$A(E) = \frac{1}{2}(\alpha F(E))^2 = \frac{1}{2}\alpha^2 E^{2\beta}$ where α is the carbon content of the production and $\alpha F(E)$ the flow of pollutant emissions. The condition $A_{EE}(E) \geq 0$ implies that $\beta \geq \frac{1}{2}$.

When CCS techniques are used, we assume that the atmospheric and underground stocks of pollutant are respectively:

- $A(E, Z) = \frac{1}{2}(\alpha F(E) - Z)^2 = \frac{1}{2}(\alpha E^{\beta} - Z)^2$ where $\alpha F(E) - Z$ represents the net atmospheric flow of pollutant emissions.
- $S(Z) = \frac{1}{2}Z^2$.

The effect induced by the double stock of pollution is assumed to be:
$G(A(E, Z), S(Z)) = \epsilon(\alpha F(E) - Z)Z$ where ϵ intercepts both underground and atmospheric effects of the pollutant emissions on the objective.

The cost due to the CCS technique use is assumed to be: $\Phi(Z) = \frac{1}{2}\phi Z^2$.

By referring to the specification above and equations (10) for the BAU case and (20) (21) for the CCS case, the optimal taxation levels are:

- In the BAU case:
  $\tau = \theta_1 A_E(E^*) = \theta_1 \beta \alpha^2 (E^*)^{2\beta-1}$
- In the CCS case:
  $\rho = \theta_1 A_E(E^{CCS}, Z^*) + G_A(A(E^{CCS}, Z^*), S(Z^*)) = \theta_1 \beta \alpha (E^{CCS})^{\beta-1}[\alpha(E^{CCS})^{\beta} - Z^*] + \epsilon\alpha\beta(E^{CCS})^{\beta-1} Z^*$
  and $\gamma = -\phi Z^* = \theta_1[Z^* - \alpha(E^{CCS})^{\beta}] + \theta_2 Z^* + \epsilon[\alpha(E^{CCS})^{\beta} - 2Z^*]$

Result 1: τ and ρ are taxes on atmospheric emissions of pollutant and are decreasing functions of the production level (for ρ, it implies $\theta_1 \geq \epsilon$).
When CCS techniques are used, a second economic tool is required: γ. As $Z \geq 0$, γ is a subsidy dedicated to CO_2 storage. $-\gamma$ is a increasing function of Z.
This idea of a subsidy dedicated to carbon storage can be found in Grimaud and Rougié [9]. Indeed, they explain that there exist many reasons for which policy makers cannot implement the Pigouvian level of the carbon tax, for example, the lack of an international consensus. Among the second best economic policies they study, there is a subsidy to carbon storage.

To run numerical simulations, several techno-economic assumptions are made (Table 1).

Table 1

4.2 Optimal taxation and social welfare, with and without CCS: numerical simulation results

We study, *ceteris paribus*, the effects of a marginal variation of θ_1, θ_2 and ϵ on the input consumption, tax levels and social welfares (Table 2).

Table 2

Numerical simulations are presented through the figures 1 to 6. The case where CCS techniques are not used is indicated by business as usual (BAU).

Figure 1
Figure 2
Figure 3
Figure 4
Figure 5
Figure 6

As Figure 1 shows, the higher θ_1, the lower the input consumption and the higher the tax level on the polluting input, Z and γ.
Figure 2 shows that the social welfare levels, with and without CCS techniques, decrease with θ_1. Indeed, to reduce the atmospheric pollution, the production level decreases. The CCS social welfare is higher and less sensitive to θ_1 variations than the BAU welfare.

As Figures 3 indicates, in the BAU case, the polluting input consumption, the production and tax levels, etc. are not affected by θ_2 variations.
The higher θ_2, the lower Z and γ. As Z decreases, net atmospheric emissions of pollutant as well as ρ increase until reaching the BAU level. Consequently, the CCS social welfare decreases with θ_2 until reaching the BAU level (Figure 4).

As previously said for θ_2, in the BAU case, ϵ variations have none effect.
Figures 5 and 6 show that the higher ϵ, the lower the input consumption (and thus the production level) as well as Z and γ. As a consequence, the CCS social welfare decreases with ϵ until reaching the BAU level (Figure 6).

To summarize, the main results issued from these numerical simulations are:

- **Result 1:** For the record, γ is a subsidy to the underground storage of CO_2.
- **Result 2:** The input consumption, and thus the production level, is higher when CCS techniques are used.
  The intuition is: when CCS techniques are used, the CO_2 is captured before it enters the atmosphere and thus the disutility caused by atmospheric pollution is reduced. Consequently, the production level is higher when CCS techniques are used.

- **Result 3:** The tax level on the polluting input is higher in the BAU than in the CCS case.

- **Result 4:** The social welfare is usually higher when CCS techniques are used.
  More precisely, with $E^{CCS} \geqslant E^{*}$, the CCS social welfare is higher than the BAU welfare if $\theta_1 \geqslant \epsilon$.
  The intuition is the following: CCS are a new tool to reduce atmospheric pollution and introduce preference for diversity. It is in accordance with Grimaud and Rougié [9] demonstrate that the availability of CCS techniques increases the social welfare.
  The CCS social welfare decreases with θ_2 and ϵ variations until reaching the BAU level. Indeed, when the marginal disutility to carbon storage increases, CCS techniques are less used; at that time, the only way to reduce the atmospheric pollution is to reduce the production level.
  Additional simulations have shown that when the marginal disutility due to atmospheric pollution is frankly lower than the marginal disutility caused by underground storage, itself lower than the marginal disutility caused by both stocks of pollutant, the CCS social welfare is lower than the BAU level. It means that when people are little concerned with the global warming issue and are very reluctant to carbon storage, the use of CCS techniques is not optimal.

- **Result 5:** The social welfare levels, with and without CCS techniques, decrease with θ_1. The CCS social welfare is less sensitive to θ_1 variations than the BAU welfare. Indeed, in the CCS case, some of the CO_2 emissions can be stored to reduce the atmospheric pollution.

4.3 Global and/or local pollution: numerical simulation results

Until now, we have studied the acceptance conditions under which the use of CCS techniques is socially optimal.
Now, we consider that our atmosphere is a public good, *ie* our atmospheric emissions of pollutant but also the one emitted by other countries/regions have an impact on the quality of the air we breathe. We also consider that the use of CCS techniques generates a local pollution. It means that optimal climate policies have to consider both local and global emissions of pollutant.

Two cases are distinguished: (1) each country/region optimizes its own climate policy by taking into account global and local pollution, (2) an unique social planner aggregates the two regions/countries. In each case, one country/region uses CCS techniques (S) whereas the other doesn't (A).
We assume that the two countries/regions are technologically identical (β is the same in A and S) but can have different acceptance levels regarding the atmospheric pollution (θ_1^A, θ_1^S).
We study the effects of a marginal variation of θ_1^A, θ_1^S, θ_2 and ϵ on the input consumption and thus the production, tax and social welfare levels. As previously, we adopt a *ceteris paribus* approach (Table 3).

Table 3

For the first case, the optimal taxation levels are issued from the comparison of equations (24) for the country/region A and (25), (26) for the country S and by referring to 3.3 and 4.1:

- In the country/region A:
  $\tau = \theta_1^A A_{E^A}(E^A + E^S, Z) = \theta_1^A \alpha\beta(E^A + E^S)^{\beta-1}\left[\alpha(E^A + E^S)^\beta - Z\right]$

- In the country/region S:
  $\rho = \theta_1^S A_E^S(E^A + E^S, Z) + G_A(A(E^A + E^S, Z), S(Z))$
  $= \alpha\beta(E^A + E^S)^{\beta-1}\left[\theta_1^S\alpha(E^A + E^S)^\beta - \theta_1^S Z + \epsilon Z\right]$
  $\gamma = -\phi Z = \alpha(E^A + E^S)^\beta \dfrac{\epsilon - \theta_1^S}{2\epsilon - \phi - \theta_1^S - \theta_2^S}$

Figure 7
Figure 8
Figure 9
Figure 10
Figure 11
Figure 12
Figure 13
Figure 14

As figures 7 and 8 suggest, when θ_1^A increases, in the country/region A, the production and the social welfare levels decrease. θ_1^A variations have none impact on the production level of the country S but decrease its social welfare (Z decreases with E^A). When θ_1^A is higher than θ_1^S, the social welfare in the country S becomes higher than in A (Figure 8).

