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Variations on an oil and gas game model in a geostrategic climate policy context[1]

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Workshop on Dynamic Games and Applications
Paris, October 27-28, 2022

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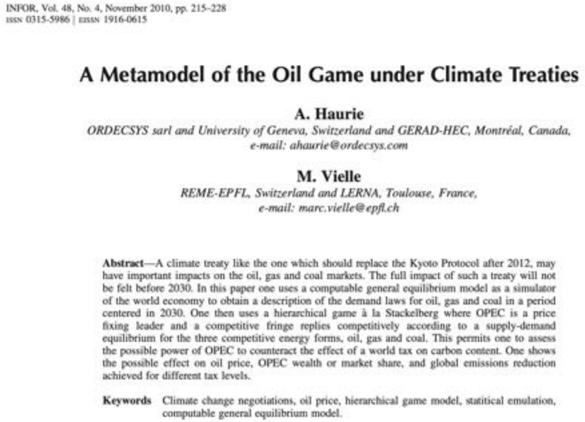
[1] Supported by the QNRF under Grant Agreement n^o 10-0212-170447

Variation-1: Declining world oil market

- Pindyck, Robert S, 1978. “Gains to Producers from the Cartelization of Exhaustible Resources," The Review of Economics and Statistics, MIT Press, vol. 60(2), pages 238-251, May.
- Special Issue in “Game Theory in Energy", G. Zaccour Guest editor.



INFOR, Vol. 48, No. 4, November 2010, pp. 215–228
ISSN 0315-5986 | EISSN 1916-0615

A Metamodel of the Oil Game under Climate Treaties

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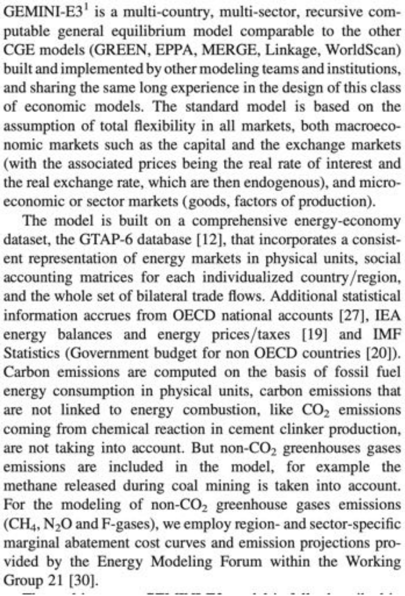
Abstract—A climate treaty like the one which should replace the Kyoto Protocol after 2012, may have important impacts on the oil, gas and coal markets. The full impact of such a treaty will not be felt before 2030. In this paper one uses a computable general equilibrium model as a simulator of the world economy to obtain a description of the demand laws for oil, gas and coal in a period centered in 2030. One then uses a hierarchical game à la Stackelberg where OPEC is a price fixing leader and a competitive fringe replies competitively according to a supply-demand equilibrium for the three competitive energy forms, oil, gas and coal. This permits one to assess the possible power of OPEC to counteract the effect of a world tax on carbon content. One shows the possible effect on oil price, OPEC wealth or market share, and global emissions reduction achieved for different tax levels.

Keywords Climate change negotiations, oil price, hierarchical game model, statitical emulation, computable general equilibrium model.

Declining world oil market

- One uses a computable general equilibrium (CGE) model as a simulator of the world economy to obtain a description of the demand laws for oil, gas and coal in a period centered in 2030.
- Using statistical emulation of the CGE, one calibrates a hierarchical game à la Stackelberg where OPEC is a price fixing leader and a competitive fringe replies competitively according to a supply-demand equilibrium for the three competitive energy forms, oil, gas and coal.
- This permits us to assess the possible power of OPEC to counteract the effect of a world tax on carbon content. One shows the possible effect on oil price, OPEC wealth or market share, and global emissions reduction achieved for different tax levels.

GEMINI



GEMINI-E3[1] is a multi-country, multi-sector, recursive computable general equilibrium model comparable to the other CGE models (GREEN, EPPA, MERGE, Linkage, WorldScan) 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).

The model is built on a comprehensive energy-economy dataset, the GTAP-6 database [12], that 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 [27], IEA energy balances and energy prices/taxes [19] and IMF Statistics (Government budget for non OECD countries [20]). Carbon emissions are computed on the basis of fossil fuel energy consumption in physical units, carbon emissions that are not linked to energy combustion, like CO_2 emissions coming from chemical reaction in cement clinker production, are not taking into account. But non-CO_2 greenhouses gases emissions are included in the model, for example the methane released during coal mining is taken into account. For the modeling of non-CO_2 greenhouse gases emissions (CH_4, N_2O and F-gases), we employ region- and sector-specific marginal abatement cost curves and emission projections provided by the Energy Modeling Forum within the Working Group 21 [30].

