ORDECSYS

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Robust equilibrium in a meta-game of burden-sharing for Europe climate policy

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Contents

Context

The facts:

- Climate policy is one of the corner stones of European Union (EU) policy
- European Commission has defined a roadmap with an objective of 80-95% GHG reduction in 2050 compared to 1990 levels
- Carbon Capture and Sequestration technologies are considered as potential backstop technologies (up to 14% of total abatements according to IEA)
- CCS deployment is highly uncertain with technical, social and legislative issues

Questions:

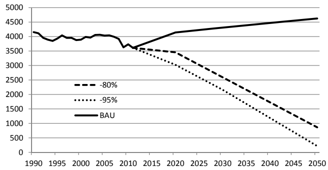
1. How to share the abatements or allocations? How to design a fair agreement among EU countries?
2. How each country will use its allocations on the horizon 2020-2050? What will be the associated costs for each country?
3. What impacts of CCS uncertainty on such agreements?

Objective and methodology

Propose a robust meta-game approach for assessing burden sharing agreements among the 28 EU-countries for the attainment of EU 2050 climate target.

Methodology:

1. Identify a global emissions budget on 2020-2050 compatible with EU objectives



2. Estimate abatement cost functions for each EU country using simulations of the Computable General Equilibrium model GEMINI-E3
3. Define a meta-game in which each country minimizes its costs according to a global share of allocations
4. Derive a robust/stochastic framework to analyze uncertainty on:
   - Meta-modelling approximations -¿ robust optimization
   - deployment of CCS technologies -¿ stochastic programming

A noncooperative meta-game approach

Assumptions:

1. **A safety emissions budget** *Bud* is distributed among the players. Let $\theta_j \in (0,1)$ be the share of player j, with $\sum_{j=1}^{m} \theta_j = 1$.
2. **A competitive market for emissions permits**, which clears at each period. Let ω_j^t be the vector of permits for country j at period t.
3. **An exogenous rate of CCS penetration**. We denote ccs_j^t the amount of emissions of country j sequestered at period t at cost C^t and $\overline{ccs}_j^t$ the upper bound for sequestration for country j at period t.

A noncooperative meta-game approach

Input Global budget *Bud* and allocations among countries (i.e., θ_j)

Model Minimize the economic impacts for each country by deciding:

1. How to use the budget on the horizon
2. Permit sales and buyings on the EU trading market
3. CO2 sequestered

Output Emissions, Permit exchanges, Permit prices, Percentage of welfare losses, ...

$\Rightarrow$ By testing different allocations, one can find a fair burden sharing. For example if we adopt a Rawlsian 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 welfare loss among the countries.

Maximizing welfare

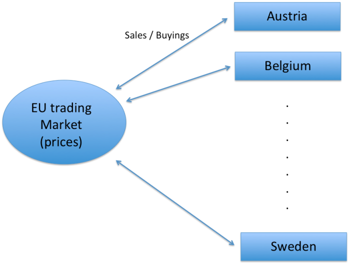
Then we consider the game where each player j controls the permit allocations schedule $(\omega_j^t : t = 0, \dots, T-1)$ with $\Omega^t = \sum_{j=1}^m \omega_j^t$ and tries to achieve

$$\max_{\omega_j, ccs_j \leq \overline{ccs}_j} \left\{ \sum_{t=0}^{T-1} \beta_j^t (\pi_j^t(\mathbf{e}_j^t(\Omega^t)) + p^t(\Omega^t)(\omega_j^t - \mathbf{e}_j^t(\Omega^t) + \mathrm{ccs}_j^t) - C^t \mathrm{ccs}_j^t \right\},$$

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

$$\sum_{t=0}^{T-1} \omega_j^t \leq \theta_j \mathrm{Bud}. \qquad (1)$$

Here $\pi_j^t(e_j^t)$ represents the economic benefits obtained from emissions by country j, at time t.