As figures 9 and 10 show, when θ_1^S increases, in the country S, Z as well as the production and the social welfare levels decrease. On the contrary, in the country A, the production and the social welfare levels increase with θ_1^S. It can be explained this way: as S decreases its atmospheric pollution, A can partly increase its polluting input consumption (the other parameters of social acceptance are steady). Consequently, when θ_1^S becomes higher than θ_1^A, the social welfare becomes higher in A than in S except when θ_2 and ϵ are low (high disutility to atmospheric pollution can be offset by CO_2 storage).

As figures 11 and 12 indicate, when θ_2 increases with $\theta_1^A \geq \theta_1^S$ (it has also been verified for $\theta_1^A = \theta_1^S$), the production level in the two countries/regions as well as Z decrease. In the two countries/regions, the social welfare level decreases with θ_2 but is higher when CCS techniques are used.
When $\theta_1^A < \theta_1^S$ and θ_2 increases (Figures 20 and 21 in the Appendix), Z as well as the production and the social welfare levels decrease. There is a social level of disutility regarding CO_2 storage beyond which the social welfare in A becomes higher than in S (the pollution storage is less allowed and thus cannot offset a higher disutility to atmospheric pollution).

With figures 13 and 14, it can be seen that when ϵ increases and $\theta_1^A = \theta_1^S < \theta_2$, the production and the social welfare levels increase in A whereas they decrease in S in spite of an increase of Z. When the marginal disutility due to both underground and atmospheric emissions of pollutant is significant, the social welfare becomes higher in A than in S.
When $\theta_1^A = \theta_1^S > \theta_2$, A and S social welfares decrease with ϵ. When ϵ is significant, the social welfare becomes higher in A than in S.

- **Result 6:** When the air quality is seen as a public good and CCS as a local pollution, changes in social preferences in one country affect the social welfare in another country.

- **Result 7:** The social welfare is higher in the country S than in A, except when $\theta_1^A < \theta_1^S$ with θ_2 and ϵ significant.

Now, let's consider the second case, *ie* the planner aggregates the two countries.
By referring to the model specification and equations 28, 29 and 30, the tax levels on atmospheric and underground emissions of CO_2 are the following:
$\tau = (\theta_1^A + \theta_1^S + G_A)A_{E^A}$
$\rho = (\theta_1^A + \theta_1^S + G_A)A_{E^S}$
$-\gamma = (\theta_1^A + \theta_1^S - G_A)A_Z + (\theta_2^S + G_Z)S_Z + G_A A_Z$
With our set of parameters and hypothesis, it means that $E^A = E^S$ and $\tau = \rho$.

Figure 15
Figure 16
Figure 17
Figure 18
Figure 19

As figures 15 to 19 indicate[3], when θ_1^A (respectively θ_1^S, ϵ) increases, the production level of the two countries/regions decreases as well as the global welfare even if Z increases.
When θ_2 increases, the production level and Z decrease. Consequently, the global welfare decreases.

- **Result 8:** The global social welfare decreases as soon as the marginal disutility to underground/ atmospheric/ both pollution increases.
  For the record, when the two countries/regions are not aggregated, an increase of θ_1^A, θ_1^S, θ_2 or ϵ in one country/region can increase the social welfare of the other country/region.

- **Result 9:** The global social welfare corresponds to a Pareto optimum. Indeed, when the two countries/regions are not aggregated and that

[3]Only one figure represents the social welfare sensitivity to θ_1^A for results are very similar for the other parameters of social acceptance.

one of them is affected by a lower social acceptance regarding pollution (atmospheric, underground, both), its production level has to be decreased to reduce pollution, while the other country/region can partly increase its pollution and thus its social welfare level.
The comparison of the two cases, when countries are or not aggregated, can allow us to assess the transfers between A and S that would encourage S to deploy CCS in order to improve the global air quality.

In relation to what has been done above and for illustration purposes, we can classify different kinds of country in order to assess more precisely the social welfare level sensitivity to the parameters featuring the disutility caused by the pollution stocks. Four main cases are represented: (1) people don't like atmospheric pollution but are not disturbed by underground pollution; it could represent Norway (EOR) or the United Kingdom, (2) people like neither underground and atmospheric pollution; it could represent Germany, (3) people are not disturbed by atmospheric pollution and don't like underground pollution; it could represent Poland, (4) people are disturbed neither by underground and atmospheric pollution; it could represent the United States. Tables 4 and 5 give, for each country, the values for social acceptance parameters and the social welfare levels obtained for each configuration.

Table 4
Table 5

For these values of social acceptance parameters, if each country only consider its pollution, the social welfare is higher with than without CCS techniques. Let's see what happens when global and local pollution are considered.
For Germany: without CCS techniques, the German social welfare is lower than in the other countries using CCS. If CCS techniques are used, the German social welfare is slightly higher than in the other countries except Poland. Thus, on average, Germany would have interest to use CCS techniques. However, the global social welfare level (with and without CCS) is higher when Germany doesn't use CCS whereas the other countries do. Indeed, Germany has a disutility to atmospheric pollution lower than or equal to the other countries and a social acceptance to CO_2 storage higher than or equal to the other countries (that can bury CO_2 to produce more). Thus Germany would have interest to subsidy the CCS deployment in another countries.
It is the same for Poland: its social welfare level is on average higher when

CCS are used in the other countries.
For Norway: whatever the configuration (either A or S), the Norvegian social welfare is lower than in the other countries, except when Germany doesn't use CCS techniques (same disutility to atmospheric pollution but more CO_2 can be stored in Norway). However, the Norvegian social welfare level as well as the global social welfare is higher when Norway uses CCS techniques. Thus Norway would have interest to be subsidized by countries like Poland and Germany to deploy CCS techniques.
For the United States: the American social welfare level is higher when the country uses CCS techniques.
The global social welfare is the highest when CCS are used in Norway.

5 Conclusion

CCS are considered as an interesting option for climate change mitigation. The two main hurdles to a widespread CCS deployment are: its very high cost and social acceptance. As very few economic models deals with CCS social acceptance, this paper focuses on it and aims at determining, from the social point of view, simultaneously the amount of production as well as the optimal allocation of CO_2 emissions between the atmosphere and underground storage sites. From a methodological point of view, the originality of this paper relies on the introduction of the marginal disutility due to both atmospheric and underground pollution, in addition to the two marginal disutilities due to atmospheric and underground pollution as it is currently done. Thanks to this third source of marginal disutility, we consider the overall problem. From a normative point of view, with numerical simulations, we show that CCS usually provides a higher social welfare if public policies tax fossil fuels and subsidize CO_2 storage.
To assess the sensitivity of tax and welfare levels to social acceptance parameters, the model is specified and numerical simulations are run. Two cases are distinguished: (1) one country isolated, (2) two countries, one with CCS the other one without, CCS being considered as a local pollution and air quality as a public good.
The model specification has given a first interesting result: the use of CCS techniques implies the introduction of a new fiscal tool, γ, which is a subsidy to CO_2 storage.
Then, thanks to numerical simulations, it has been shown that usually, the

social welfare is higher when CCS techniques are used, except when:

- for (1), the marginal disutility due to atmospheric pollution is frankly lower than the marginal disutility caused by underground storage, itself lower than the marginal disutility caused by both stocks of pollutant.
- for (2), θ_2 or/and ϵ is/are significant, and the marginal disutility to atmospheric pollution is higher in the country A than in S. Indeed, if the marginal disutility to atmospheric pollution is high and the social acceptance to CO_2 storage is low, the only way to reduce the pollution is to decrease the production level.