Coalitions

European Union (EUR)	Rest of OECD (R-OE)	Rest of the World (DCs)
DEU	USA	CHI
FRA	JAP	ASI
GBR	CAN	IND
ITA	CHE	BRA
ESP	XEU	LAT
NLD	AUZ	MEX
BEL		MID
OEU		AFR
POL		RUS
		XSU
		TUN
		TUR
		VEN

Table: The three economic regions (coalitions)

Business As Usual / GEMINI

	2000	2006	2015	2030	2050
IEA Crude oil price $ per barrel	32.46	61.72	100	100	100
Natural gas price (US imports) $ per MMBtu	4.49	7.22	10.58	10.58	10.58
OECD steam coal imports $ per tonne	39	62.87	62.87	62.87	62.87

Table: Fossil fuel price assumption (2006 $ per unit)

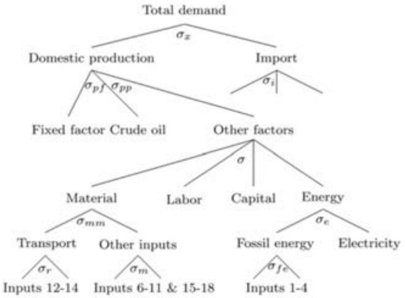


Figure 1. Nesting CES structure of production in GEMINI-E3

- 1 MMBtu → 0.1724 boe;
- 1 T coal → 4.426 boe,
- All 2030 prices in $/boe.

Oil	100
Gas	61.43
Coal	14.20

Extraction cost Oil

Denote q^O_C (resp. q^O_F) the supply of the oil cartel (resp. competitive fringe). The average cost functions for the cartel and the fringe are given by

$$\begin{aligned} c^O_C(q^O_C) &= C^o_C e^{\eta^O_C q^O_C} = 7\, e^{0.0003 q^O_C} && (1) \\ c^O_F(q^O_F) &= C^o_F e^{\eta^O_F q^O_C} = 12\, e^{0.0006 q^O_F}, && (2) \end{aligned}$$

respectively. The marginal cost functions (supply curves) are thus

$$\begin{aligned} \Gamma^O_C(q^O_C) &= (1 + 0.0003\, q^O_C) 7\, e^{0.0003 q^O_C} && (3) \\ \Gamma^O_F(q^O_F) &= (1 + 0.0006\, q^O_F) 12\, e^{0.0006 q^O_F} && (4) \end{aligned}$$

Extraction cost Gas and Coal

The marginal cost which is also the supply curve of the gas producers in a competitive market is given by:

$$\Gamma_i(q_i^G) = (1 + \eta_i^G q_i^G) C_{iG}^o e^{\eta_i^G q_i^G}. \tag{5}$$

region i	C_{iG}^o	η_i^G
EUR	18	0.00122
R-OE	12	0.00088
DCs	8	0.00017

Table: Parameters of gas extraction cost functions (2010-$/boe)

Finally, one assumes a constant extraction cost for coal at $-2010 14.2/boe, also corresponding to the IEA forecast.

Model

The model is summarized by the following equations:

$$
\begin{aligned}
\max &= 7.33(\pi^O - C_C^o e^{\eta_C^O q_C}) q_C^O && (6)\\
\text{s.c.} & && \\
q_C^O &= \sum_{i \in I} D_i^O - q_F^O && (7)\\
\pi^C &= 14.2 && (8)\\
\pi^O &= (1 + \eta_F^O q_F^O) C_F^O e^{\eta_F^O q_F^O} && (9)\\
\pi_i^G &= (1 + \eta_i^G q_i^G) C_{iG}^o e^{\eta_i^G q_i^G}, \quad i \in I && (10)\\
q_i^G &= D_i^G, \quad i \in I && (11)\\
\ln[D_i^j] &= \omega_i^j + \sum_{k \in J} \varepsilon_i^{jk} \ln[P_i^k], \quad i \in I, j \in \{\text{oil, gas, coal}\} && (12)\\
P_i^O &= \pi^O + \delta_i^O + \mu^O \theta, \quad i \in I && (13)\\
P_i^C &= \pi^C + \delta_i^C + \mu^C \theta, \quad i \in I && (14)\\
P_i^G &= \pi_i^G + \delta_i^G + \mu^G \theta, \quad i \in I && (15)\\
I &= \{\text{EUR, R-OE, DCs}\} && (16)
\end{aligned}
$$

Counterfactual

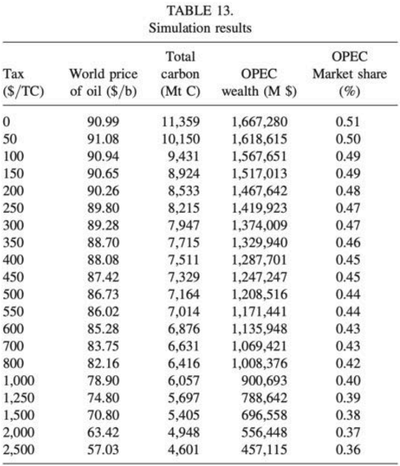


TABLE 13.
Simulation results

Tax ($/TC)	World price of oil ($/b)	Total carbon (Mt C)	OPEC wealth (M $)	OPEC Market share (%)
0	90.99	11,359	1,667,280	0.51
50	91.08	10,150	1,618,615	0.50
100	90.94	9,431	1,567,651	0.49
150	90.65	8,924	1,517,013	0.49
200	90.26	8,533	1,467,642	0.48
250	89.80	8,215	1,419,923	0.47
300	89.28	7,947	1,374,009	0.47
350	88.70	7,715	1,329,940	0.46
400	88.08	7,511	1,287,701	0.45
450	87.42	7,329	1,247,247	0.45
500	86.73	7,164	1,208,516	0.44
550	86.02	7,014	1,171,441	0.44
600	85.28	6,876	1,135,948	0.43
700	83.75	6,631	1,069,421	0.43
800	82.16	6,416	1,008,376	0.42
1,000	78.90	6,057	900,693	0.40
1,250	74.80	5,697	788,642	0.39
1,500	70.80	5,405	696,558	0.38
2,000	63.42	4,948	556,448	0.37
2,500	57.03	4,601	457,115	0.36

