Economic Assessment of the Development of CO_2 Direct Reduction Technologies in Long-term Climate Strategies of the Gulf Countries

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Electronic Supplemental Material

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A Model formulation

We report in this section the mathematical formulation of the meta-game model used in this paper to design and assess burden sharing agreements.

A.1 Model's equations

Variables and parameters

$j \in \{1, \ldots, m\}$: index of coalition;

$t \in \{1, \ldots, T\}$: time periods;

$\delta(t)$: duration of time period t;

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B**:** global safety emission budget over the time horizon $[0, T]$;

θ_j**:** share of the global emission budget allocated to coalition j;

$b_j = \theta_j B$**:** cumulative emission budget for coalition j at period 0;

$b_j(t)$ remaining emission budget for coalition j at end of period t;

$\nu_j(t)$**:** K-T multiplier for global budget constraint of coalition j at period t;

$\omega_j(t)$**:** supply of emission permits at period t by coalition j;

$\Omega(t)$**:** total supply of emission permits at period t;

$v_j(t)$**:** negative emission activity (CDR) by coalition j at period t;

$v_j(0)$**:** negative emission activity (CDR) by coalition j at period 0;

$\kappa_j(v_j(t), t)$**:** cost of CDR for coalition j at period t;

$q_j(t)$**:** abatement level by coalition j at period t;

$\epsilon_j(t)$**:** BaU emission level by coalition j at period t;

$e_j(t)$**:** emission level by coalition j at period t;

$e_j(0)$**:** emission level by coalition j at period 0;

$\varpi_j(q_j(t), t)$**:** Abatement cost for coalition j at time t;

$\mathbf{e}(t)$**:** vector of all m emission levels at period t;

$\pi_j(\mathbf{e}(t), t)$**:** Net abatement cost (including changes in the terms of trade) for coalition j at time t;

$\gamma_j(\sum_{k=1}^{m} q_k(t), t)$**:** gains from the changes in terms of trade for coalition j at time t;

β_j**:** discount factor for coalition j equals 3%;

Emissions from abatement. This equation relates the abatement and emission levels relative to BaU

$$e_j(t) = \epsilon_j(t) - q_j(t) \tag{1}$$

Emission budget constraints. Let $b_j(\tau)$ denote the remaining emission budget, for region j at the end of period τ, $\tau = 0, \dots, T-1$. We approximate the integral of net emissions up to period τ, using the trapezoidal method. The part of the emissions budget remaining at period τ is thus defined as

$$0 \le b_j - (\frac{1}{2}\sum_{t=0}^{\tau-1} \delta(t+1)(\omega_j(t) + \omega_j(t+1) - v_j(t) - v_j(t+1))),$$
$$j = 1, \dots, m, \quad \tau = 0, \dots, T-1. \quad (2)$$

By imposing non negative remaining budgets, we eliminate the possibility for each "player" to perform short-selling of the future DAC activities.

This expression can also be rewritten

$$b_j - (\frac{1}{2}\delta(1)(\omega_j(0) - v_j(0)) + \frac{1}{2}\sum_{t=1}^{\tau-1}(\delta(t) + \delta(t+1))(\omega_j(t) - v_j(t))$$
$$+ \frac{1}{2}\delta(\tau)(\omega_j(\tau) - v_j(\tau))) \ge 0, \quad j = 1, \dots, m, \quad \tau = 0, \dots, T-1. \quad (3)$$

Note that the modeling approach in [6, 5], is a Ramsey optimal growth model with a constraint on SAT increase, expressed in terms of cumulative emissions. In these cases, the optimal solution normally proposes some overshooting, with not insignificant negative emissions occurring at the end of the planning horizon; and indeed, the higher the discount rate, the greater the negative emissions at the end of the planning horizon. In contrast, our approach uses an oligopoly game model, where each coalition strives to optimize the use of a given fixed emissions budget, over a planning horizon, where a net-zero emissions regime should be reached at the end of the planning period. This will provide a natural end-of-period condition: net-zero emissions for the whole world. However, at each intermediate period, a negative remaining budget for one coalition would allow it to supply emission rights on the current market as CO_2 they promise to capture in the future: in other words, short selling, associated with high risk and temptation for each player to cheat. Under these conditions, and to ensure that each permit supplied corresponds to existing abatements or CO_2 capture, then, it would be necessary to forbid short selling.

Net-zero emissions in the final period. At the end of the planning horizon one must reach a net-zero emission regime. So there should be a coupled constraint of the form.

$$\sum_j (v_j(T) - e_j(T)) \geq 0. \tag{4}$$

However, this constraint will probably be redundant with the emission budget constraints and we will not consider it.

Emissions trading. An international carbon market determines a price and emissions levels.

$$\begin{aligned} p(t) &= \frac{\partial}{\partial q_j(\cdot)} \varpi_j(q_j(t), t) = -\frac{\partial}{\partial e_j(\cdot)} \varpi_j(\epsilon_j(t) - e_j(t), t) & (5) \\ \Omega(t) &= \sum_{k=1}^{m} e_k(t); \quad j = 1, \dots m. & (6) \end{aligned}$$

The price and emission levels are thus functions of the total permit supply $\Omega(t)$, thus denoted $\tilde{\mathbf{e}}(\Omega(t), t)$ and $\tilde{p}(\Omega(t), t)$, respectively.

