Impact of uncertain CCS deployment on EU climate negotiations

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Abstract

In this paper we propose a stochastic non-cooperative meta-game approach to assess the role of uncertain CCS deployment on climate agreements among 28 European countries. The game model is identified through statistical emulation of a large set of numerical simulations performed with the computable general equilibrium model GEMINI-E3. In this game the players are the 28 European countries, the payoffs are related to the welfare losses due to abatements and the strategies correspond to the supply of emission rights on the European carbon market. The paper then analyzes the potential contribution of the penetration of Carbon Capture and Storage (CCS) technologies to European CO_2 abatements and the impact of CCS uncertainty pertaining to the rate of penetration of CCS technologies and to their cost on the design of burden sharing agreements.

1 Introduction

In this paper we use a stochastic meta-game approach to analyze and assess the role of the uncertain CCS deployment on the sharing among the 28 European MSs of the burden of implementing the EU 2050 climate target. We call our approach "meta-modeling" since the game model is identified through statistical emulation of a large set of numerical simulations performed with the computable general equilibrium (CGE) model GEMINI-E3 as proposed in [21] and we apply stochastic programming to take into consideration uncertainty of CCS deployment. We formulate a stochastic non-cooperative game where the players are the 28 European MSs, the payoffs are related to the welfare losses, expressed as the compensating variation of income (CVI) plus the gains from the terms of trade (GTT), and where the degree of freedom (or strategic variable) for each MS corresponds to choosing the share of its emission rights to be exchanged on an European carbon market (we assume a competitive market for emissions permits, which clears at each period).

This game model is inspired from [13, 24], where international emission trade in the absence of cooperative climate policy is studied. In these papers, it is shown that the permit endowments can be

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considered as strategic variables while the countries implement a cost/benefit approach taking into account damage cost due to climate change and welfare loss due to abatement cost. In our formulation we have opted for a cost/effectiveness approach, by replacing the damage cost function by a constraint on the cumulative emissions over the 2011-2050 period. The game is thus subject to a coupled constraint, in the sense proposed by Rosen [39], corresponding to the global emission budget decided by the EU over the planning horizon 2050. A game with coupled constraints admits a manifold of normalized equilibrium as shown in [39]. It has been shown [2] that this manifold of normalized equilibria corresponds to the set of Nash equilibria in the games with decoupled constraints defined when one considers the different possible distributions or allocations of the global emission budget to the different countries participating in the agreement. One may then look for an allocation that would lead to a Nash equilibrium solution which is "balanced" i.e. which tends to equalize the relative welfare losses for all countries. The balanced normalized equilibrium solution is then compared with different allocation rules of the EU emission budget that have been proposed in the burden sharing literature. The paper also analyzes the potential contribution of the penetration of Carbon Capture and Storage (CCS) technologies to the European CO_2 abatements. Indeed CCS has recently been presented as a key technology for abatement [31]. IEA [26] found that in a 2^oC scenario (i.e. a scenario leading to a 2^oC warming by the end of the century), CCS could contribute to 14% of the cumulative emissions reduction between 2015 and 2050. As CCS technologies are not explicitly described by GEMINI-E3 model, we integrate the CCS option into the meta-game as a backstop technology with uncertainties on its cost and potential deployment. This leads us to formulate and solve a stochastic dynamic game model, using the S-adapted equilibrium solution concept [22, 23].

The paper is organized as follows. In Section 2, we briefly present the EU climate agenda and analyze the policies that have already been implemented on this issue. Then, we formulate the stochastic dynamic game model that will be used to assess the burden sharing for 28 EU countries and the impact of uncertainty on CCS deployment. Section 4 is dedicated to implementation issues. In Section 5, we report the numerical solutions for the equilibria under stochastic assumptions and give the interpretation in terms of distribution of effort among the EU countries. Finally, in section 6 we conclude.

2 EU climate negotiations: agenda and modelling

2.1 The EU climate agenda

Since the Kyoto Protocol, EU has pushed hard for a stringent climate policy, and it must be recognized that Europe is one of the leading regions in fighting global warming [9]. Even though, after the US rejection, the Kyoto Protocol is considered as symbolic policy on a global scale [11], it is widely recognized that its implementation in the EU is a success. At Kyoto, EU was initially committed to a 8% abatement of GHG emissions with respect to 1990 levels during the period 2008-2012. In 1998, the European countries have agreed to share the burden of this abatement non-uniformly across countries on the basis of several criteria [34]. Among them we find the historical emissions, the level of economic development and the abatement opportunities. Table 1 gives the burden sharing of the Kyoto protocol adopted in 1998. The implementation of the GHG emissions committed at Kyoto followed a subsidiary principle where each of the MSs must define its domestic policy to achieve the required abatement while taking into account the local existing situation.

The "Energy–Climate" directive adopted in 2008 has divided the European economy into two parts: (i) the sectors subject to the European Trading Scheme (ETS) chosen among the most energy-intensive ones (mainly electricity generation), and (ii) all other sectors (non-ETS) including households and their fossil energy consumption. The ETS, a central pillar of the EU climate policy, is the first cap and trade

Table 1: EU burden sharing of the Kyoto Protocol (reduction from 1990 levels)

Austria	-13.0%
Belgium	-7.5%
Denmark	-21.0%
Finland	0.0%
France	0.0%
Germany	-21.0%
Greece	25.0%
Ireland	13.0%
Italy	-6.5%
Luxembourg	-28.0%
Netherlands	-6.0%
Portugal	27.0%
Spain	15.0%
Sweden	4.0%
United Kingdom	-12.5%
EU-15	-8.0%

system dedicated to carbon emissions that has been implemented at an international level. It defines for each participant a cap on CO_2 emissions, and allows them to buy or sell carbon credits. The ETS applies to the 28 EU MSs as well as to 3 of the 4 members of the European Free Trade Association (Norway, Iceland, and Liechtenstein). It covers 45% of EU GHG emissions and more than 11'000 energy-intensive plants in power generation and manufacturing industry. In the non-ETS sectors, targets have been set for each country, after a bargaining process between MSs. The Directive does not set nor even recommend tools for reaching the targets in the non-ETS sectors, and the member countries are free to select the most appropriate ones. The "Energy–Climate" directive established also a European GHG emissions target for 2020, set at 80% of their 1990 levels. Finally the Directive set two other goals regarding the energy efficiency that has to improve by 20% in 2020 and the share of renewables that have to represents 20% of total energy consumption in 2020. The 20% targets was strengthened in the Copenhagen COP-15 agreement, where EU committed to a more stringent target equal to 30% provided other developed countries commit to comparable cuts.