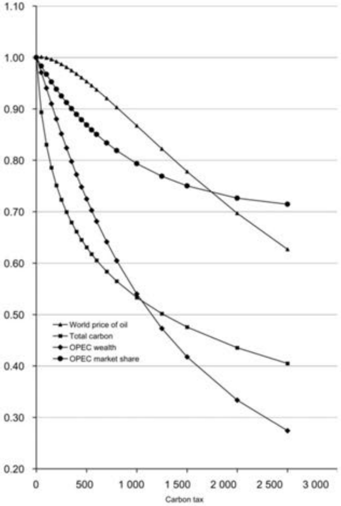
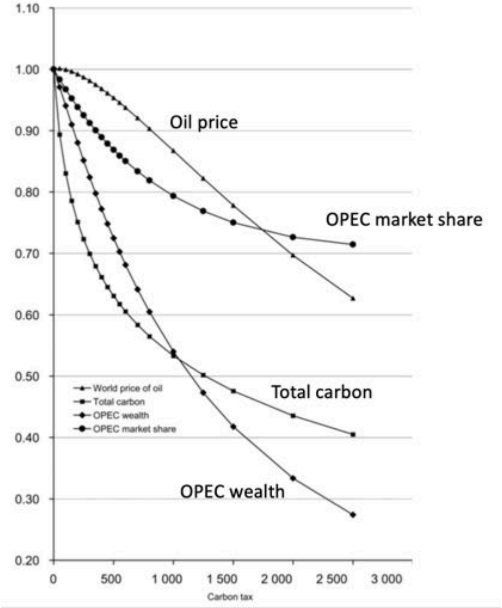


Figure 4. Normalized indicators in function of the carbon tax ($/TC)


1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0
500
1 000
1 500
2 000
2 500
3 000
Carbon tax
Oil price
OPEC market share
Total carbon
OPEC wealth
World price of oil
Total carbon
OPEC wealth
OPEC market share

BAU: No carbon tax

World price of oil: $91/bbl

Demand		
Non_OECD	coal	3031.93
Non_OECD	gas	1894.35
Non_OECD	oil	3196.58
OECD_EU	coal	301.82
OECD_EU	gas	377.03
OECD_EU	oil	710.94
Rest_OECD	coal	954.53
Rest_OECD	gas	798.05
Rest_OECD	oil	1558.31

PRICEC		
Non_OECD	coal	12.26
Non_OECD	gas	26.84
Non_OECD	oil	101.95
OECD_EU	coal	16.62
OECD_EU	gas	60.85
OECD_EU	oil	133.23
Rest_OECD	coal	13.23
Rest_OECD	gas	55.67
Rest_OECD	oil	111.58

OPEC margin: 1’670’830 M$.

Tax: \$600 / tC gives \$164 / tCO_2)

World price of oil: \$85/bbl

Demand		
Non_OECD	coal	1115.74
Non_OECD	gas	1078.74
Non_OECD	oil	2674.11
OECD_EU	coal	109.40
OECD_EU	gas	283.14
OECD_EU	oil	611.60
Rest_OECD	coal	342.71
Rest_OECD	gas	634.38
Rest_OECD	oil	1304.97

PRICEC		
Non_OECD	coal	104.18
Non_OECD	gas	77.07
Non_OECD	oil	164.18
OECD_EU	coal	108.54
OECD_EU	gas	106.88
OECD_EU	oil	195.46
Rest_OECD	coal	105.15
Rest_OECD	gas	100.57
Rest_OECD	oil	173.81

OPEC margin: 1’138’350 M\$. (-32 %).

Extra delivery cost for gas in EU

$$c_{1-gas}[r] * exp(extra_{gas}[r] * Q_G AS[r])$$

$$c_{1-gas}['EU'] = 1; \quad extra_{gas}['EU'] = 0.02$$

World price of oil: $91bbl

Demand		
Non_OECD	coal	3033.73
Non_OECD	gas	1894.36
Non_OECD	oil	3193.04
OECD_EU	coal	324.64
OECD_EU	gas	221.42
OECD_EU	oil	720.79
Rest_OECD	coal	954.73
Rest_OECD	gas	798.21
Rest_OECD	oil	1556.87

PRICEC		
Non_OECD	coal	12.26
Non_OECD	gas	26.84
Non_OECD	oil	102.18
OECD_EU	coal	16.62
OECD_EU	gas	132.96
OECD_EU	oil	133.46
Rest_OECD	coal	13.23
Rest_OECD	gas	55.68
Rest_OECD	oil	111.81

OPEC margin: 1'676'470 M$. (+0.34 %)