A Nash equilibrium

Applying standard Kuhn-Tucker multiplier method, with multipliers ν_j, the first order necessary conditions for a Nash equilibrium are now

$$0 = \beta_j^t(\pi_j^{t\prime}(\mathbf{e}_j^t(\Omega^t)) + p^{t\prime}(\Omega^t)(\omega_j^t - \mathbf{e}_j^t(\Omega^t) - \mathrm{ccs}_j^t) - C^t - \nu_j \qquad t = 0, \ldots, T-1; \quad j = 1, \ldots, m. \tag{2}$$

$$0 = \nu_j(\theta_j \mathrm{Bud} - \sum_{t=0}^{T-1} \omega_j^t) \tag{3}$$

$$0 \leq \theta_j \mathrm{Bud} - \sum_{t=0}^{T-1} \omega_j^t \tag{4}$$

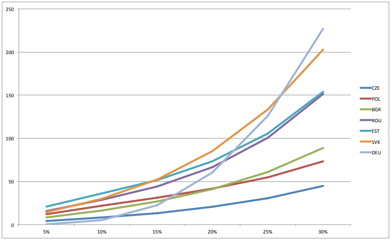
$$0 \leq \overline{ccs}_j - ccs_j \tag{5}$$

$$0 \leq \nu_j. \tag{6}$$

Estimation of the abatement cost functions

- We use the CGE model GEMINI-E3 as a the provider of data for the estimation of the abatement cost functions for each EU country
- Estimations are based on statistical emulations of a sample of 200 GEMINI-E3 numerical simulations (4 periods $\times 28$ = nb estimations)
- The abatement costs are polynomial functions of degree 4 in the country abatement level

$$AC_j(t) = \alpha_1^j(t)\, q_j(t) + \alpha_2^j\, q_j(t)^2 + \alpha_3^j(t)\, q_j(t)^3 + \alpha_4^j(t)\, q_j(t)^4. \qquad (7)$$



Results without CCS - Different sharing rules

	Historical emissions	Ability to pay	Population rule	Fair Equilibrium
AUT	1.90	1.11	1.70	1.85
BEL	3.10	2.74	2.10	3.27
BGR	1.20	1.69	1.50	0.83
CYP	0.20	0.53	0.20	0.42
CZE	3.10	3.89	2.10	1.38
DEU	20.80	11.80	16.10	13.81
DNK	1.30	2.12	1.10	1.85
EST	0.50	0.71	0.30	0.40
FIN	1.70	1.59	1.10	1.50
FRA	9.60	6.75	12.80	12.15
GBR	13.10	13.56	12.30	14.82
GRC	2.20	7.99	2.20	5.05
HRV	0.50	0.88	0.90	0.85
HUN	1.30	1.49	2.00	1.30
IRL	1.00	1.43	0.90	1.43
ITA	10.60	8.29	11.90	11.72
LAT	0.20	0.36	0.40	0.30
LIT	0.40	0.40	0.60	0.30
LUX	0.30	0.63	0.10	0.56
MLT	0.10	0.15	0.10	0.13
NLD	5.10	3.81	3.30	4.40
POL	8.50	12.25	7.60	6.22
POR	1.30	1.51	2.10	1.50
ROU	2.10	2.89	4.20	1.93
SPN	7.20	9.54	9.10	8.95
SVK	1.00	1.20	1.10	0.84
SVN	0.40	0.49	0.40	0.46
SWE	1.40	0.19	1.90	1.79
EU-28	100.00	100.00	100.00	100.00

Results without CCS - welfare losses

	Historical emissions	Ability to pay	Population rule	Fair Equilibrium
AUT	0.84	4.14	1.67	1.05
BEL	1.59	2.69	4.60	1.08
BGR	-10.52	-26.19	-20.01	1.16
CYP	15.37	-6.54	15.37	1.05
CZE	-15.67	-23.55	-5.82	1.24
DEU	-1.90	2.17	0.22	1.25
DNK	3.89	-0.36	4.92	1.05
EST	-5.70	-20.04	7.86	1.20
FIN	-0.10	0.58	3.59	1.13
FRA	2.58	4.13	0.85	1.20
GBR	1.95	1.75	2.30	1.20
GRC	12.36	-10.39	12.36	1.18
HRV	8.67	0.62	0.09	1.16
HUN	1.03	-0.68	-5.11	1.03
IRL	4.24	1.12	4.97	1.13
ITA	1.95	3.51	1.08	1.21
LAT	5.77	-1.55	-3.36	1.21
LIT	-1.83	-1.91	-8.03	1.27
LUX	8.55	-1.09	14.36	1.01
MLT	6.79	-2.06	6.79	1.14
NLD	-0.59	2.37	3.52	1.01
POL	-5.60	-16.90	-2.92	1.18
POR	2.18	1.03	-2.28	1.07
ROU	-0.11	-6.01	-15.78	1.15
SPN	2.98	0.62	1.06	1.21
SVK	-1.49	-4.73	-3.13	1.12
SVN	2.91	0.27	2.91	1.20
SWE	2.65	6.89	0.87	1.26
EU-28	1.18	1.18	1.19	1.18