The declared EU goal is to limit global warming to 2^oC at the end of the century that, according to the authors in [35], can be translated into a limit on cumulative emissions budget of CO_2. This requires an increase of the abatement after 2020 and a worldwide reduction of 50% of GHG emissions in 2050. As mentioned in the introduction, the EU Commission confirmed in [18] the GHG reduction objective of 80-95% in 2050 compared to 1990 levels. A recent modelling analysis [18] has shown that the pathway to a low carbon society requires a 40% reduction of GHG emissions by 2030 and 60% reduction by 2040. Figure 1 displays the two pathways associated to 80% and 95% reduction by 2050.

In the following analysis on the design of EU climate agreements, we constrain MSs to satisfy a global EU emissions budget for the period 2011-2050. We estimate this budget to be compatible with the pathway associated to 80% reduction by 2050 on Figure 1. It leads to a budget of 99 Gt CO_2.

2.2 A dynamic game meta-model

In classical approaches, the design of climate agreements is usually the result of a fully normative approach, where a benevolent planner (e.g., UN) completely organizes the international permit trading system. Not only does it decide the share of the budget which is given to each country, but it also decides, at each period how much of this share is allocated to this period by the region. These approaches totally bypass the possibility which exists for each country to exploit strategically its share of the safety emission budget.

In this section, we formulate a stochastic dynamic game that helps to model and assess these non-cooperative climate strategies. In this game, the players are the 28 European countries, the strategies are the supply schedules of emission rights on the European carbon market and the development of CCS technologies while the payoffs are the discounted sum of welfare gains (or losses). A coupled constraint on the global emission budget is imposed. A first version of the model taking its inspiration from [24] has been proposed in [1, 21] to analyze a fair distribution of effort among 12 coalitions of countries in the world. We extend here this work by considering uncertain penetration and cost of CCS technologies and by applying this methodology to the European context. This leads us to formulate a stochastic dynamic game as in [14], which is played under the S-adapted information structure, which means that the players define strategies that are adapted to the history of the random perturbations that affect the system.

3 A game model

3.1 Nonlinear capture and sequestration cost

We first give a general deterministic formulation of the game with consideration of CCS deployment. There are m countries indexed $j = 1, \ldots, m$, that generate emissions e_j^t on periods $t \in \{0, 1, \ldots, T-1\}$. The model assumes:

1. **A competitive market for emissions permits**, which clears at each period, we denote $(\omega_j^t)_{j=1,\ldots,m}$ the vector of endowment in permits for country j at period t, $\Omega^t = \sum_{j=1}^m \omega_j^t$ the total supply of permits on the market at period t and $p^t(\Omega^t)$ the permit price function at period t.
2. **A safety emissions budget** called `Bud` which represents a global limit on cumulative emissions from all countries over the T periods. This global budget is distributed among the players. Let $\theta_j \in (0, 1)$ be the share of player j, with $\sum_{j=1}^m \theta_j = 1$. The θ parameters are thus design variables that will change the game structure, and therefore the equilibrium solution.
3. **CCS opportunities**. We introduce in the model the possibility to exploit CCS as a backstop technology. We assume that this technology will become available from period $\bar{t}$, where $0 < \bar{t} < T-1$. We denote u_j^t the amount of emissions of country j sequestered at period t at cost $C_j^t(u_j^t)$. The capture and sequestration is indeed level is upper bounded by the emission level

$$u_j^t \le e_j^t. \tag{1}$$

   Note that sequestered emissions can by constrained by the technological CCS development, geological capacities and/or the share of domestic emissions candidate for CCS. We denote $\overline{ccs}_j^t$ the upper bound for sequestration for country j at period t. Therefore, we assume that the nominal sequestration cost is convex and satisfies

$$\lim_{u_j^t \to \overline{ccs}_j^t} C_j^t(u_j^t) = \infty.$$

Let us consider the game where each player (country) j defines for itself a permit endowment schedule $(\omega_j^t : t = 0, \ldots, T-1)$. The total supply of permits on the market at period t is $\Omega^t = \sum_{j=1}^m \omega_j^t$. The emission levels and the amount of carbon that will be sequestrated using CCS technology is determined by the market at each period, so the payoff to player j is defined by

$$\sum_{t=0}^{T-1} \beta_j^t(\pi_j^t(\mathbf{e}_j^t(\Omega^t)) + p^t(\Omega^t)(\omega_j^t - \mathbf{e}_j^t(\Omega^t) + u_j^t(\Omega^t)) - C_j^t(u_j^t(\Omega^t)), \tag{2}$$

where each player i, $i = 1, \dots, m$, chooses $(\omega_i^t, t = 1, \dots, T-1)$ so that the budget sharing constraint

$$\sum_{t=0}^{T-1} \omega_i^t \leq \theta_i \texttt{Bud}, \tag{3}$$

remains satisfied.

Here β_j^t is a discount factor and $\pi_j^t(e_j^t)$ represents the economic benefits obtained from emissions by country j, at time t. One assumes positive diminishing marginal returns, i.e. $\pi_j^{t\prime}(e_j^t) > 0$ and $\pi_j^{t\prime\prime}(e_j^t) < 0$.