As shown in Helm [4], the derivatives w.r.t. Ω of price and emission levels are given by

$$\begin{aligned} \tilde{p}'(\Omega, t) &= \frac{1}{\sum_{j=1}^{m} \frac{1}{\frac{\partial^2 \varpi_j(q_j, t)}{\partial q_j^2}}} & (7) \\ \tilde{e}_j'(\Omega, t) &= \frac{1}{\sum_{k=1}^{m} \frac{\frac{\partial^2 \varpi_j(q_j, t)}{\partial q_j,^2}}{\frac{\partial^2 \varpi_j(q_k, t)}{\partial q_k^2}}} & (8) \end{aligned}$$

respectively. Since $\Omega(t) = \sum_{j=1}^{m} \omega_j(t)$ the derivatives w.r.t. $\omega_j(t)$ are the same as the derivatives w.r.t. $\Omega(t)$.

Payoffs. The periodic net cost to coalition j includes the abatement cost plus the cost of buying permits on the market (negative if selling) and is given by

$$\psi_j(t) = [\pi_j(\tilde{\mathbf{e}}(\Omega(t), t) + \kappa_j(v_j(t), t) - \tilde{p}(\Omega(t), t)(\omega_j(t) - e_j(\Omega(t), t))], \tag{9}$$

where

$$\pi_j(\mathbf{e}(t), t) = \varpi_j(q_j(t), t) - \gamma_j(\sum_k p_k(t), t). \tag{10}$$

The payoff coalition j is defined by the integral of the discounted periodic costs

$$J_j(\cdot) = \frac{1}{2}\delta(1)\psi_j(0) + \frac{1}{2}\sum_{t=1}^{T-1}\beta_j^t(\delta(t)+\delta(t+1))\psi_j(t) + \frac{1}{2}\beta_j^T\delta(T)\psi_j(T),$$
$$j = 1,\ldots,m. \quad (11)$$

We assume that the supply of permits and the DAC activities of each coalitions are strategically defined as the open-loop Nash equilibrium for the game defined by payoffs (11) and constraints (1)-(8).

A.2 Nash equilibrium conditions

We write now the first order conditions for a Nash equilibrium solution. The existence of a solution is implied by the convexity of the cost functions. Denoting $\nu_j(t)$ the K-T multiplier of the emission budget constraint (3) for coalition j, we may write the Lagrangian for each player j as given by

$$\mathcal{L}_j(\cdot) = \frac{1}{2}(\delta(1)\psi_j(0) + \beta_j^T\delta(T)(\psi_j(T)) + \frac{1}{2}\sum_{t=0}^{T-1}\beta_j^t(\delta(t)+\delta(t+1))(\psi_j(t)+$$
$$\nu_j(t)(b_j - \frac{1}{2}\sum_{s=0}^{t-1}\delta(s+1)(\omega_j(s)+\omega_j(s+1)-v_j(s)-v_j(s+1)))$$
$$j = 1,\ldots,m. \quad (12)$$

Complementarity conditions for $\omega_j(t)$

$$0 \leq \beta_j^t\frac{\partial}{\partial\omega_j(t)}[\pi_j(\tilde{\mathbf{e}}(\Omega(t),t) - \tilde{p}(\Omega(t),t)(\omega_j(t) - e_j(\Omega(t),t))] + \nu_j \quad (13)$$
$$0 \leq \omega_j(t) \quad (14)$$
$$0 = \omega_j(t)\left\{\beta_j^t\frac{\partial}{\partial\omega_j(t)}[\pi_j(\tilde{\mathbf{e}}(\Omega(t),t) - \tilde{p}(\Omega(t),t)(\omega_j(t) - e_j(\Omega(t),t))]\right.$$
$$\left.+\nu_j\right\}. \quad t = 1\ldots T \quad (15)$$

Developing the expression

$$\frac{\partial}{\partial \omega_j(t)}[\pi_j(\tilde{\mathbf{e}}(\Omega(t),t) - \tilde{p}(\Omega(t),t)(\omega_j(t) - e_j(\Omega(t),t))] =$$

$$\begin{aligned} &\frac{\partial}{\partial \sum_k q_k(t)} \gamma_j(\sum_k q_k(t),t) \frac{\partial}{\partial \omega_j(t)} (\sum_{k=1}^{m} e_k(\Omega(t),t)) \\ &- (\frac{\partial}{\partial q_j(t)} \varpi(q_j(t),t) - \tilde{p}(\Omega(t),t)) \frac{\partial}{\partial \omega_j(t)} e_j(\Omega(t),t)) \\ &- \tilde{p}(\Omega(t),t) - \frac{\partial}{\partial \omega_j(t)} \tilde{p}(\Omega(t),t)(\omega_j(t) - e_j(\Omega(t),t)), \quad (16) \end{aligned}$$