This result of a CCS social welfare higher than the BAU welfare can be explained this way: when CCS techniques are used, the CO_2 is captured before it enters the atmosphere and thus the disutility caused by atmospheric pollution is reduced. As a consequence, the polluting input consumption and thus the production level can be higher with CCS. Besides, the use of CCS techniques introduces a new tool to reduce atmospheric pollution. Therefore, the preference for diversity can also explain a higher welfare with CCS techniques than without. Note that the tax level on the polluting input is lower when CCS techniques are used.
When the geographical dimension is taken into account, we show that there exist configurations of social preferences for which one country can use CCS techniques and increase simultaneously its social welfare and the one of its neighbour without CCS. The comparison of the two cases, when countries have their own climate policy or are aggregated, allows us to assess the transfers required to encourage the CCS deployment in the CCS country.
The specific configurations of social preferences where CCS is not socially optimal allows us to explain the failure of some CCS projects.

Thus it can be said that CCS techniques are a really interesting option for climate change mitigation and that assessing accurately social preferences is interesting to determine their optimal level of deployment.
All these results are obtained in static. One direct and natural extension of this paper, among others, might be to study the dynamic problem in order to give more recommendations for the optimal deployment of CCS and the associated taxation.

6 Appendix

Figure 20
Figure 21

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Figure 1: Pollutant emissions and tax levels sensitivity to θ_1