We assume a competitive market for emissions permits, which clears at each period. Given a price p^t, the producers in each country choose emissions and sequestration in order to optimize their margins, i.e. they solve

$$\max_{e_j^t, u_j^t} \left\{ \pi_j^t(e_j^t) + p^t(\omega_j^t - \mathbf{e}_j^t(\Omega^t) + u_j^t) - C_j^t(u_j^t) \right\}. \tag{4}$$

s.t

$$0 \leq u_j^t \leq e_j^t. \tag{5}$$

Assuming that the constraints (31) are not active, the equilibrium conditions of profit maximization and market clearing at period t are then

$$\begin{aligned} C_j^{t'}(u_j^t) &= p^t \quad j = 1, \dots, m, && (6)\\ \pi_j^{t'}(e_j^t) &= p^t \quad j = 1, \dots, m, && (7)\\ \Omega^t + \sum_{j=1}^m u_j^t &= \sum_{j=1}^m e_j^t. && (8) \end{aligned}$$

This system implicitly defines after-trade equilibrium emissions, $\mathbf{e}_j^t(\Omega^t)$, capture and sequestration levels $u_j^t(\Omega^t)$ and the permit price $\mathbf{p}^t(\Omega^t)$. Differentiating (6)-(21) we obtain

$$\begin{aligned} C_j^{t''}(u_j^t(\Omega^t))u_j^{t'}(\Omega^t) &= p^{t'}(\Omega^t) \quad j = 1, \dots, m, && (9)\\ \pi_j^{t''}(e_j^t(\Omega^t))e_j^{t'}(\Omega^t) &= p^{t'}(\Omega^t) \quad j = 1, \dots, m, && (10)\\ 1 + \sum_{j=1}^m u_j^{t'}(\Omega^t) &= \sum_{j=1}^m e_j^{t'}(\Omega^t). && (11) \end{aligned}$$

We can then compute the derivatives

$$\begin{aligned}
\mathbf{p}^{t'}(\Omega^t) &= \frac{1}{\sum_{j=1}^m \left(\frac{1}{\pi_j^{t''}(\mathbf{e}_j^t(\Omega^t))} - \frac{1}{C_j^{t''}(u_j^t(\Omega^t))} \right)} && (12)\\
\mathbf{e}_j^{t'}(\Omega^t) &= \frac{1}{\sum_{i=1}^m \left(\frac{\pi_j^{t''}(\mathbf{e}_j^t(\Omega^t))}{\pi_i^{t''}(\mathbf{e}_i^t(\Omega^t))} - \frac{\pi_j^{t''}(\mathbf{e}_j^t(\Omega^t))}{C_i^{t''}(u_i^t(\Omega^t))} \right)} && (13)\\
u_j^{t'}(\Omega^t) &= \frac{1}{\sum_{i=1}^m \left(\frac{C_j^{t''}(u_j^t(\Omega^t))}{\pi_i^{t''}(\mathbf{e}_i^t(\Omega^t))} - \frac{C_j^{t''}(u_j^t(\Omega^t))}{C_i^{t''}(u_i^t(\Omega^t))} \right)}. && (14)
\end{aligned}$$

The Kuhn-Tucker conditions for a Nash equilibrium of the meta-game, where the strategic variables are the permit supplies ω_j^t are thus obtained as follows

$$\begin{aligned}
0 &= \beta_j^t(\pi_j^{t'}(\mathbf{e}_j^t(\Omega^t)) + p^{t'}(\Omega^t)(\omega_j^t - \mathbf{e}_j^t(\Omega^t) + u_j^t(\Omega^t)) - \nu_j && (15)\\
0 &= \nu_j(\theta_j \mathtt{Bud} - \sum_{t=0}^{T-1} \omega_j^t) && (16)\\
0 &\le \theta_j \mathtt{Bud} - \sum_{t=0}^{T-1} \omega_j^t && (17)\\
0 &\le \nu_j. && (18)\\
& t = 0, \ldots, T-1; \quad j = 1, \ldots, m.
\end{aligned}$$

Here, we have used the fact that $\pi_j^{t'}(\mathbf{e}_j^t(\Omega^t) = p^t(\Omega^t) = C_i^{t'}(u_i^t(\Omega^t))$.

3.2 The simpler case of linear CCS cost

Let us assume that the capture and sequestration cost is defined as a linear function $C_j^t(u_j^t) = c_j^t u_j^t$ if $0 \le u_j^t \le \overline{ccs}_j^t$ and $C_j^t(\overline{ccs}) = \infty$ if $u_j^t > \overline{ccs}_j^t$.

Then, the equilibrium conditions (6)-(8) become

$$\begin{aligned}
u_j^t &= \begin{cases} \overline{ccs}_j^t \text{ if } p^t \ge c_j^t \\ 0 \text{ otherwise} \end{cases} \qquad j = 1, \ldots, m, && (19)\\
\pi_j^{t'}(e_j^t) &= p^t \quad j = 1, \ldots, m, && (20)\\
\Omega^t + \sum_{j=1}^m u_j^t &= \sum_{j=1}^m e_j^t. && (21)
\end{aligned}$$

Then almost everywhere the following holds true

$$\begin{aligned}
\mathbf{p}^{t'}(\Omega^t) &= \frac{1}{\sum_{j=1}^m \frac{1}{\pi_j^{t''}(\mathbf{e}_j^t(\Omega^t))}} && (22)\\
\mathbf{e}_j^{t'}(\Omega^t) &= \frac{1}{\sum_{i=1}^m \frac{\pi_j^{t''}(\mathbf{e}_j^t(\Omega^t))}{\pi_i^{t''}(\mathbf{e}_i^t(\Omega^t))}} && (23)\\
u_j^{t'}(\Omega^t) &= 0. && (24)
\end{aligned}$$

If the capture and sequestration levels happens to be constantly at their upper bounds the first order necessary conditions for a Nash equilibrium of the upper-game are now

$$
\begin{aligned}
0 &= \beta_j^t(\pi_j^{t\prime}(\mathbf{e}_j^t(\Omega^t)) + p^{t\prime}(\Omega^t)(\omega_j^t - \mathbf{e}_j^t(\Omega^t) + \overline{ccs}_j^t) - \nu_j & (25)\\
0 &= \nu_j(\theta_j \mathtt{Bud} - \sum_{t=0}^{T-1} \omega_j^t) & (26)\\
0 &\leq \theta_j \mathtt{Bud} - \sum_{t=0}^{T-1} \omega_j^t & (27)\\
0 &\leq \nu_j. & (28)\\
& t = 0, \dots, T-1; \quad j = 1, \dots, m.
\end{aligned}
$$

Here, we have used the fact that $\pi_j^{t\prime}(\mathbf{e}_j^t(\Omega^t) = p^t(\Omega^t)$ whereas $u_i^{t\prime}(\Omega^t) = 0$.

