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Integrated MARKAL modeling of world cooperative and non-cooperative CO_2 mitigation strategies

Maryse Labriet[1], Richard Loulou[2], Amit Kanudia[3]
[1] University of Quebec in Montreal and Group for Research in Decision Analysis
[2] McGill University and Group for Research in Decision Analysis
[3] KanORs and Group for Research in Decision Analysis
Montreal (Canada)

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Outline

- Introduction
  Non-cooperative climate scenarios
- Integrated MARKAL model
  Coupling of climate damages and MARKAL optimization model
- How to guarantee cooperation of all regions?
  Gain of cooperation over non-cooperation
  Allocation of the gain between the regions
- Conclusion

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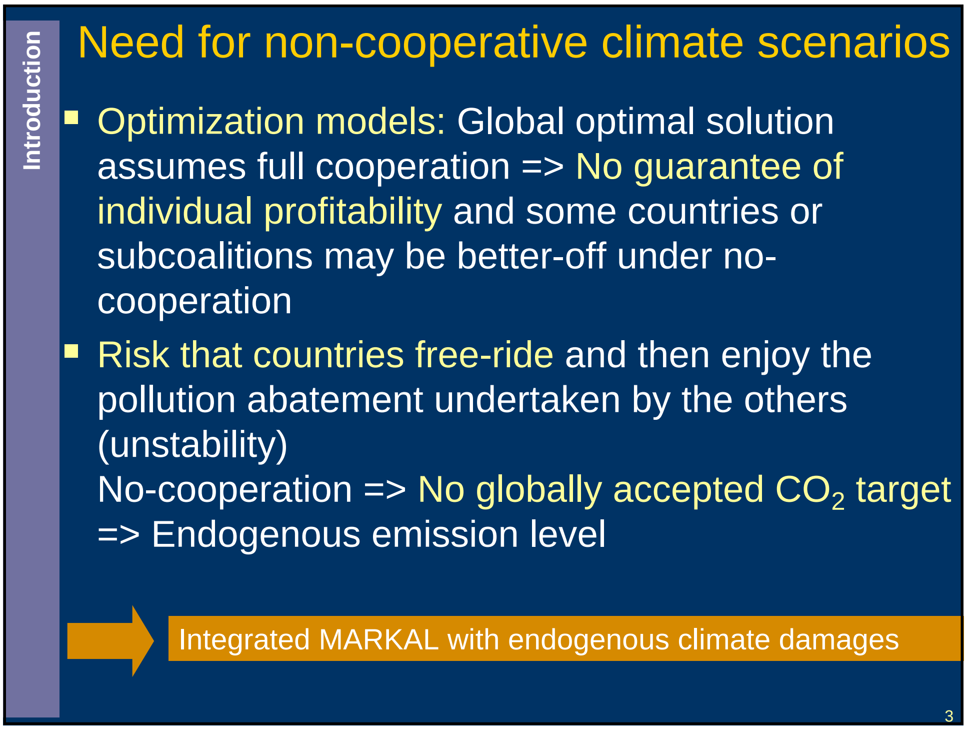
Introduction
Need for non-cooperative climate scenarios
Optimization models: Global optimal solution assumes full cooperation => No guarantee of individual profitability and some countries or subcoalitions may be better-off under no-cooperation
Risk that countries free-ride and then enjoy the pollution abatement undertaken by the others (unstability)
No-cooperation => No globally accepted CO_2 target => Endogenous emission level
Integrated MARKAL with endogenous climate damages