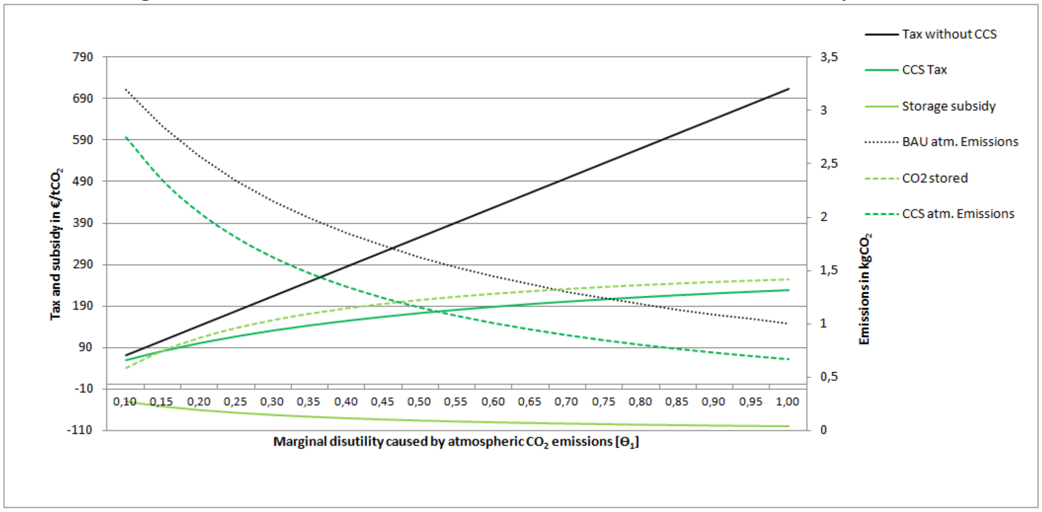


Figure 2: Social welfare sensitivity to θ_1

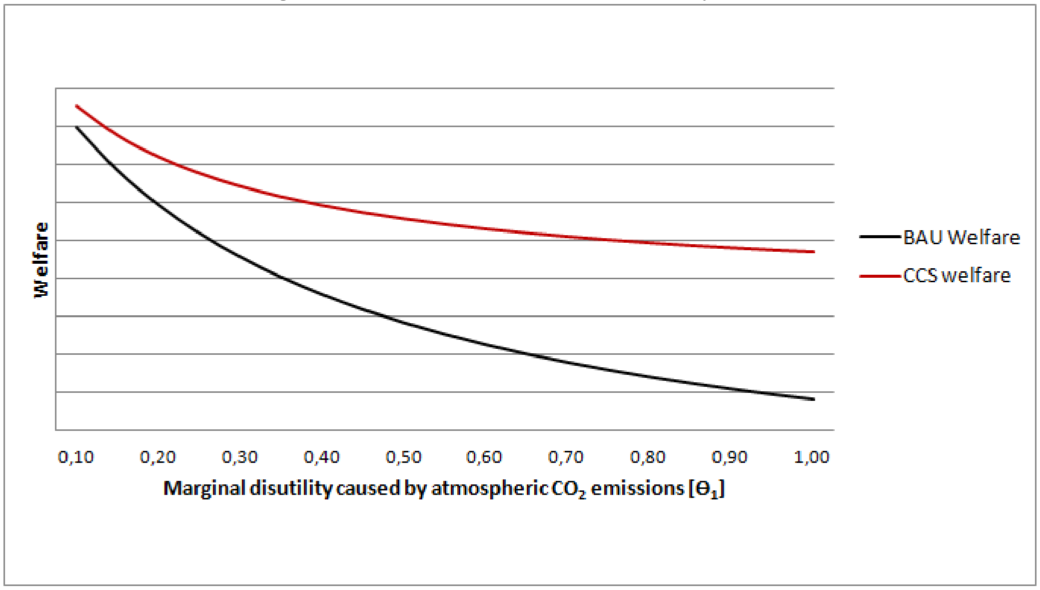


Figure 3: Pollutant emissions and tax levels sensitivity to θ_2

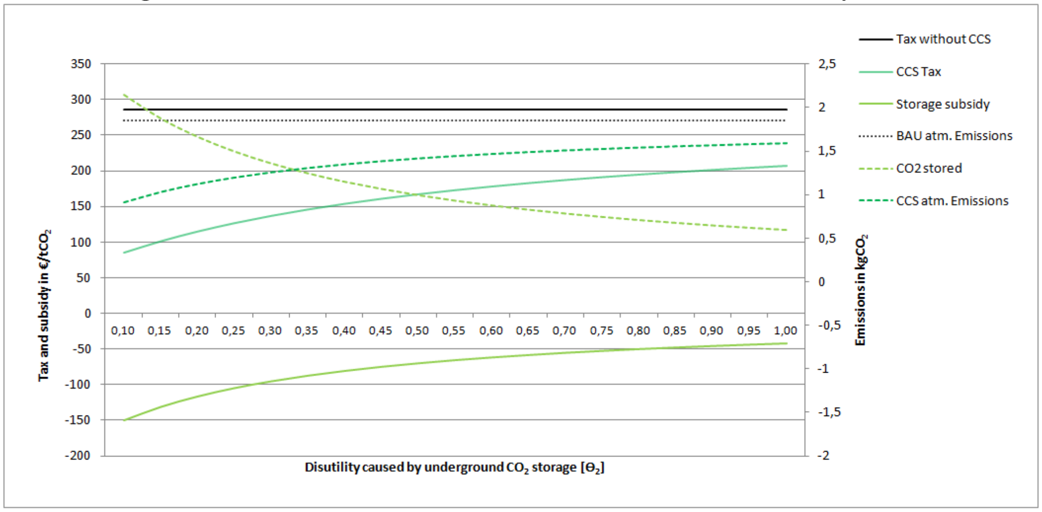


Figure 4: Social welfare sensitivity to θ_2

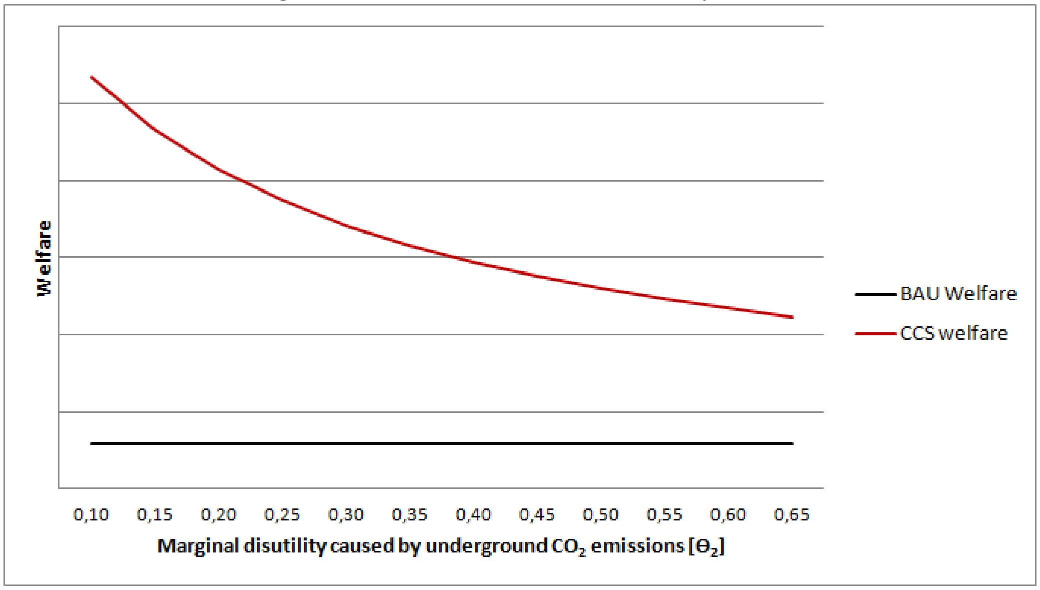


Figure 5: Pollutant emissions and tax levels sensitivity to ϵ, $\theta_1 > \theta_2$