Tax + Extra delivery cost for gas in EU

World price of oil: $85/bbl

Demand		
Non_OECD	coal	1116
Non_OECD	gas	1078.74
Non_OECD	oil	2672.97
OECD_EU	coal	114.048
OECD_EU	gas	208.892
OECD_EU	oil	616.495
Rest_OECD	coal	342.734
Rest_OECD	gas	634.441
Rest_OECD	oil	1304.49
PRICEC		
Non_OECD	coal	104.184
Non_OECD	gas	77.0742
Non_OECD	oil	164.325
OECD_EU	coal	108.544
OECD_EU	gas	167.04
OECD_EU	oil	195.605
Rest_OECD	coal	105.154
Rest_OECD	gas	100.573
Rest_OECD	oil	173.955

OPEC margin: 1’141’100 M$. (-31.7 %)

Geopolitics

Demand (Mtoe)		BAU	EU-Gas short.	Tax[2]: 600	Tax+shortage
Non_OECD	coal	3031.93	3033.73	1115.74	1116
Non_OECD	gas	1894.35	1894.36	1078.74	1078.74
Non_OECD	oil	3196.58	3193.04	2674.11	2672.97
OECD_EU	coal	301.82	324.64	109.40	114.048
OECD_EU	gas	377.03	221.42	283.14	208.892
OECD_EU	oil	710.94	720.79	611.60	616.495
Rest_OECD	coal	954.53	954.73	342.71	342.734
Rest_OECD	gas	798.05	798.21	634.38	634.441
Rest_OECD	oil	1558.31	1556.87	1304.97	1304.49
PRICEC ($/boe)		BAU	EU-Gas short.	Tax: 600	Tax+shortage
Non_OECD	coal	12.26	12.26	104.18	104.184
Non_OECD	gas	26.84	26.84	77.07	77.07
Non_OECD	oil	101.95	102.18	164.18	164.33
OECD_EU	coal	16.62	16.62	108.54	108.54
OECD_EU	gas	60.85	132.96	106.88	167.04
OECD_EU	oil	133.23	133.46	195.46	195.605
Rest_OECD	coal	13.23	13.23	105.15	105.15
Rest_OECD	gas	55.67	55.68	100.57	100.57
Rest_OECD	oil	111.58	111.81	173.81	173.96
OPEC margin	($M)	1’670’830	1’676’470	1’138’350	1’141’100

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[2] \$600 / tC gives \$164 / tCO_2

Possible development

Model ”OPEC+", where OPEC and Russia are both leaders, with some competition (in supplying China and India)...

Variation-2: DAC saves the Game

Reaching Paris Agreement Goal through CDR/DAC Development: a Compact OR Model

Frédéric Babonneau* Alain Haurie† Marc Vielle‡

December 8, 2021

Abstract

A compact operations research (OR) model is proposed to analyse the prospects of meeting the Paris Agreement targets when direct air capture technologies can be used or not. The main features of the model are (i) the representation of the economy and energy use with a nested constant elasticity of substitution production function; (ii) the representation of climate policy through the use of a safety emissions budget concept; and (iii) the representation of an international emissions trading scheme for the implementation of climate policy. Using dynamic optimisation, several contrasting scenarios are analysed and the potential use of the model in future developments of climate/economy modelling is discussed.

keywords. Climate policy, Optimal economic growth, Dynamic optimisation model, Market equilibrium constraints and CO_2 direct reduction.

DAC saves the Game

Climatic Change (2021) 165: 64
https://doi.org/10.1007/s10584-021-03058-4

Economic assessment of the development of CO_2 direct reduction technologies in long-term climate strategies of the Gulf countries

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Received: 26 June 2020 / Accepted: 9 March 2021 / Published online: 23 April 2021

Abstract

This paper proposes an assessment of long-term climate strategies for oil- and gas-producing countries—in particular, the Gulf Cooperation Council (GCC) member states—as regards the Paris Agreement goal of limiting the increase of surface air temperature to 2°C by the end of the twenty-first century. The study evaluates the possible role of carbon dioxide removal (CDR) technologies under an international emissions trading market as a way to mitigate welfare losses. To model the strategic context, one assumes that a global cumulative emissions budget will have been allocated among different coalitions of countries—the GCC being one of them—and the existence of an international emissions trading market. A meta-game model is proposed in which deployment of CDR technologies as well as supply of emission rights are strategic variables and the payoffs are obtained from simulations of a general equilibrium model. The results of the simulations indicate that oil and gas producing countries and especially the GCC countries face a significant welfare loss risk, due to "unburnable oil" if a worldwide climate regime as recommended by the Paris Agreement is put in place. The development of CDR technologies, in particular direct air capture (DAC) alleviates somewhat this risk and offers these countries a new opportunity for exploiting their gas reserves and the carbon storage capacity offered by depleted oil and gas reservoirs.

Keywords GCC countries · Climate negotiations · Carbon dioxide removal · Financial compensation · Negative emissions · CDR technologies

DAC saves the Game

Please, visit the following web site
https://climeworks.com/

Compact OR model

- One uses an optimal economic growth model with 3 world regions (OECD,BRIC,ROW) over an horizon of 100 years.
- One represents the climate policy as imposing a limit on cumulative GHG emissions (1170 Gt CO_2).
- One assumes a world permit trading scheme.
- One represents the possibility to develop DAC technology.