Robust optimization

Consider the constraint $\sum_j a_j x_j \leq 0$ where a_j are uncertain and the uncertain model for a_j .

$$a_j = a_j^0 + a_j \xi_j$$

a_j^0 is the *nominal value* and ξ is the uncertainty factor acting through a_j.
The uncertain constraint is

$$\underbrace{\sum_j a_j^0 x_j}_{\text{certain}} + \underbrace{\sum_j a_j x_j \xi_j}_{\text{uncertain}} \leq 0. \quad (8)$$

In addition, we define an uncertainty set which contains reasonable realizations of uncertainties that we want to consider

$$\mathcal{U} = \{\xi : (\sum_i \xi_i^2)^{\frac{1}{2}} \leq \kappa, \ -1 \leq \xi_i \leq 1\}$$

Equivalent robust counterpart with an ellipsoidal set

- Set $z_k = \sum_i a_i^k x_i$. The robust counterpart of the uncertain constraint is

$$\sum_i a_i^0 x_i + \max_{\xi}\{\sum_k z_k \xi_k : ||\xi||_2 \leq \kappa,\ -1 \leq \xi_k \leq 1\} \leq 0.$$

- The dual of the inner maximization problem is

$$\min_u \left(||u||_1 + \kappa||z - u||_2\right).$$

- The *equivalent robust counterpart* of the uncertain constraint is

$$\sum_i a_i^0 x_i + \min_u \left(||u||_1 + \kappa||z - u||_2\right) \leq 0.$$

- If the constraint is embedded in an optimization problem, we can drop the min operator and let the overall optimization scheme manage the auxiliary variable u

$$\sum_i a_i^0 x_i + ||u||_1 + \kappa||z - u||_2 \leq 0.$$

Applying RO to MAC

In order to extract robust predictions from the game meta-model we robustify the marginal abatement cost represented by the following expression:

$$MAC_j^t = \frac{\partial}{\partial q_j^t} AC_j^t \qquad (9)$$

where AC_j^t is assumed to be given by a polynomial of degree 4, $\sum_{i=1}^{4} \alpha_{ij}^t (q_j^t)^i$. Let $\bar{\alpha}_{ij}^t$ be this estimate and $\hat{\alpha}_{ij}^t$ be the estimate error, we describe the uncertain coefficients as linear functions of an underlying random factor ξ_j^t

$$\alpha_{ij}^t = \bar{\alpha}_{ij}^t + \xi_{ij}^t \hat{\alpha}_{ij}^t$$

Let us consider the following uncertainty set

$$\Xi_j^t = \{\xi : \sum_{i=1}^{4} |\xi_{ij}^t|^2 \leq k^2\}.$$

Robust counterpart

MAC now depends on ξ. The worst case of the marginal abatement cost function is given by

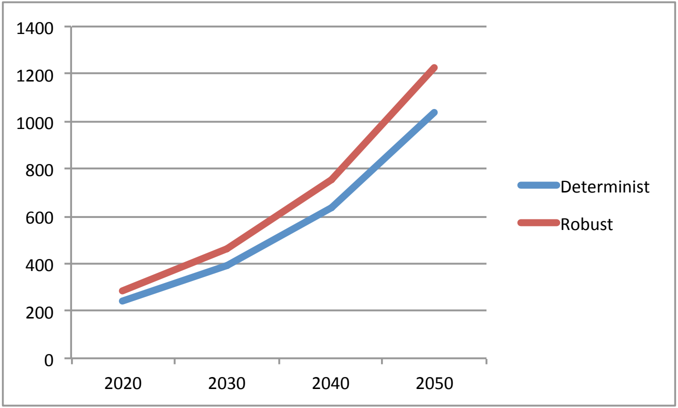
$$\overline{MAC}_j^t = \sum_{i=1}^{4} i\bar{\alpha}_{ij}^t \,(q_j^t)^{i-1} + k\sqrt{\sum_{i=1}^{4}(i\hat{\alpha}_{ij}^t\,(q_j^t)^{i-1})^2}.$$

Theorem (Ben-Tal, El Ghaoui and Nemirovski)