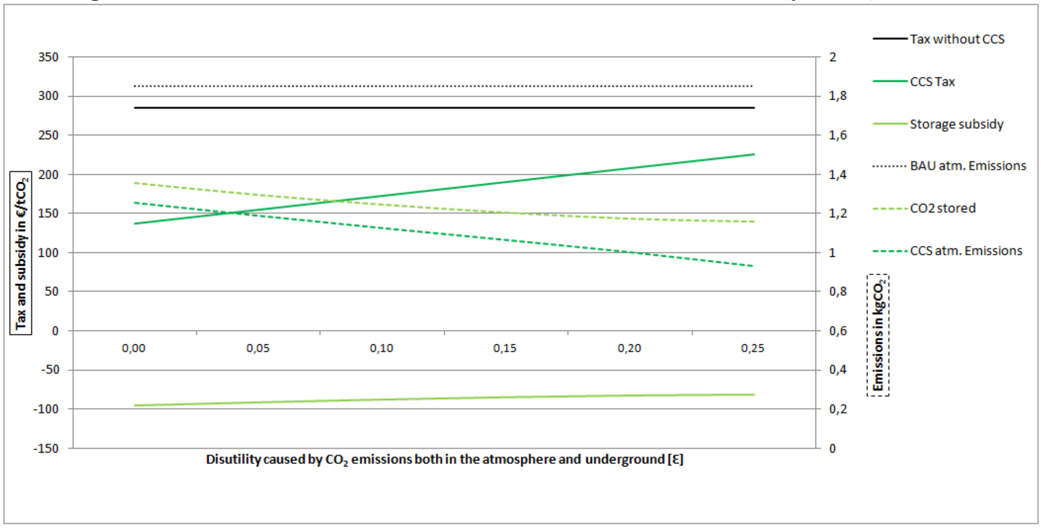


Figure 6: Social welfare sensitivity to ϵ, $\theta_1 > \theta_2$

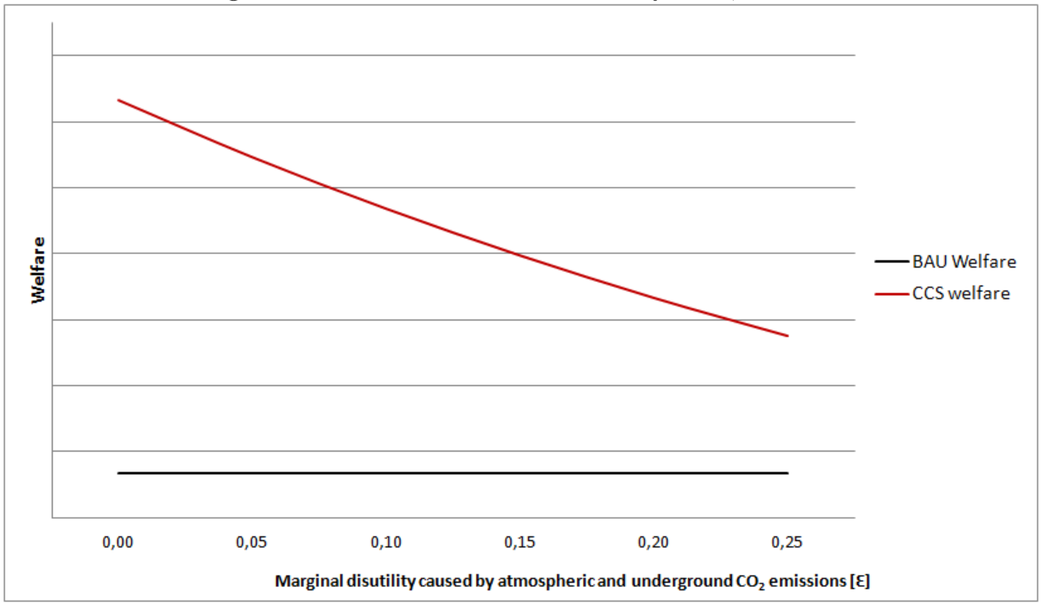


Figure 7: Emission and tax levels sensitivity to θ_1^A

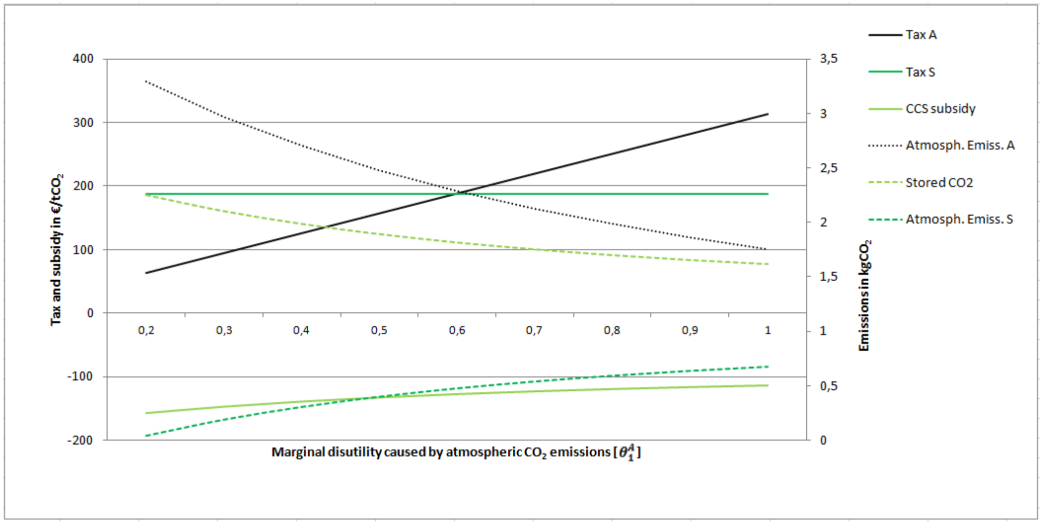


Figure 8: Welfare sensitivity to θ_1^A

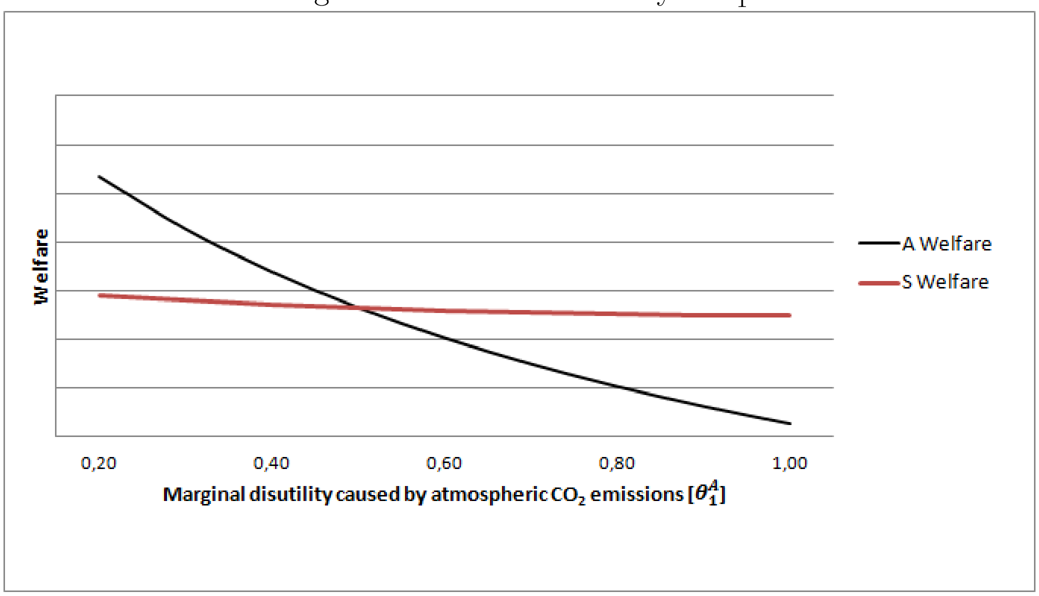


Figure 9: Emission and tax levels sensitivity to θ_1^S

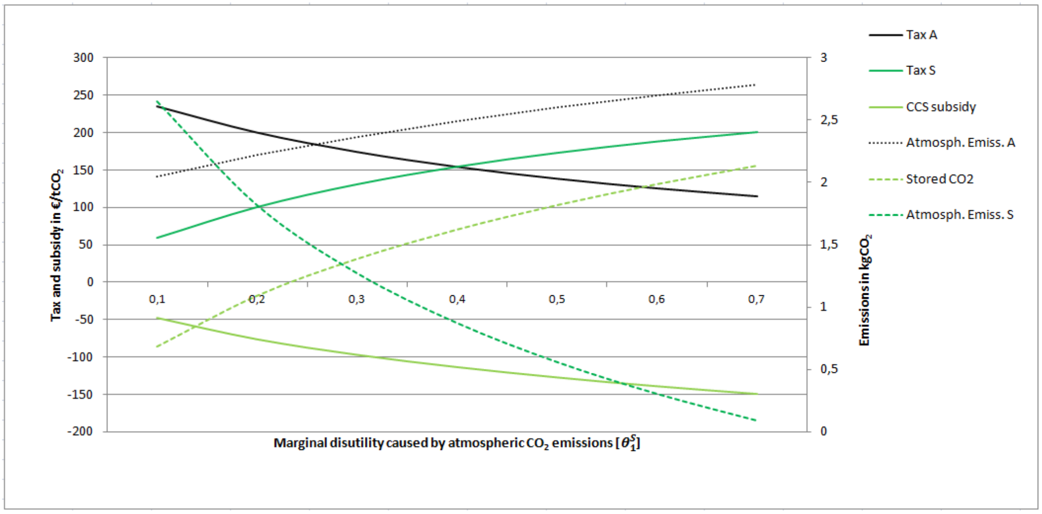