Nested CES functions

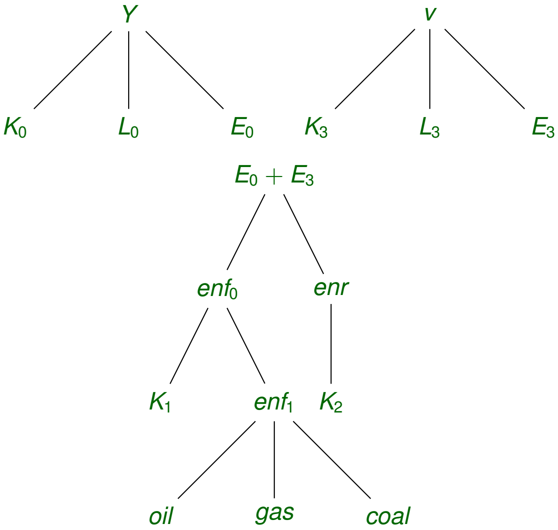


Figure: Nested structure for general economy and CDR-DAC activity

General economic good production

$$Y(t,j) - A_0(j)tg(t,j)\left[\alpha_{0K}K_0(t,j)^{\frac{s_0(j)-1}{s_0(j)}} + \alpha_{0L}L_0(t,j)^{\frac{s_0(j)-1}{s_0(j)}} + \alpha_{0E}E_0(t,j)^{\frac{s_0(j)-1}{s_0(j)}}\right]^{\frac{s_0(j)}{s_0(j)-1}} \leq 0. \quad (17)$$

where $Y(t,j)$ is the annual output of the general economic good that can be consumed or invested, α_{0K}, α_{0L} and α_{0E} are the input share parameters, $A_0(j)$ the factor productivity parameter, $s_0(j)$ the elasticity of substitution between inputs and $tg(t,j)$ a disembodied technical progress.

Negative emissions production

Annual negative emissions $v(t,j)$ are represented through a CES function with three factors (capital, labor and energy), an elasticity of substitution equal to $s_3(j)$ and a disembodied technical progress represented by $tgv(t,j)$:

$$v(t,j) - A_3(j)tgv(t,j)\left[\alpha_{3K}(j)K_3(t,j)^{\frac{s_3(j)-1}{s_3(j)}} + \alpha_{3L}(j)L_3(t,j)^{\frac{s_3(j)-1}{s_3(j)}} + \alpha_{3E}(j)E_3(t,j)^{\frac{s_3(j)-1}{s_3(j)}}\right]^{\frac{s_3(j)}{s_3(j)-1}} \leq 0. \quad (18)$$

where $v(t,j)$ is the quantity of negative emissions produced, $K_3(t,j)$ is the stock of CDR/DAC capital, $L_3(t,j)$ is the labor used for negative emissions production, $E_3(t,j)$ is the energy used for negative emissions production, for coalition j at period t.

Useful energy production

Annual useful energy production is represented by a CES function that combines renewable energy and secondary fossil energy:

$$E_0(t,j) + E_3(t,j) - A_e(j)\left[\alpha_{Ef}(j) enf(t,j)^{\frac{s_e(j)-1}{s_e(j)}} + \alpha_{Er}(j) enr(t,j)^{\frac{s_e(j)-1}{s_e(j)}}\right]^{\frac{s_e(j)}{s_e(j)-1}} \leq 0. \quad (19)$$

where $enf(t,j)$ is the fossil fuel energy input to deliver useful energy, $enr(t,j)$ is the renewable energy input to deliver useful energy, for coalition j at period t.

Fossil secondary energy production

Fossil secondary energy production is represented by a CES function that combines capital and primary fossil energy:

$$enf_0(t,j) = A_1(j)\left[\alpha_{1K}(j)(tgenf(t,j)K_1(t,j))^{\frac{s_1(j)-1}{s_1(j)}} + \alpha_{1em}(j)enf_1(t,j)^{\frac{s_1(j)-1}{s_1(j)}}\right]^{\frac{s_1(j)}{s_1(j)-1}}. \quad (20)$$

where $K_1(t,j)$ is the stock of capital and $enf_1(t,j)$ is the fossil energy source used to produce fossil secondary energy, for coalition j at period t.

Fossil primary energy extraction

The mix of fossil primary energy forms defines $enf_1(t, j)$ through a CES function that combines oil, gas and coal:

$$\begin{aligned} enf_0(t, j) = A_{ef}(j) \Big[& \alpha_{oil}(j) oil(t, j)^{\frac{s_{ef}(j)-1}{s_{ef}(j)}} \\ & + \alpha_{gas}(j) gas(t, j)^{\frac{s_{ef}(j)-1}{s_{ef}(j)}} + \alpha_{coal}(j) coal(t, j)^{\frac{s_{ef}(j)-1}{s_{ef}(j)}} \Big]^{\frac{s_{ef}(j)}{s_{ef}(j)-1}} . \qquad (21) \end{aligned}$$

Renewable secondary energy:

- Production function of REN

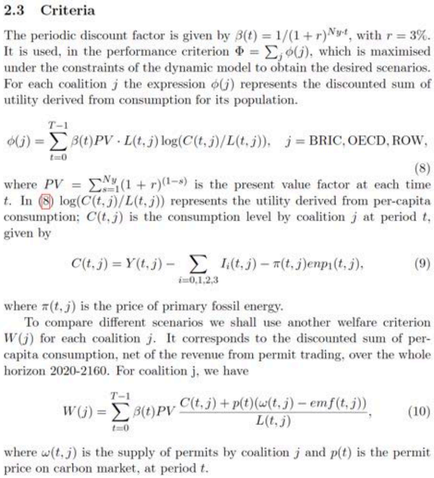
$$enr(t,j) = A_2(j)(tgenr(t,j)K_2(t,j))^{s_2(j)}. \tag{22}$$

- where $K_2(t,j)$ is the stock of capital used to produce renewable secondary energy, for coalition j at period t.