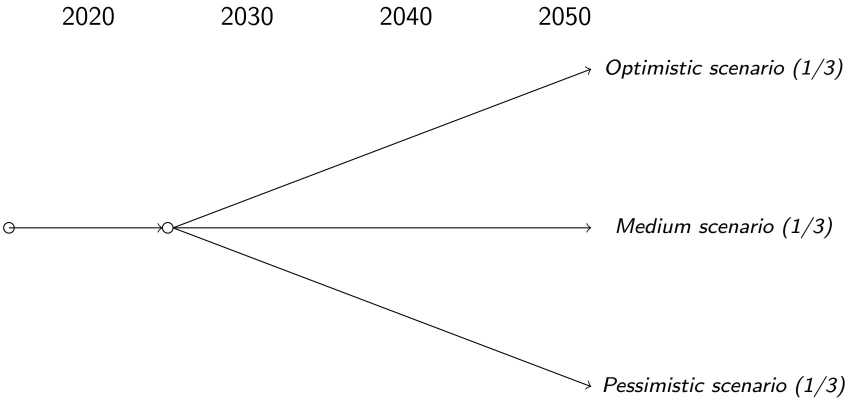
Let ξ_i, $i = 1, \ldots, n$ be independent random variables with values in interval $[-1, 1]$ and with average zero: $E(\xi_i) = 0$. If z_i, $i = 1, \ldots, n$, are deterministic coefficients, we have for all $k \geq 0$

$$Prob\left\{\xi \mid \sum_{i=1}^n z_i\xi_i > k\sqrt{\sum_{i=1}^n z_i^2}\right\} \leq \exp(-\frac{k^2}{2.5}).$$

Impacts on permit prices ($ per tC) - 96%



Event tree for CCS uncertainty



CCS assumptions

Assuming that CCS technologies will be implemented only on gas and coal power plants, we define three contrasted scenarios of CCS deployment

- **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 quarter of emissions from gas and coal power plants in 2050.

Finally the penetration rate is assumed to be linear between 2030 and 2050.

A stochastic dynamic game

$$
\begin{aligned}
0 &= \beta_j^t(\pi_j^{t\prime}(\mathbf{e}_j^t(\Omega^t)) + p^{t\prime}(\Omega^t)(\omega_j^t - \mathbf{e}_j^t(\Omega^t)) - \sum_{s\in S}\mathcal{P}(s)\nu_j(s), \ \forall t < \bar{t}, \ \forall j. && (10)\\
0 &= \beta_j^t(\pi_j^{t\prime}(\mathbf{e}_j^t(\Omega^t), s) + p^{t\prime}(\Omega^t, s)(\omega_j^t(s) - \mathbf{e}_j^t(\Omega^t, s) - \mathrm{ccs}_j^t(s)) - C_j^t(s) && (11)\\
& -\nu_j(s), \ \forall t \geq \bar{t}, \ \forall j, \ \forall s \in S. && (12)\\
0 &= \nu_j(s)(\theta_j \mathrm{Bud} - \sum_{t<\bar{t}} \omega_j^t - \sum_{t\geq\bar{t}} \omega_j^t(s)) \ \forall j, \ \forall s \in S && (13)\\
0 &\leq \theta_j \mathrm{Bud} - \sum_{t<\bar{t}} \omega_j^t - \sum_{t\geq\bar{t}} \omega_j^t(s) \ \forall j, \ \forall s \in S && (14)\\
0 &\leq \overline{ccs}_j^t(s) - ccs_j^t(s), \ \forall t \geq \bar{t}, \ \forall s \in S && (15)\\
0 &\leq \nu_j(s), \ \forall j, \ \forall s \in S. && (16)
\end{aligned}
$$

Results with stochastic CCS - Equilibrium

	Burden Sharing	Welfare losses			
		Average	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

Results with stochastic CCS - Emissions

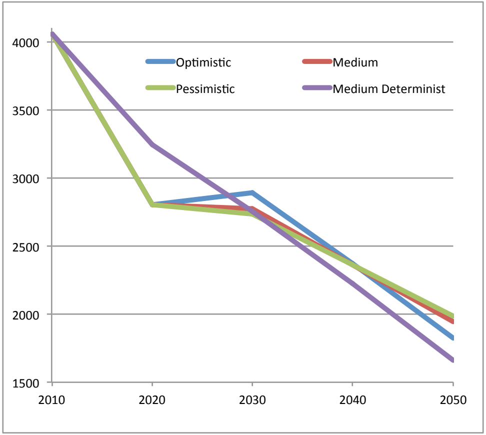


Figure: Emisisons in stochastic scenarios (in $MtCO_2$)