3.3 Uncertainties on CCS deployment

We now extend the model to an S-adapted formulation to take into consideration uncertain CCS costs. We introduce a set $S_{\bar{t}}$ of contrasted scenarios for CCS costs after the period $\bar{t}$. We will give a probability $\mathcal{P}(s)$ to each scenario s. Each decision and state variables are now indexed on s for $t \geq \bar{t}$.

To take the uncertainty into account, the game is formulated over an event tree, as defined in [22]. We will characterize the S-adapted equilibria, as defined in [23]. In the S-adapted information structure each player (country) j defines for itself a permit endowment schedule and a sequence of sequestration actions using CCS technology which must be adapted to the history of the stochastic perturbation, as represented by the event tree.

The payoff of player j in an S-adapted equilibrium satisfies :

$$
\begin{aligned}
\max_{\omega_j} \quad & \Big\{ \sum_{t<\bar{t}} (\beta_j^t(\pi_j^t(\mathbf{e}_j^t(\Omega^t)) + p^t(\Omega^t)(\omega_j^t - \mathbf{e}_j^t(\Omega^t))) + & (29a)\\
& \sum_{s\in S} \mathcal{P}(s) \sum_{t\geq\bar{t}} (\beta_j^t(\pi_j^t(\mathbf{e}_j^t(\Omega^t, s)) + p^t(\Omega^t, s)(\omega_j^t(s) - \mathbf{e}_j^t(\Omega^t, s) + & (29b)\\
& u_j^t(\Omega^t, s)) - C_j^t(u_j^t(\Omega^t, s))) \Big\}, & (29c)
\end{aligned}
$$

subject to actions chosen by the other players and under the budget sharing constraint

$$
\sum_{t<\bar{t}} \omega_j^t + \sum_{t\geq\bar{t}} \omega_j^t(s) \leq \theta_j \mathtt{Bud}, \quad \forall s \in S. \tag{30}
$$

and CCS capacity constraints

$$
0 \leq u_j^t(\Omega^t, s) \leq e_j^t(\Omega^t, s), \quad \forall t \geq \bar{t},\ \forall s \in S. \tag{31}
$$

Applying standard Kuhn-Tucker multiplier method on (29), one can define a system of first order conditions for a Nash equilibrium. This system characterizes an equilibrium in a supply strategy of emission permits, adapted to the history of random events, when a repartition of the global budget is given, i.e. when the parameters θ_j are fixed. If we adopt a Rawlsian [38] approach to distributive justice, the optimal game design problem consists in finding the θ_j's in such a way that one minimizes the largest average welfare loss among the countries. In order to have comparable measures of welfare losses, we use in this paper the criterion corresponding to the ratio of the welfare loss to the total consumption in the BAU scenario.

The first order necessary conditions for a Nash equilibrium are now

$$\begin{array}{rcll} 0 & = & \beta_j^t(\pi_j^{t'}(\mathbf{e}_j^t(\Omega^t)) + p^{t'}(\Omega^t)(\omega_j^t - \mathbf{e}_j^t(\Omega^t)) - \sum_{s\in S}\mathcal{P}(s)\nu_j(s),\ \forall t < \bar{t},\ \forall j. & (32) \\ 0 & = & \beta_j^t(\pi_j^{t'}(\mathbf{e}_j^t(\Omega^t), s) + p^{t'}(\Omega^t, s)(\omega_j^t(s) - \mathbf{e}_j^t(\Omega^t, s) - \mathrm{ccs}_j^t(s)) - C_j^t(s) & (33) \\ & & -\nu_j(s),\ \forall t \geq \bar{t},\ \forall j,\ \forall s \in S. & (34) \\ 0 & = & \nu_j(s)(\theta_j \mathtt{Bud} - \sum_{t<\bar{t}}\omega_j^t - \sum_{t\geq\bar{t}}\omega_j^t(s))\ \forall j,\ \forall s \in S & (35) \\ 0 & \leq & \theta_j \mathtt{Bud} - \sum_{t<\bar{t}}\omega_j^t - \sum_{t\geq\bar{t}}\omega_j^t(s)\ \forall j,\ \forall s \in S & (36) \\ 0 & \leq & \overline{ccs}_j^t(s) - ccs_j^t(s),\ \forall t \geq \bar{t},\ \forall s \in S & (37) \\ 0 & \leq & \nu_j(s),\ \forall j,\ \forall s \in S. & (38) \end{array}$$

4 Implementation issues

In this section we calibrate the stochastic dynamic game model, using the CGE GEMINI-E3 as the provider of the data used in the estimation of the abatement cost functions for each EU country. We also give our assumptions on CCS deployment.

4.1 Estimation of the abatement cost functions

GEMINI-E3, a CGE model. GEMINI-E3 [7] [1] is a multi-country, multi-sector, recursive CGE model comparable to other CGE models (EPPA, ENV-Linkage, etc) built and implemented by other modeling teams and institutions, and sharing the same long experience in the design of this class of economic models. The standard model is based on the assumption of total flexibility in all markets, both macroeconomic markets such as the capital and the exchange markets (with the associated prices being the real rate of interest and the real exchange rate, which are then endogenous), and microeconomic or sector markets (goods, factors of production). GEMINI-E3 has been extensively used to derive total costs and benefits of various energy and climate policies. The GEMINI-E3 model is now built on a comprehensive energy-economy dataset, the GTAP-8 database [36]. This database incorporates a consistent representation of energy markets in physical units, social accounting matrices for each individualized country/region, and the whole set of bilateral trade flows. Additional statistical information accrues from OECD national accounts, IEA energy balances and energy prices/taxes and IMF Statistics. We use an European version of GEMINI-E3 that described 8 sectors/goods and the 28 European member states plus a remaining region representing non-EU countries (called Rest Of the World). Table 2 gives statistics on CO_2 emissions, GDP and population for each European countries.