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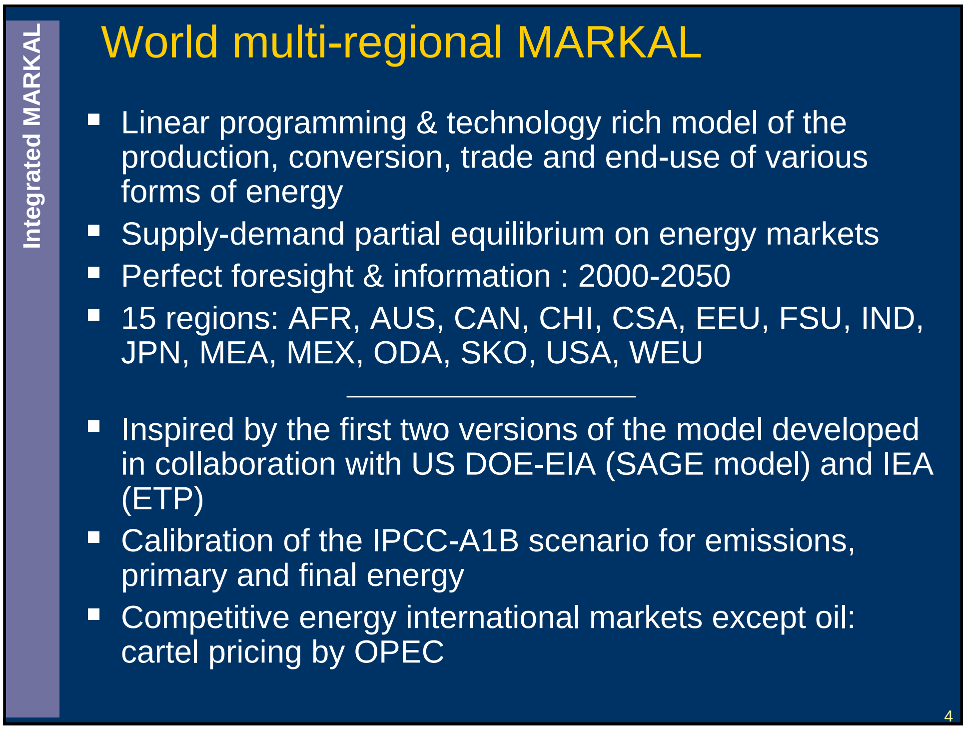
Integrated MARKAL
World multi-regional MARKAL
Linear programming & technology rich model of the production, conversion, trade and end-use of various forms of energy
Supply-demand partial equilibrium on energy markets
Perfect foresight & information : 2000-2050
15 regions: AFR, AUS, CAN, CHI, CSA, EEU, FSU, IND, JPN, MEA, MEX, ODA, SKO, USA, WEU
Inspired by the first two versions of the model developed in collaboration with US DOE-EIA (SAGE model) and IEA (ETP)
Calibration of the IPCC-A1B scenario for emissions, primary and final energy
Competitive energy international markets except oil: cartel pricing by OPEC
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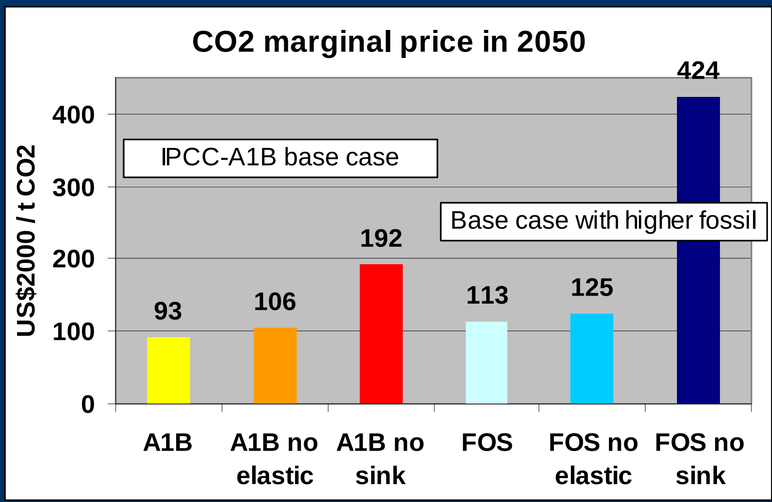
Cooperative scenario 550 ppm

Integrated MARKAL



More details on the version of the MARKAL model used for this work : Labriet et al., 2004 (in press)

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Damages and MARKAL coupling

Integrated MARKAL

- Facilitated by the hypothese (empirical verified) that
  Cum $D_i = a_i$ * Cum Emi $_{world} + b_i$
  (climate model and damages from Nordhaus and Boyer, 1999)
- Under no-cooperation (Nash open-loop), energy decisions by country i depend only on the part of its own damages due to its own emissions
  => MARKAL: min $C_i(X_i,E_i) + a_i * E_i$