Parameters

- The elasticities ($s_\cdot$) and share parameters ($\alpha_\cdot$), are obtained from calibration (The conventional approach is to calibrate functional parameters to a single benchmark equilibrium.).
- The parameters $tg(t, j)$, $tgv(t, j)$, $tgenf(t, j)$, $tgenr(t, j)$ are exogenously defined productivity growth factors.

Criteria



2.3 Criteria

The periodic discount factor is given by $\beta(t) = 1/(1+r)^{Ny \cdot t}$, with $r = 3\%$. It is used, in the performance criterion $\Phi = \sum_j \phi(j)$, which is maximised under the constraints of the dynamic model to obtain the desired scenarios. For each coalition j the expression $\phi(j)$ represents the discounted sum of utility derived from consumption for its population.

$$\phi(j) = \sum_{t=0}^{T-1} \beta(t) PV \cdot L(t,j) \log(C(t,j)/L(t,j)), \quad j = \text{BRIC}, \text{OECD}, \text{ROW}, \tag{8}$$

where $PV = \sum_{s=1}^{Ny} (1+r)^{(1-s)}$ is the present value factor at each time t. In (8) $\log(C(t,j)/L(t,j))$ represents the utility derived from per-capita consumption; $C(t,j)$ is the consumption level by coalition j at period t, given by

$$C(t,j) = Y(t,j) - \sum_{i=0,1,2,3} I_i(t,j) - \pi(t,j) enp_1(t,j), \tag{9}$$

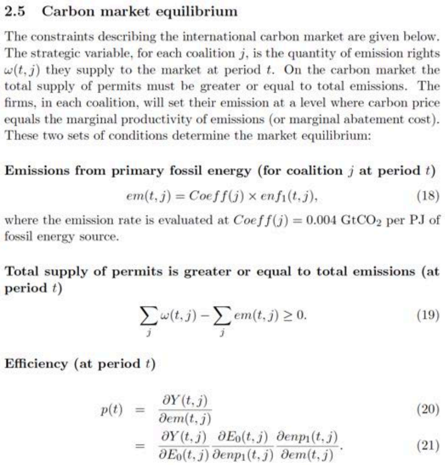
where $\pi(t,j)$ is the price of primary fossil energy.

To compare different scenarios we shall use another welfare criterion $W(j)$ for each coalition j. It corresponds to the discounted sum of per-capita consumption, net of the revenue from permit trading, over the whole horizon 2020-2160. For coalition j, we have

$$W(j) = \sum_{t=0}^{T-1} \beta(t) PV \frac{C(t,j) + p(t)(\omega(t,j) - emf(t,j))}{L(t,j)}, \tag{10}$$

where $\omega(t,j)$ is the supply of permits by coalition j and $p(t)$ is the permit price on carbon market, at period t.

Carbon price



2.5 Carbon market equilibrium

The constraints describing the international carbon market are given below. The strategic variable, for each coalition j, is the quantity of emission rights $\omega(t,j)$ they supply to the market at period t. On the carbon market the total supply of permits must be greater or equal to total emissions. The firms, in each coalition, will set their emission at a level where carbon price equals the marginal productivity of emissions (or marginal abatement cost). These two sets of conditions determine the market equilibrium:

Emissions from primary fossil energy (for coalition j at period t)

$$em(t,j) = Coeff(j) \times enf_1(t,j), \qquad (18)$$

where the emission rate is evaluated at $Coeff(j) = 0.004$ $GtCO_2$ per PJ of fossil energy source.

Total supply of permits is greater or equal to total emissions (at period t)

$$\sum_j \omega(t,j) - \sum_j em(t,j) \geq 0. \qquad (19)$$

Efficiency (at period t)

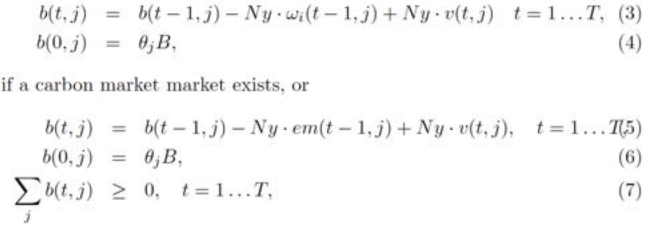
$$\begin{aligned} p(t) &= \frac{\partial Y(t,j)}{\partial em(t,j)} && (20) \\ &= \frac{\partial Y(t,j)}{\partial E_0(t,j)} \frac{\partial E_0(t,j)}{\partial enp_1(t,j)} \frac{\partial enp_1(t,j)}{\partial em(t,j)}. && (21) \end{aligned}$$

Safety emissions budget

- A global cumulative emissions budget of 1170 Gt of CO_2 must be shared among the three coalitions. The sharing summarizes the climate negotiations, e.g.