A business as usual scenario. We build a business as usual (BAU) scenario on the period 2007-2050 with yearly timesteps. Assumptions on population and GDP are based on the recent joint work of the Economic Policy Committee and the European Commission (DG ECFIN) published in 2011 [19]. They

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[1] All information about the model can be found at `http://gemini-e3.epfl.ch`, including its complete description.

Table 2: Contribution of European countries to CO_2 emissions, GDP, and population in percentage and economic and environmental indicators- year 2010 - Source [25]

	CO_2	GDP	Population	CO_2 capita^a	GDP per capita^b
Austria (AUT)	1.9%	2.3%	1.7%	8.3	38935
Belgium (BEL)	3.1%	2.8%	2.1%	10.6	36829
Bulgaria (BGR)	1.2%	0.2%	1.5%	6.0	4379
Cyprus (CYP)	0.2%	0.1%	0.2%	8.9	23882
Czech Republic (CZE)	3.1%	1.0%	2.1%	11.0	14118
Germany (DEU)	20.8%	20.5%	16.1%	9.5	36193
Denmark (DAN)	1.3%	1.8%	1.1%	8.5	46394
Estonia (EST)	0.5%	0.1%	0.3%	14.9	10450
Finland (FIN)	1.7%	1.4%	1.1%	11.9	38053
France (FRA)	9.6%	15.3%	12.8%	5.5	34029
United Kingdom (GBR)	13.1%	16.4%	12.3%	7.9	37955
Greece (GRC)	2.2%	1.7%	2.2%	7.2	21308
Croatia (HRV)	0.5%	0.3%	0.9%	4.4	10475
Hungary (HUN)	1.3%	0.8%	2.0%	4.9	10936
Ireland (IRL)	1.0%	1.4%	0.9%	8.5	45386
Italy (ITA)	10.6%	12.2%	11.9%	6.6	29163
Latvia (LAT)	0.2%	0.1%	0.4%	3.6	6924
Lithuania (LIT)	0.4%	0.2%	0.6%	4.2	8320
Luxembourg (LUX)	0.3%	0.3%	0.1%	20.8	81219
Malta (MLT)	0.1%	0.0%	0.1%	6.3	15993
Netherlands (NLD)	5.1%	4.7%	3.3%	11.5	41160
Poland (POL)	8.5%	2.6%	7.6%	8.2	9933
Portugal (POR)	1.3%	1.4%	2.1%	4.6	18536
Romania (ROU)	2.1%	0.8%	4.2%	3.6	5334
Spain (SPN)	7.2%	8.2%	9.1%	5.8	25588
Slovak Republic (SVK)	1.0%	0.4%	1.1%	6.7	11081
Slovenia (SVN)	0.4%	0.3%	0.4%	7.5	19037
Sweden (SWE)	1.4%	2.8%	1.9%	5.5	42822
EU-28	100.0%	100.0%	100.0%	7.4	28519

^{a} ton of CO_2

^{b} 2005 US dollars using market exchange rate

suppose that European GDP will grow by 1.6% per year on the period 2010-2050. Evolution of energy prices are based on assumptions on the *current policies* scenario of the *World Energy Outlook 2013* of the International Energy Agency [27]. The oil price is assumed to reach 162$ in 2050, the price of imported gas in Europe is equal to 15.6$ per Mbtu in 2050, and the price of steam coal imported in OECD countries reaches 125$ per ton in 2050.

Note that, in this BAU scenario, no climate policy is implemented since it will serve to evaluate the burden for each participating country of implementing the European climate policy, considering 2050 target as well as existing 2020 objectives. Associated CO_2 emissions computed by GEMINI-E3 are presented in Figure 1. In 2050, the total of European CO_2 emissions reaches 4'625 $MtCO_2$ corresponding to an annual growth rate of 0.5%. Our BAU is consistent with the "no-policy baseline scenario" performed within the EMF28 project [30] where most of the models suggest a more modest increase of CO_2 emissions. Our emissions will generate a cumulative emissions budget of 173 Gt CO_2 over the period 2011-2050.

Statistical analysis of an ensemble of GEMINI-E3 numerical simulations. We apply regression analysis to identify the payoff functions of a game where the strategic variables are the quotas supplied on an EU emissions trading scheme by the different regions, at different periods. The statistical analysis is based on an ensemble of 200 numerical simulations of different possible European climate policy scenarios performed with GEMINI-E3. In each scenario, we assume that a carbon tax is implemented at the European level without emissions trading. We suppose that only carbon emissions are taxed. We compute for each group of countries:

- The abatement level relative to the BAU emissions ($\bar{e}_j^t$) expressed in million ton of carbon; The abatement is thus defined by $\bar{e}_j^t - e_j^t$

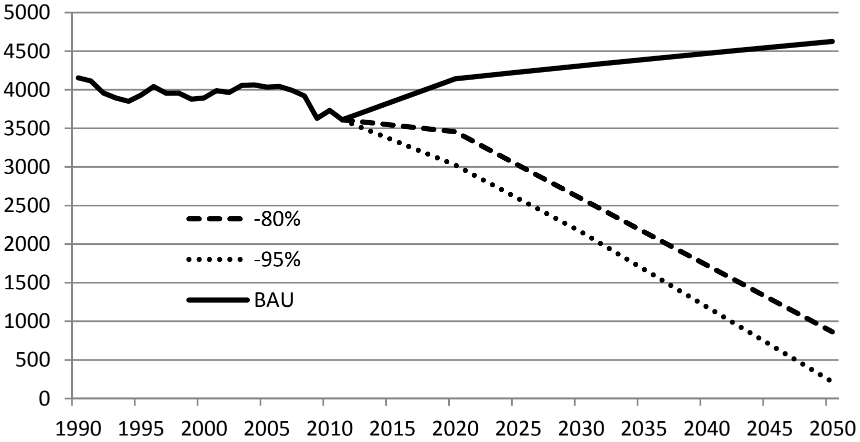

Figure 1: EU CO_2 emissions in the BAU scenario (1990-2010: Historical, 2011-2050: GEMINI-E3 BAU scenario) and climate targets in Mt CO_2

- The welfare cost measured by the households' surplus, and represented by the CVI expressed in US \$ [8];
- The GTT representing the spill-over effects due to changes in international prices. In a climate change policy these GTT come mainly from the drop in fossil energy prices due to the decrease of world energy demand. The GTT are expressed in US \$.