Equivalent to a carbon tax
(23$/tCO2 in 2000 up to 261$/tCO2 in 2050

	a_i (US$/tCO2)
AFR	4.15
AUS	0.01
CAN	0.02
CHI	0.68
CSA	1.84
EEU	0.04
FSU	-0.03
IND	3.66
JAP	0.31
MEA	1.33
MEX	0.65
ODA	4.15
SKO	1.06
USA	0.79
WEU	4.10
World	22.75

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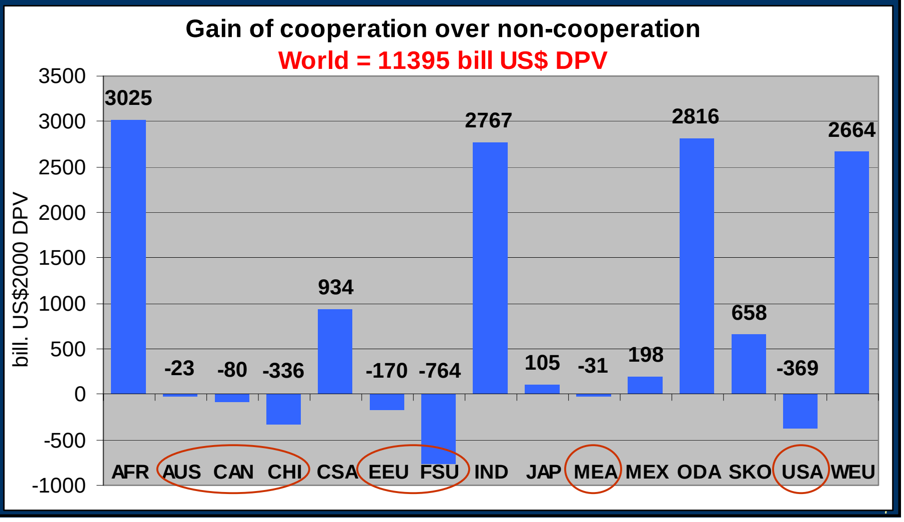
Total gain

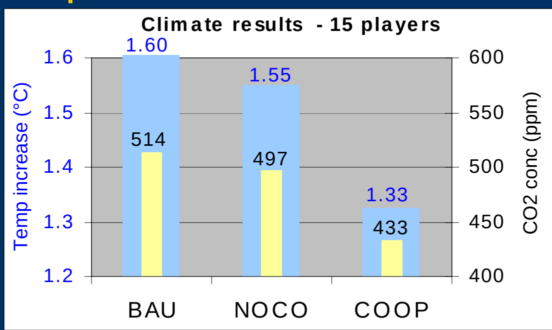
15 players analysis

- Gain = Cost NOCO (15 singletons) - Cost COOP (global coop)
  => Available for side-payments
- Threat = The whole agreement collapses if one region defects

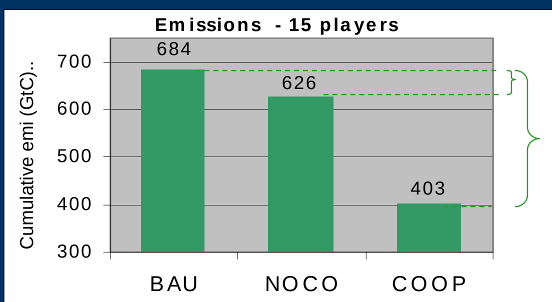


Gap between COOP and NO-COOP (2050)

15 players analysis



NOCO "does less" than the 550 ppm scenario:
ΔT = 1.39 °C
CO_2 = 457 ppm
Cum emi = 482 GtC



NOCO is closer to BAU than to COOP:
cum emission reduction under NOCO = 21% of reduction under COOP

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4 players

Distribution issues

- How to allocate the gain of cooperation among the regions to deter any free-riding behavior?
- 4 players => 15 coalition structures = 15 runs ~ 30h

1 = USA	3 = DC (Developing countries)
2 = WEU	4 = OCD+ (Economy in transition + other OECD)