BUDGET SHARE	
OECD	10%
BRIC	40%
ROW	50%

- BUDGET DYNAMICS

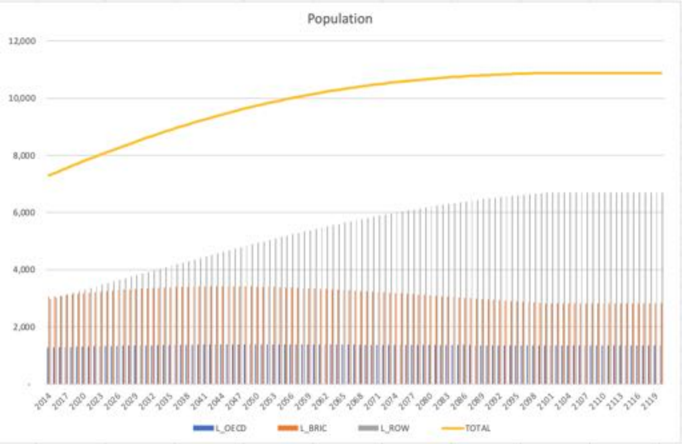


$$\begin{aligned} b(t,j) &= b(t-1,j) - Ny \cdot \omega_i(t-1,j) + Ny \cdot v(t,j) \quad t = 1 \dots T, & (3) \\ b(0,j) &= \theta_j B, & (4) \end{aligned}$$

if a carbon market market exists, or

$$\begin{aligned} b(t,j) &= b(t-1,j) - Ny \cdot em(t-1,j) + Ny \cdot v(t,j), \quad t = 1 \dots T & (5) \\ b(0,j) &= \theta_j B, & (6) \\ \sum_j b(t,j) &\geq 0, \quad t = 1 \dots T, & (7) \end{aligned}$$

Main driver


Population
12,000
10,000
8,000
6,000
4,000
2,000
2014
2017
2020
2023
2026
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2092
2095
2098
2101
2104
2107
2110
2113
2116
2119
L_OECD
L_BRIC
L_ROW
TOTAL

BAU SCENARIO

No climate policy.