By subtracting the GTT from the surplus we obtain the deadweight loss of taxation i.e. the domestic cost that would occur in a closed economy and which only depends on the abatement done within the country. The GTT represents the imported cost: negative for energy exporting countries such as OPEC and positive for net energy importing countries like Europe and Japan [10]. This imported cost/benefit is function of the European carbon abatement.

Using regression analysis, we estimate the parameters $\alpha_j^1(t)$, $\alpha_j^2(t)$, $\alpha_j^3(t)$ and $\alpha_j^4(t)$ in a polynomial of degree 4 describing the abatement cost of player j and period t as a function of the abatement level (with constraint ${\pi_j^t}'(.) > 0$ and ${\pi_j^t}''(.) < 0$).

$$AC_j^t(e_j^t) = \alpha_j^1(t)\,(\bar{e}_j^t - e_j^t) + \alpha_j^2\,(\bar{e}_j^t - e_j^t)^2 + \alpha_j^3(t)\,(\bar{e}_j^t - e_j^t)^3 + \alpha_j^4(t)\,(\bar{e}_j^t - e_j^t)^4. \tag{39}$$

The time periods (t) are 2020, 2030, 2040, 2050 with 10 years for each period. Figure 2 presents the marginal abatement cost (MAC) curves for 28 EU member states (i.e. the derivative of the abatement cost function with respect to the abatement) estimated for the year 2020. It shows where it is the cheapest to abate carbon emissions (Germany, Slovakia, Estonia, Romania, Bulgaria, Poland and Czechoslovakia) and where it is the most expensive (Sweden, Luxembourg, Cyprus, Malta, Latvia).

The GTT of player j is assumed to be a linear function of the global abatement in a given period

$$GTT_j^t(e_j^t) = \mu_j(t) \sum_i (\bar{e}_i^t - e_i^t). \tag{40}$$

Using these definitions, the economic benefits $\pi_j^t(.)$ introduced in (29) is defined as the opposite of welfare loss induced by abatement such as

$$\pi_j^t(e_j^t) = GTT_j^t(e_j^t) - AC_j^t(e_j^t).$$

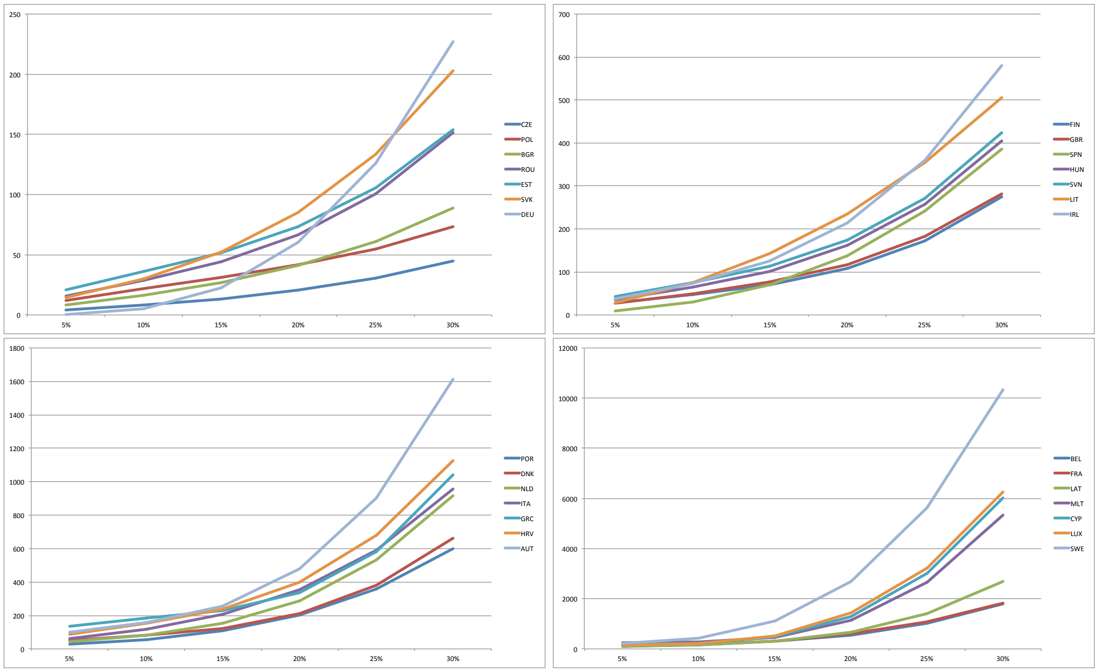

Figure 2: Estimated MAC functions in 2007 US \$ per CO_2 equivalent for the year 2020, proportional abatement

4.2 European CO_2 storage capacity and deployment

The estimation of the potential of CO_2 storage in 25 of the 28 European countries considered in this paper is based on capacity estimates provided by the EU-FP6 project GeoCapacity [20, 44] for deep salines aquifers, hydrocarbon fiels and coal beds for the European sedimentary basins suitable for CO_2 storage. The capacity estimates rely on effective storage capacity as defined by Carbon Sequestration Leadership Forum. Regarding the countries not represented in the GeoCapacity project (i.e. Austria, Cyprus, Estonia, Finland, Ireland, Malta and Portugal), we use the following sources to consolidate the GeoCapacity estimates [40, 33, 32, 28]. Finally, concerning Cyprus and Malta, due to the lack of statistical information, we assume no CO_2 storage potential. Based on these estimations, the total European CO_2 storage potential is found to be 72 Gt CO_2. This corresponds to around 19 years of current European annual emission of carbon dioxide. Deep saline aquifers represent 70% of the storage capacity. Note that, according to [5], the evaluation of these fiels is very complex and should therefore be considered with caution.