and using the relations $\frac{\partial}{\partial q_j(t)} \varpi(q_j(t),t) = \tilde{p}(\Omega(t),t)$ and $\sum_{k=1}^{m} e_k(\Omega(t),t) = \Omega(t)$ that hold on the emission permit market the complementarity condition (15) can be rewritten more simply

$$\begin{aligned} \omega_j(t) \Big\{ &-\beta_j^t [-\frac{\partial}{\partial \sum_k q_k(t)} \gamma_j(\sum_k q_k(t),t) + \tilde{p}(\Omega(t),t) \\ &+ \frac{\partial}{\partial \omega_j(t)} \tilde{p}(\Omega(t),t)(\omega_j(t) - e_j(\Omega(t),t))] + \nu_j \Big\} = 0. \quad (17) \end{aligned}$$

Complementarity conditions for $v_j(t)$

$$0 \leq \beta_j^t \frac{\partial}{\partial v_j(t)} \kappa_j(v_j(t),t) - \nu_j \quad (18)$$

$$0 \leq v_j(t) \quad (19)$$

$$0 = v_j(t) \left\{ \beta_j^t \frac{\partial}{\partial v_j(t)} \kappa_j(v_j(t),t) - \nu_j \right\}. \quad (20)$$

Complementarity conditions for $\nu_j(t)$

$$0 \leq b_j - \frac{1}{2} \sum_{s=0}^{t-1} \delta(s+1)(\omega_j(s) + \omega_j(s+1) - v_j(s) - v_j(s+1)) \quad (21)$$

$$0 \leq \nu_j(t) \quad (22)$$

$$0 = \nu_j(t) \left\{ b_j - \frac{1}{2} \sum_{s=0}^{t-1} \delta(s+1)(\omega_j(s) + \omega_j(s+1) - v_j(s) - v_j(s+1)) \right\}$$
$$, j = 1, \ldots, m. \quad (23)$$

A.3 Model calibration - CO_2 emissions and payoff functions

We use the GEMINI-E3 model [2, 3] to calibrate the dynamic game model. GEMINI-E3 is a worldwide multi-country, multi-sector, computable general equilibrium (CGE) model that has been specifically designed to assess energy and climate change policies. GEMINI-E3 is used to compute the CO_2 emissions and economic variables within the business as usual (BaU) scenario and calibrate the payoff functions (π_j). The methodology used to calibrate our game theory model using an applied CGE is detailed in our previous papers, e.g. see Appendix 2 in [1]. In short, various climate policies are simulated by GEMINI-E3, then we perform econometric estimations of the abatement cost ($\varpi_j(q_j(t),t)$) and gains from term of trade ($\gamma_j(\sum_{k=1}^{m} q_k(t),t)$) functions. However, the time horizon of GEMINI-E3 is limited to the first part of our century (i.e. up to 2050), therefore we have to implement a procedure extending the variables for the years 2070 and 2100. We use a versatile representation based on a steady state growth approach for the end of our century.

$$
\begin{aligned}
\frac{gdp_j(t)-gdp_j(t-1)}{gdp_j(t-1)} &= \frac{pop_j(t)-pop_j(t-1)}{pop_j(t-1)} \cdot (1+\nu_j^1(t))^{\delta(t)} \\
\frac{e_j(t)-e_j(t-1)}{e_j(t-1)} &= \frac{gdp_j(t)-gdp_j(t-1)}{gdp_j(t-1)} \cdot (1+\nu_j^2(t))^{\delta(t)} \\
\nu_j^1(t) = \nu_j^1(t-1) - \delta(t) &\cdot (\nu_j^1(t-1) - \nu_j^1(T))/(\delta(T-1)+\delta(T)) \\
\nu_j^2(t) = \nu_j^2(t-1) - \delta(t) &\cdot (\nu_j^2(t-1) - \nu_j^2(T))/(\delta(T-1)+\delta(T)) \\
\nu_j^1(T) &= \nu^1 \quad \forall j \\
\nu_j^2(T) &= \nu^2 \quad \forall j
\end{aligned}
\tag{24}
$$

First, we select a demographic scenario among the projections done by the United Nations [7] and determine the working population[1] ($pop_j(t)$). Then, we follow a production function approach linking GDP per capita ($gdp_j(t)/pop_j(t)$) to a total productivity factor (TFP) $\nu_j^1(t)$. We assume that for each region the TFP converges to a common value (ν^1) at the end of our century. Finally, we assume that for each region CO_2 emissions per GDP ($e_j(t)/gdp_j(t)$) decrease with an annual rate that converges to a single value ν^2. Thus we can simulate various BaU scenarios by setting a value for the three parameters defined above, demographic scenario, ν^1 and ν^2.

The abatement functions ($\varpi_j(q_j(t),t)$) are extrapolated for the years 2070 and 2100 by assuming a proportionally rule with respect to the level

[1] Male and female population aged from 20 to 64.

of abatement for the year 2050. The GTT functions $(\gamma_j(\sum_{k=1}^{m} q_k(t), t))$ in 2070 and 2100 are supposed unchanged with respect to 2050 figures.

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