Figure 10: Welfare sensitivity to θ_1^S

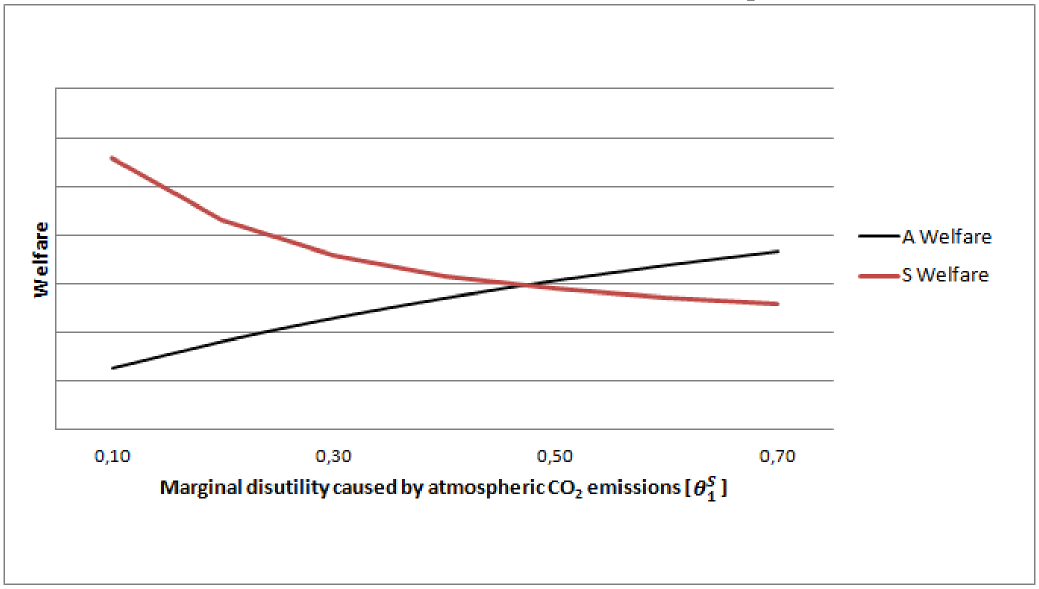


Figure 11: Emission and tax levels sensitivity to θ_2, $\theta_1^A > \theta_1^S$

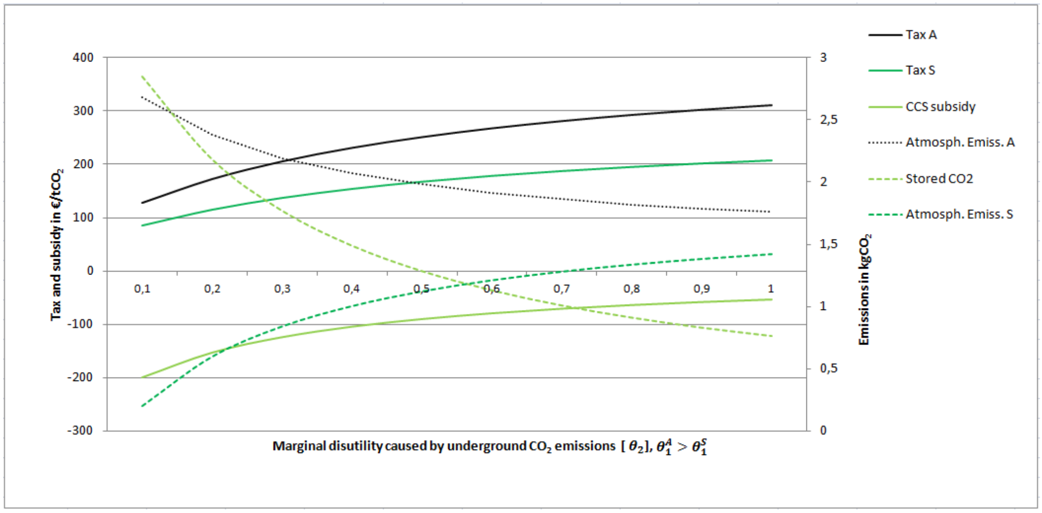


Figure 12: Welfare sensitivity to θ_2, $\theta_1^A > \theta_1^S$

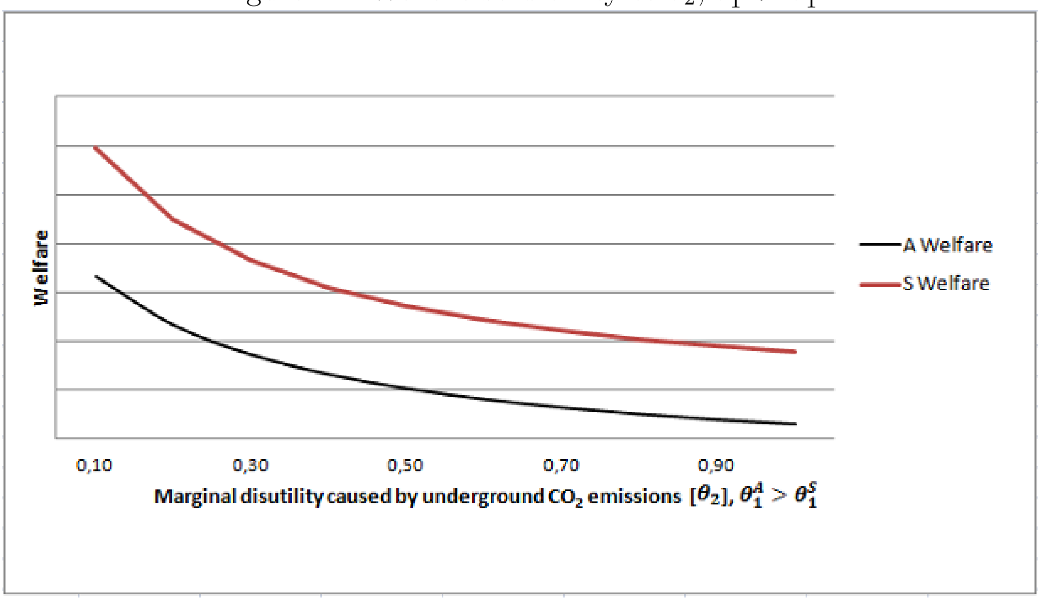


Figure 13: Emission and tax levels sensitivity to ϵ, $\theta_1^A = \theta_1^S < \theta_2$