While CCS is expected to play an important role in climate policies, its deployment is subject to technical, social and legislative uncertainties. Several studies have analyzed the role of the CCS in the European energy transition under different assumptions concerning the treatment of uncertainties. First, we retain the *EU Reference scenario 2013* published by the European Commission [17]. This reference scenario, elaborated with the PRIMES model, determines the development of the EU energy system under current trends and adopted policies until spring 2012. This concerns various policies on energy efficiency, power generation, climate and transport[2]. The scenario assumes the implementation of an ETS with a price of 100 € per ton of CO_2 in 2050. CCS-equipped facilities penetrate mainly after 2030 reaching 7% of electricity generation by 2050 and representing a capacity of 38 GWe. Another study performed on the POLES model [16] gives a similar capacity for the CCS deployment (i.e. 34 GWe) but

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[2] For a detail list of policies that are included see the Table 2 of the report.

for the year 2030 within a scenario that assumes a faster commercial availability of CCS in the power sector. In the Roadmap dedicated to CCS [26], IEA finds a more optimistic deployment where the European CCS-equipped generation capacity reaches 68 GWe in 2050. Finally a study that combines a techno-economic model of Europe's electricity sector with a model on CO_2 transport infrastructure [29] evaluates that about 15.2 Gt CO_2 would be captured over the period 2020-2050. Based on theses studies the CO_2 stored over the period 2020-2050 ranges from 670 Mt to 15 Gt CO_2 with intermediate values of 3 and 7 Gt[3].

In this paper, we use three contrasted scenarios of CCS cost each one being characterized by a uniform cost per ton of sequestered CO_2 and a maximum CCS potential in 2050 for each EU country j. To estimate these maximum CCS potentials in 2050, we first consider that CCS technologies will be implemented only on gas and coal power plants. Then maximum CCS potentials in 2050 correspond to a share of BAU emissions associated to these plants. Finally the penetration rate is assumed to be linear between 2030 and 2050. Note that CCS deployment is also bounded by national geological capacities and total emissions.

The three scenarios are defined as follows:

- **Optimistic**: The cost of CCS is 200 \$/tC and CCS technologies are expected to sequester all emissions from gas and coal power plants in 2050.
- **Medium**: The cost of CCS is 400 \$/tC and CCS technologies are expected to sequester half of emissions from gas and coal power plants in 2050. These assumptions are those that have been used in the deterministic scenario.
- **Pessimistic**: The cost of CCS is 600 \$/tC and CCS technologies are expected to sequester a quarter of emissions from gas and coal power plants in 2050.

Note that in these scenarios, a higher penetration comes with a lower CCS cost, and conversely. This reflects the expected economies of scale in technology deployment.

5 Numerical analysis

We present in this section the S-adapted equilibrium solutions when the players payoffs are obtained through statistical emulation of GEMINI-E3, as described above. In this computational economics exercise we use an annual discount factor equal to 5% and we impose a cumulative emissions budget of 99 Gt CO_2 which is consistent with the target of 80% reduction by 2050. Figure 3 gives a graphical representation of the three scenarios of CCS deployment (i.e., optimistic, medium and pessimistic) we consider in this analysis. They are as "equiprobable" and we suppose that the cost and the potential of CCS technology will be revealed in 2030.

Table 3 gives the budget shares that equalize the welfare costs in average among the three scenarios, the associated average welfare costs and finally the welfare costs associated to each scenario. On average the EU welfare cost is equal to 0.5% and close to the one computed under the deterministic scenario with medium assumptions. With the optimistic scenario, the EU welfare cost is reduced to 0.12% and it reaches 0.9% for the pessimistic assumption. In 2050, the CO_2 price ranges between 440 and 991 depending on the scenario.

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[3] Some studies do not give the cumulative CO_2 sequestered we approximate this value using some assumptions on the fuel used, the efficiency and the availability rate of the power plants equipped with CCS.

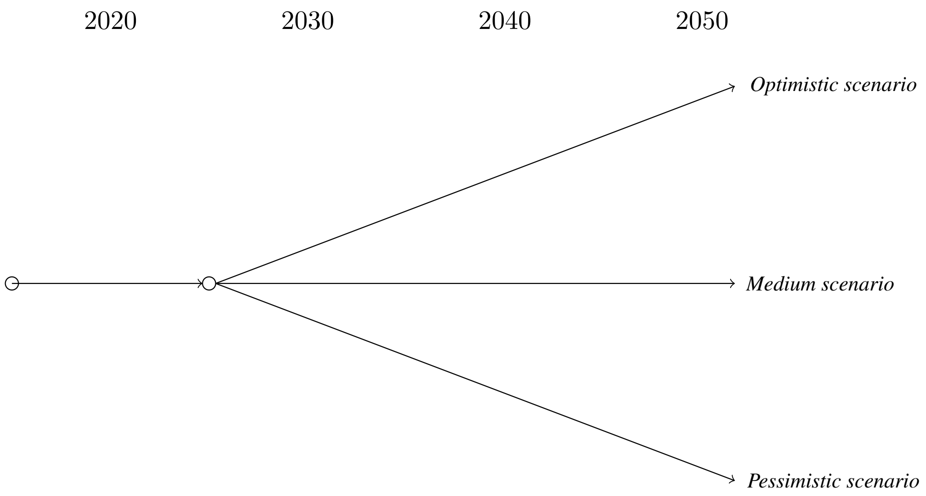

Figure 3: Event tree for CCS uncertainty

Table 3: Stochastic fair equilibrium and welfare losses (in %)