BAU emissions

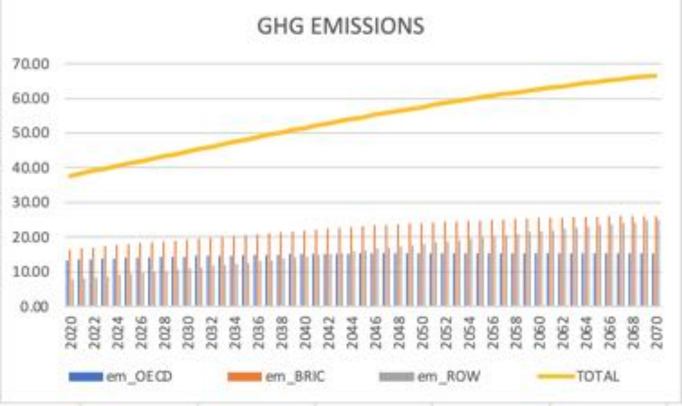

Figure: Emissions in BAU

BAU PER CAPITA CONSUMPTION

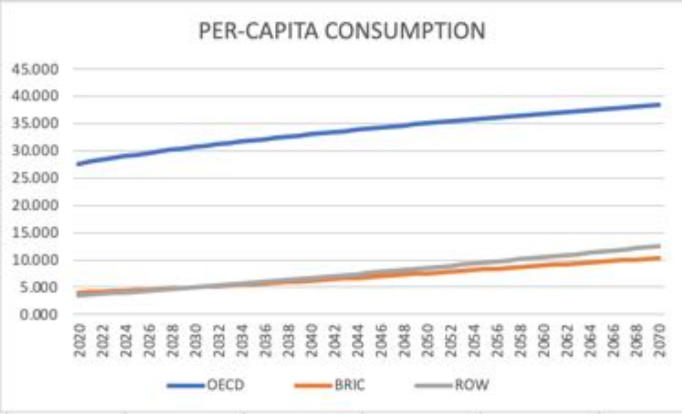

Figure: Per capita consumption in BAU

GREEN SCENARIO

Transition to 100% renewables, NO-DAC

Emissions / GREEN

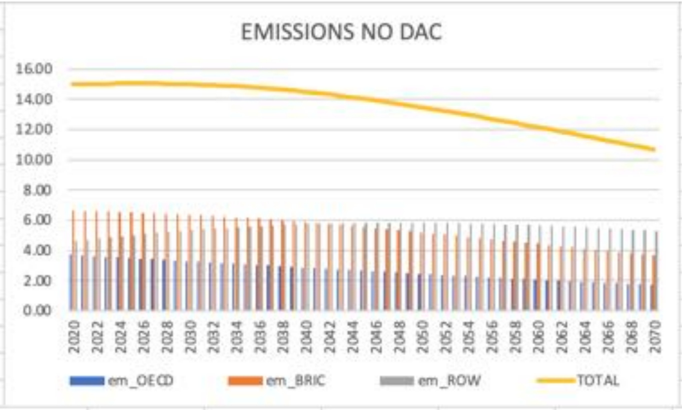

Figure: Emissions NO-DAC

PER CAPITA CONSUMPTION / GREEN

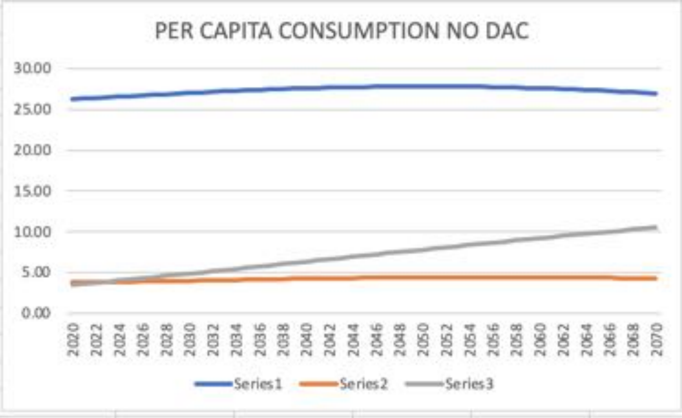

Figure: Per capita consumption NO-DAC

CDR/DAC SCENARIO

CO2 direct reduction with DAC

CO2 MARKET PRICE ($/T)

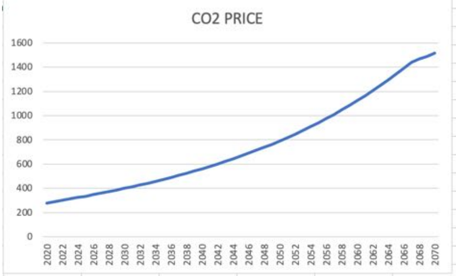

Figure: Carbon price with DAC

CONVERGENCE TO ZNE (GT)

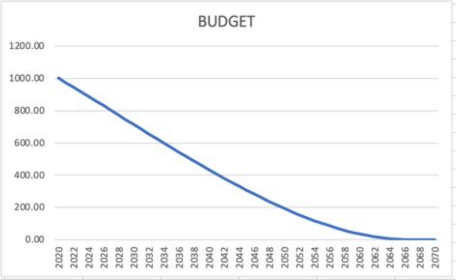

Figure: CUMULATIVE EMISSIONS BUDGET with DAC

dac PER CAPITA CONSUMPTION

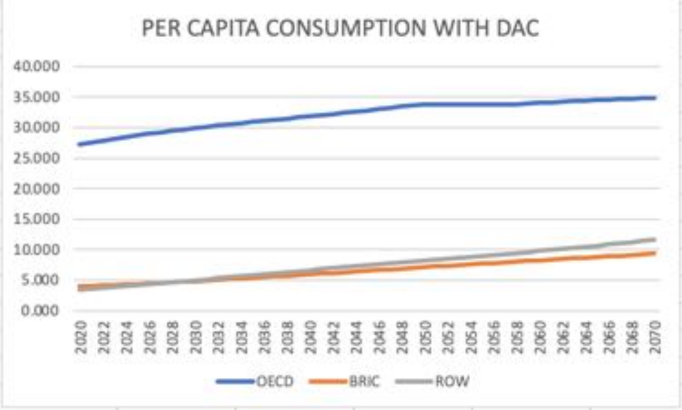

Figure: Per capita consumption / With DAC

DAC & emissions ROW

Figure: Emissions & DAC activity for ROW

DAC & emissions BRIC

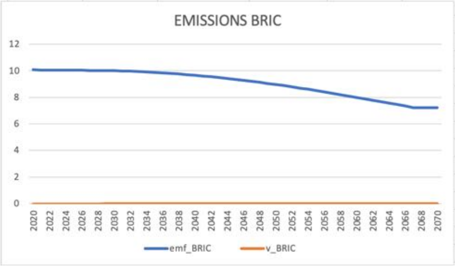

Figure: Emissions & DAC activity for BRIC

DAC & emissions OECD

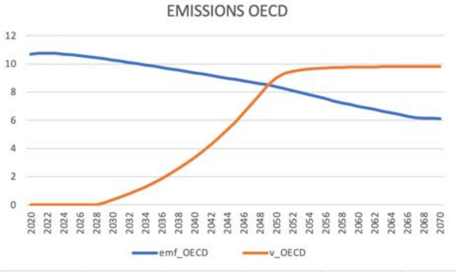

Figure: Emissions & DAC activity for OECD

Total DAC & Emissions

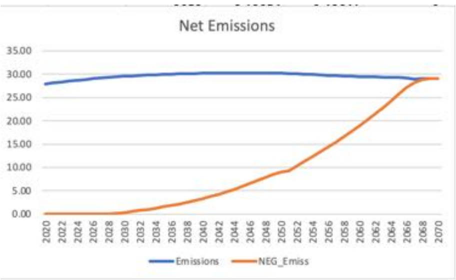

Figure: Emissions & DAC activity

Conclusion

- A compact (Ramsey-type) model, which is calibrated to represent the fundamental options in climate geopolitics.
- Will lend itself to the use of robust control theory or differential games.
- Can easily be adapted to a Markov Decision Process or Markov Game format (though will necessitate large scale Dynamic Programming methods).

Papers

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Alain Haurie

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