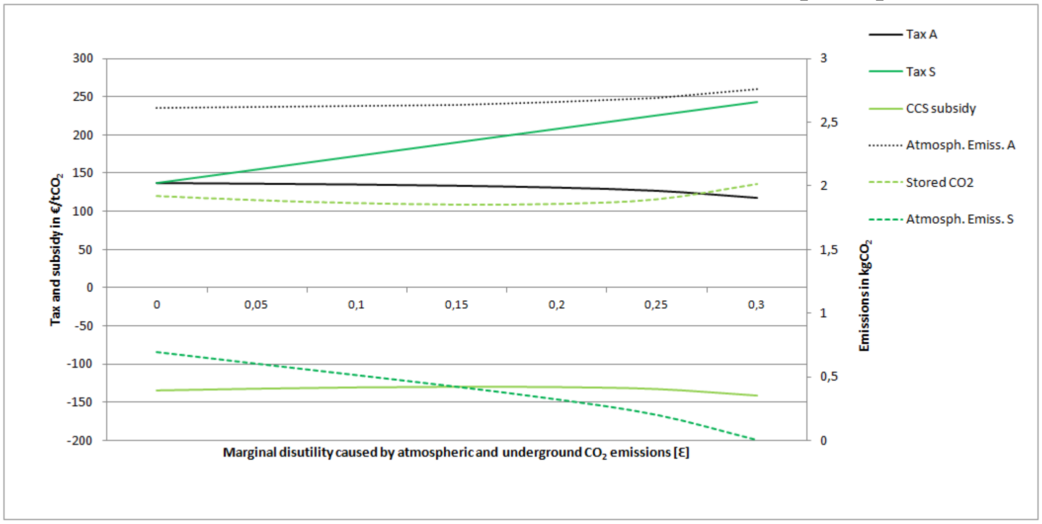


Figure 14: Welfare sensitivity to ϵ, $\theta_1^A = \theta_1^S < \theta_2$

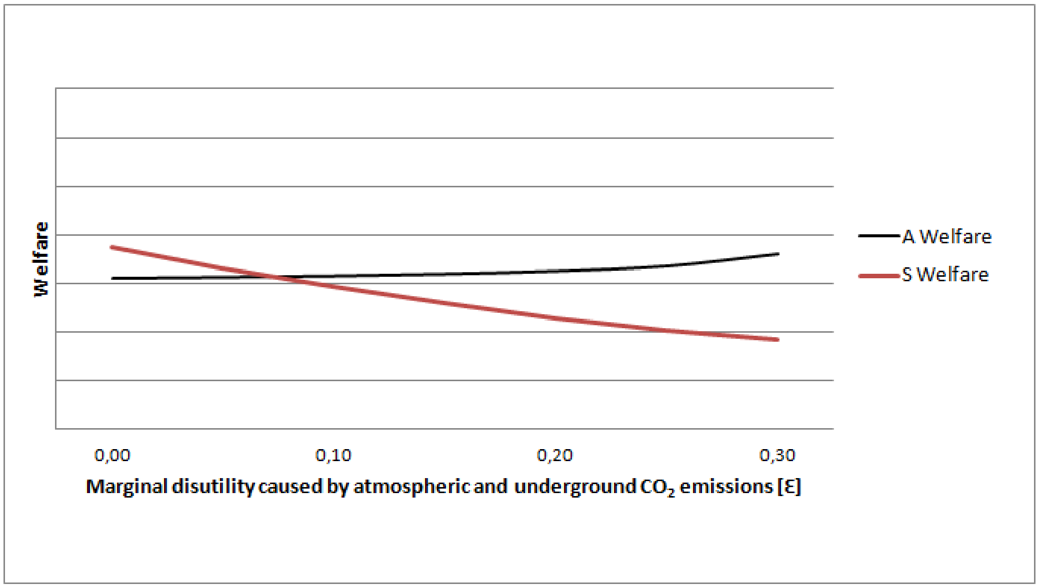


Figure 15: Emission and tax levels sensitivity to θ_1^A, unique planner

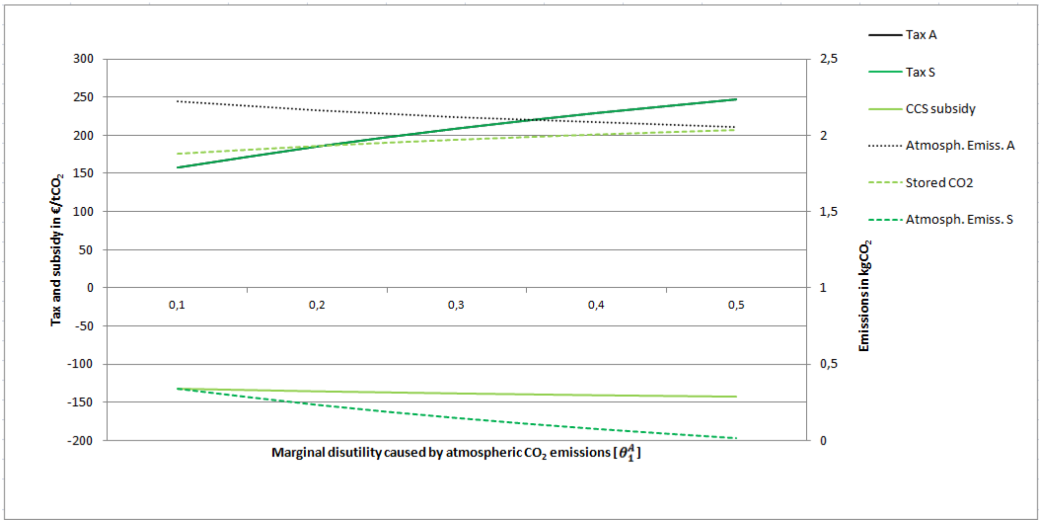
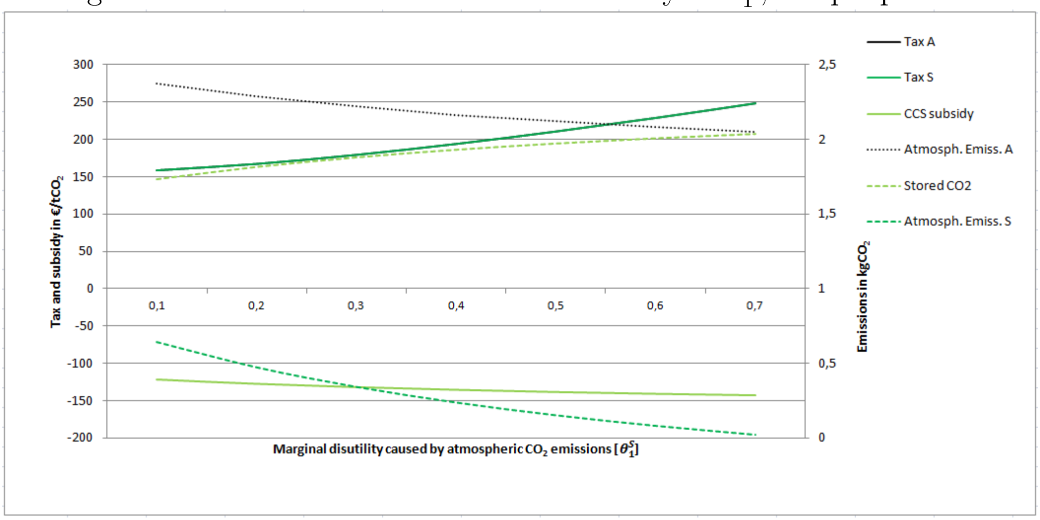


Figure 16: Emission and tax levels sensitivity to θ_1^S, unique planner



[a] α corresponds to the emission factor of a supercritical coal plant that uses hard coal.
[b] Coal price is from the IEA New Policy Scenario (2012) for 2015.
[c] CCS cost is issued from Renner (2013) (it is similar to a CO_2 avoided cost calculated from the IEA study, with its 2030 cost projections).

Figure 17: Emission and tax levels sensitivity to θ_2, $\theta_1^A > \theta_1^S$, unique planner

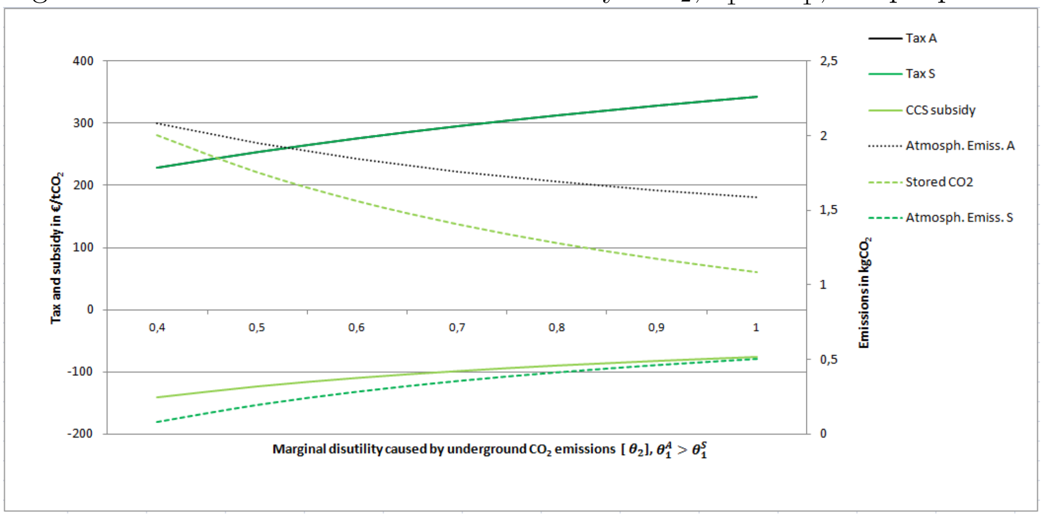
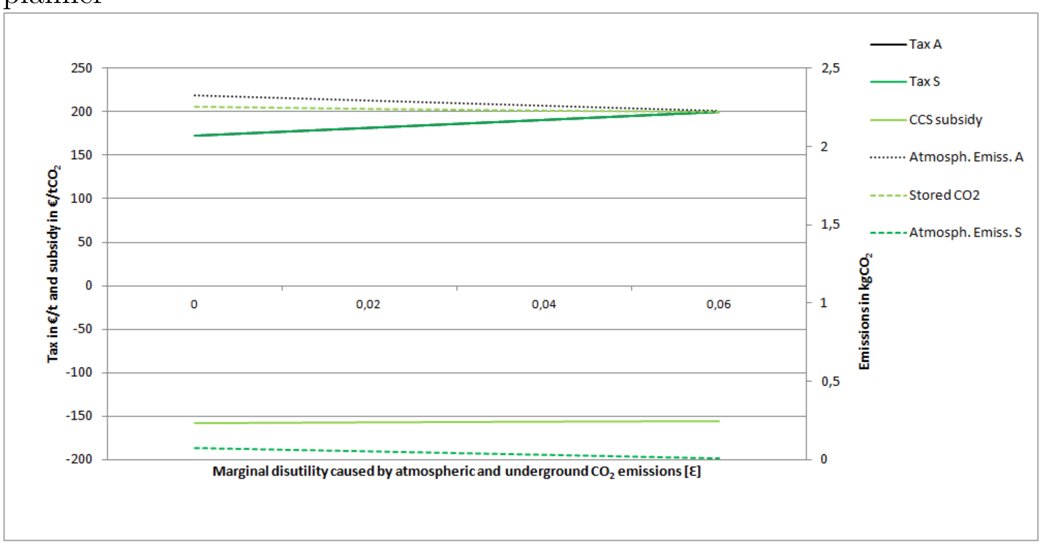


Figure 18: Emission and tax levels sensitivity to ϵ, $\theta_1^A = \theta_1^S < \theta_2$, unique planner



Note that the subsidy is expressed in €$/tCO_2$ whereas taxes on the polluting input are expressed in €/t. In order to compare their level, we convert τ and ρ into €/tCO_2. The multiplying factor is issued from ADEME.