	Burden sharing	Welfare losses			
		Expected	Optimistic	Medium	Pessimistic
AUT	1.82	0.51	0.07	0.58	0.89
BEL	3.24	0.50	0.11	0.54	0.86
BGR	0.79	0.56	-0.42	0.57	1.53
CYP	0.40	0.53	-1.04	0.87	1.75
CZE	1.31	0.51	0.11	0.30	1.12
DEU	13.59	0.52	0.03	0.57	0.96
DNK	1.60	0.53	-0.51	0.63	1.46
EST	0.43	0.52	0.86	0.65	0.06
FIN	1.64	0.52	0.53	0.57	0.48
FRA	12.63	0.53	0.24	0.58	0.77
GBR	15.20	0.50	0.20	0.53	0.78
GRC	4.60	0.49	-1.32	0.82	1.96
HRV	0.87	0.51	0.24	0.56	0.74
HUN	1.26	0.54	0.04	0.60	1.00
IRL	1.34	0.50	-0.30	0.61	1.20
ITA	12.10	0.51	0.22	0.55	0.76
LAT	0.30	0.50	-0.06	0.60	0.96
LIT	0.29	0.54	-0.09	0.60	1.12
LUX	0.53	0.47	-0.56	0.65	1.31
MLT	0.13	0.50	-0.72	0.77	1.46
NLD	4.00	0.50	-0.32	0.59	1.24
POL	6.35	0.53	0.45	0.47	0.67
POR	1.45	0.48	-0.03	0.54	0.94
ROU	1.97	0.54	0.36	0.54	0.72
SPN	8.95	0.50	0.06	0.56	0.89
SVK	0.86	0.54	0.31	0.58	0.73
SVN	0.46	0.52	0.09	0.57	0.92
SWE	1.90	0.52	1.26	0.09	0.21
EU-28	100.00	0.51	0.12	0.55	0.87

Table 4: Permit prices in stochastic scenarios (in \$ per tCO_2)

	Optimistic	Medium	Pessimistic
2020	195	195	195
2030	132	219	272
2040	249	425	545
2050	440	761	991

As shown in Figure 4, in the optimistic scenario, the cumulative sequestered CO_2 reaches 21.4 Gt CO_2 which is quite high with respect to existing studies [17, 16, 25, 29]. It corresponds to 29% of the EU abatement that is required to achieve the 2°C target. Six countries exhaust the capacity of their reservoirs: Belgium, Czechoslovakia, Greece, Lithuania, Poland and Slovenia. In the medium and the pessimistic scenarios, the cumulative CO_2 sequestered is respectively equal to 11.1 and 5.5 Gt CO_2 which corresponds to the upper sample of the results previously cited.

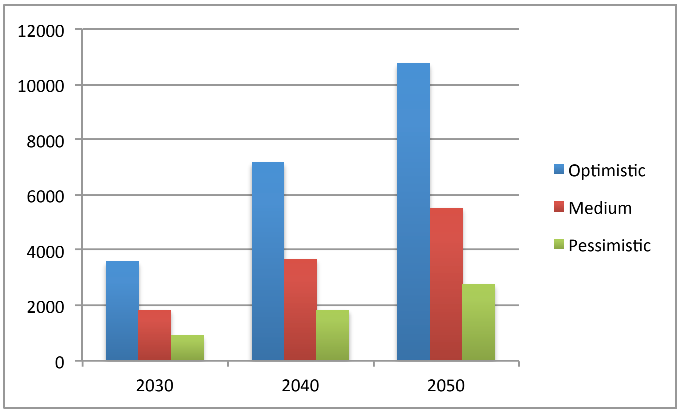

Figure 4: Carbon sequestered (in $MtCO_2$) per decade

One important result concerns the timing of abatement. Figure 5 describes the CO_2 emissions profile within the deterministic (i.e., under medium assumptions for CSS deployment) and the stochastic scenarios. The emissions profile in the deterministic scenario follows the CO_2 target as it was defined by the European Commission in the roadmap to a low carbon economy with slightly more abatements in the first commitment period (2020-2035) and less in the second period. In contrast, in the stochastic case, due to the risk associated to the CCS deployment, the optimal strategy related to CO_2 emissions is to abate more in the first decade with respect to the deterministic case. This precautionary principle that requires more abatement until the information on the potential of the CCS is revealed has already been shown in stochastic integrated assessment models with uncertain technological breakthrough and climate sensitivity [3, 4]. In addition to CCS penetration the exact contribution of renewable energy sources and energy efficiency improvements could also be considered as highly uncertain and thus included in the stochastic modeling.

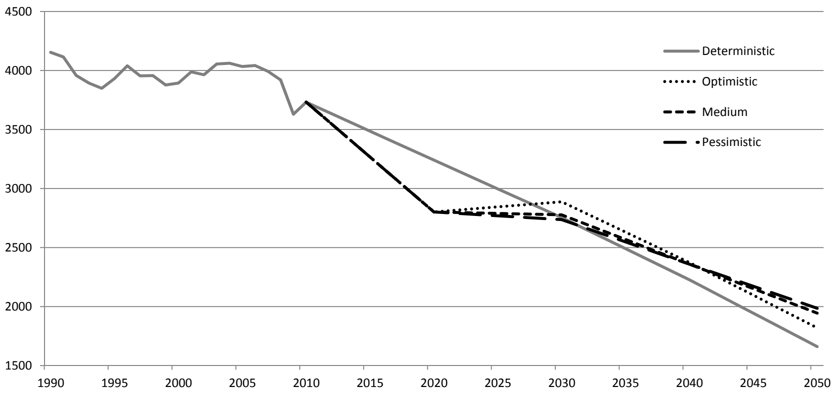

Figure 5: Emissions in stochastic scenarios (in $MtCO_2$)

6 Conclusion

In this paper we have proposed a stochastic meta-game approach based on statistical emulation of a comprehensive general economic equilibrium model to numerically simulate the burden sharing of the European roadmap to a low carbon economy on the 2050 horizon. Several insights can be drawn from this numerical exercice.

First we show that CCS is one key technology of the EU climate change policy. Indeed, under the different assumptions on the cost and the potential of CCS, the EU welfare cost ranges between to 0.12% and 0.87%. Our results indicates that until 2050 EU CO_2 storage capacities do not represent any physical limit on CCS deployment at least if we retain the estimates recently published by the GeoCapacity project. We also show that the CO_2 quotas as well as the quantity of sequestered CO_2 are concentrated in a limited number of European countries, i.e., United Kingdom, Germany, France, Italy, Spain and Poland.

Finally, our stochastic analysis, which assumes a certain CCS deployment but with uncertain costs and potentials, demonstrates that a postponement strategy for CO_2 abatement that we find within the deterministic scenario is no longer optimal. In other words, even if we know that CCS technologies will penetrate, one has to anticipate abatements to reduce the risk related on its deployment intensity.

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