Figure 19: Global social welfare sensitivity to θ_1^A

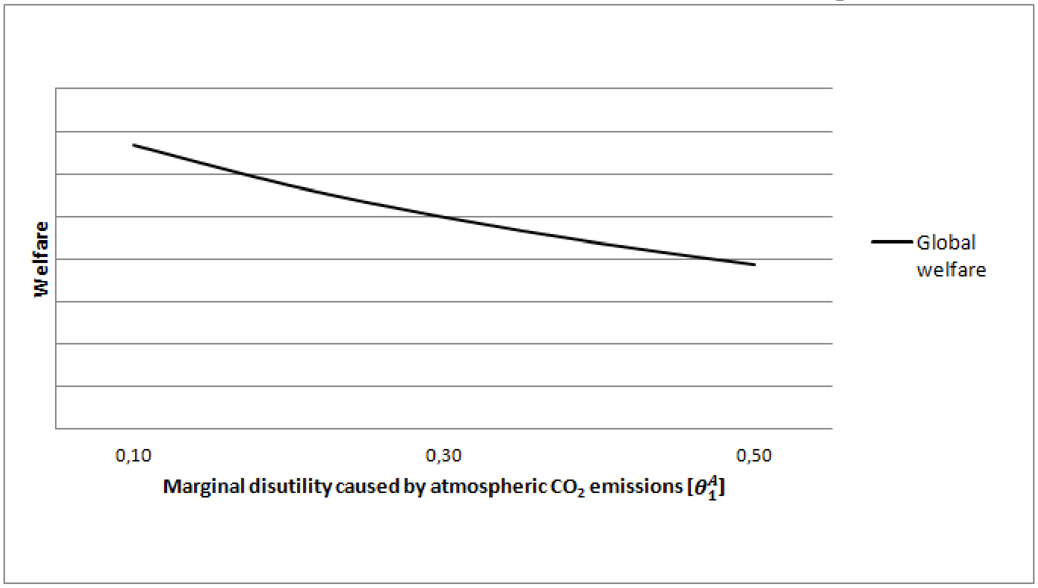


Figure 20: Emission and tax levels sensitivity to θ_2, $\theta_1^A < \theta_1^S$

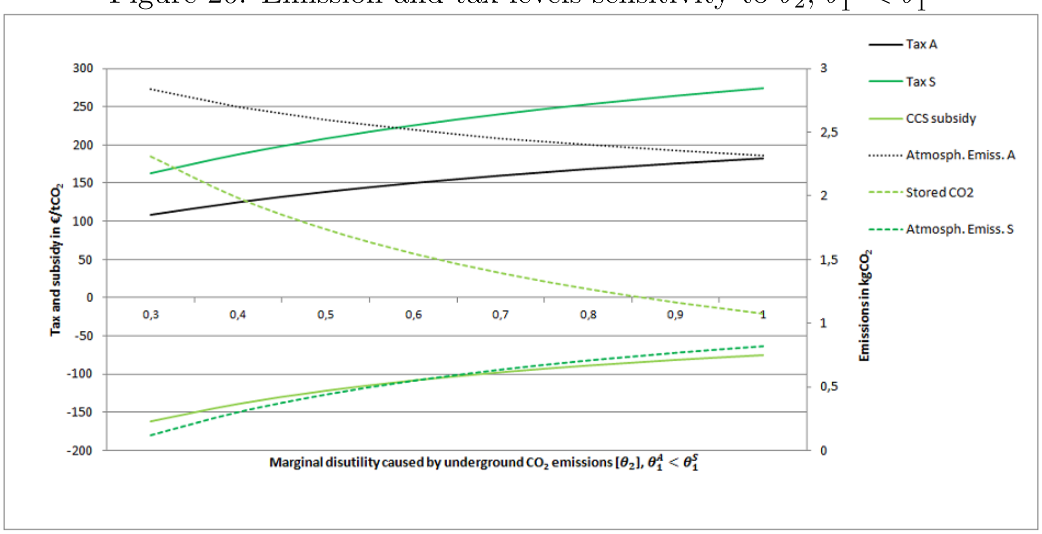


Figure 21: Welfare sensitivity to θ_2, $\theta_1^A < \theta_1^S$

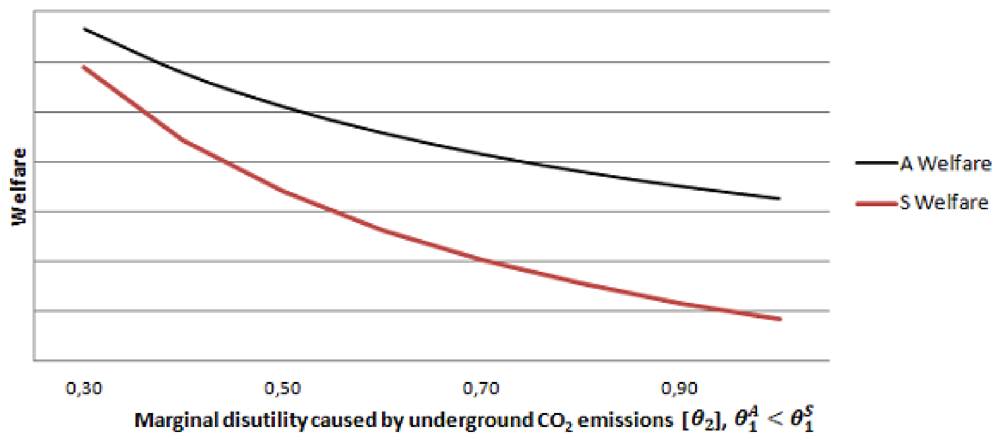


Table 1: Techno-economic assumptions required to run numerical simulations

Fixed parameters	Character	Value	Comments
Production CO_2 content	α^a	0.76	tCO_2/MWh
Coal price [b]	q	0.09	€/kg
CCS cost [c]	ϕ	0.046	€/kg
Coefficient of the production function	β	0.5	-

Table 2: Variation range for the parameters featuring social acceptance

Variable parameters	Character	Range
Marginal disutility due to atmospheric emissions of pollutants	θ_1	[0.10;1]
Marginal disutility due to underground emissions of pollutants	θ_2	[0.10;1]
Marginal disutility due to atmospheric and underground emissions of pollutants	ϵ	[0;0.35]

Table 3: Variation range for the parameters featuring social acceptance - geographical approach

Variable parameters	Character	Range
Marginal disutility due to atmospheric emissions of pollutants in the country A	θ_1^A	[0.10;1]
Marginal disutility due to atmospheric emissions of pollutants in the country S	θ_1^S	[0.10;1]
Marginal disutility due to underground emissions of pollutants	θ_2	[0.10;1]
Marginal disutility due to atmospheric and underground emissions of pollutants	ϵ	[0;0.3]

Table 4: Social acceptance parameters for four kinds of countries[a]

Country	θ_1	θ_2
Poland	0.4	1
Germany	0.7	1
Norway	0.7	0.4
United States	0.4	0.4

[a] $\epsilon = 0.01$

Table 5: Social welfare simulations for four kinds of countries

	Germany with CCS	Poland with CCS	Norway with CCS	USA with CCS
Germany	X	$W_A = 1.1$ $W_S = 1.5$	$W_A = 1.5$ $W_S = 1.6$	$W_A = 1.3$ $W_S = 1.7$
Poland	$W_A = 1.6$ $W_S = 1.2$	X	$W_A = 1.8$ $W_S = 1.6$	$W_A = 1.6$ $W_S = 1.7$
Norway	$W_A = 1.2$ $W_S = 1.2$	$W_A = 1.1$ $W_S = 1.5$	X	$W_A = 1.3$ $W_S = 1.7$
USA	$W_A = 1.4$ $W_S = 1.5$	$W_A = 1.6$ $W_S = 1.2$	$W_A = 1.8$ $W_S = 1.6$	X

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Contact us :
Chaire Economie du Climat - Palais Brongniart (4e étage)
28 Place de la Bourse, 75 002 Paris
Tel : +33 (0)1 73 01 93 31

Email : contact@chaireeconomieduclimat.org

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