- Player = pre-existing coalition
  => No-cooperation with 4 players is <u>more</u> than with 15 players: $\Delta T_{4\ players} = 1.43$ °C < $\Delta T_{15\ players} = 1.55$ °C (2050)
- Left-out-players : play individually (no multi-coalition, no punishing behavior)

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4 players

Allocation of the gain of Coop over No-coop

USA & OCD+ are better off in no-cooperation
=> won't cooperate without transfer

Gain of cooperation

A1B-REF		USA	WEU	DC	OCD+	Total
Gain of COOP over Nash w/o transfers (bill. $US\$_{2000}$-DPV)	NASH - COOP	-632	953	4767	-453	4635
Allocation of the gain (bill. $US\$_{2000}$-DPV)	Nucleolus	862	924	1690	1160	4635
	Shapley	774	833	1930	1099	4635
	GTT	161	836	3353	286	4635
	Abatement cost / GDP	889	1052	1799	895	4635
Transfers (payments if negative) (bill. $US\$_{2000}$-DPV)	Nucleolus	1493	**-28**	**-3078**	1613	0
	Shapley	1405	**-120**	**-2838**	1552	0
	GTT	792	**-117**	**-1415**	740	0
	Abatement cost / GDP	1521	99	***-2968***	1348	0

Different normative rules => Different axiomatic properties
=> Different allocations and transfers

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Intermediate coalitions

Stability of coalitions without transfers

- Internal stability: No region has an incentive to leave the coalition (coalition formation approach by Barrett, Carraro & Siniscalco)
- Farsighted players: Takes into account the possibility of subsequent deviations (more realistic)
- No multi-coalitions: When a region deviates, it can not merge with another deviating region

- Starting from [USA WEU DC OCD+]
  => no intermediate coalition is internally stable
- Starting from proposed Kyoto coalition [USA WEU OCD+]
  => coalition [WEU, OCD+] is internally stable

[WEU OCD+] internally stable
(starting from Kyoto coalition)

A1B-REF		Total cost (bill. US$-DPV)				GtC
Coalition	Defector	USA	WEU	DC	OCD+	Total emi
1111	*(COOP)*	59342	53657	147902	52353	403
1101	DC	58772	54094	150308	51782	467
1100	OCD+	58799	54425	151769	51852	493
1001	WEU	58712	54479	152121	51866	498
0101	USA	58659	54328	151326	51830	484
0000	*(NASH)*	58711	54610	152669	51900	507

Final remarks

Conclusion

- First step towards an Integrated MARKAL (energy+climate+damages)
  - Climate is represented by specific damage factors
  - Facilitated by linear damage functions. Non-linear damage functions could also be accommodated (if convex)
  - Two uses of the model for climate change studies
    - COOP: Cost-efficient attainment of a globally agreed CO_2 target (exogenously defined)
    - NO-COOP: Cost-benefit analysis of mitigation strategies where the model balances cost of abatement and climate damages and computes the resulting emissions
  - Few applications related to the use of game theory principles in such a large empirical model

- Future work / limitations
  - More complex climate model could be used with same approach
  - Longer time horizon desirable (TIMES model) => review Dam = f(Cum Emi)
  - Other GHG to be modeled
  - Regular update of MARKAL technologies

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Final remarks

Conclusion

- Future work / limitations
  - Open-loop Nash => perfect foresight and binding commitments => unrealistic? + only lump sum transfers (no allocation over time)
  - Limited number of players => they consist of a large number of different countries assumed to cooperate => lack of realism
  - Uncertainties on: climate parameters, damages, discount rate
- Distribution issues
  - Different allocation rules => different allocation
    => to be chosen by decision-makers
  - Institutional implementation?
  - Sensitivity analyses on base case, damages and sinks (not shown here)
    => level and regional distribution of damages are crucial for transfers and stability
    => base case and sinks are crucial for mitigation cost and technology choices

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Groupe d'Études et de Recherche en Analyse des Décisions (GERAD)
3000 chemin de la Côte Sainte Catherine
Montréal (Qc), H3T 2A7, Canada
Tél.: (514) 340-6053 ext.6033
Fax: (514) 340-5665

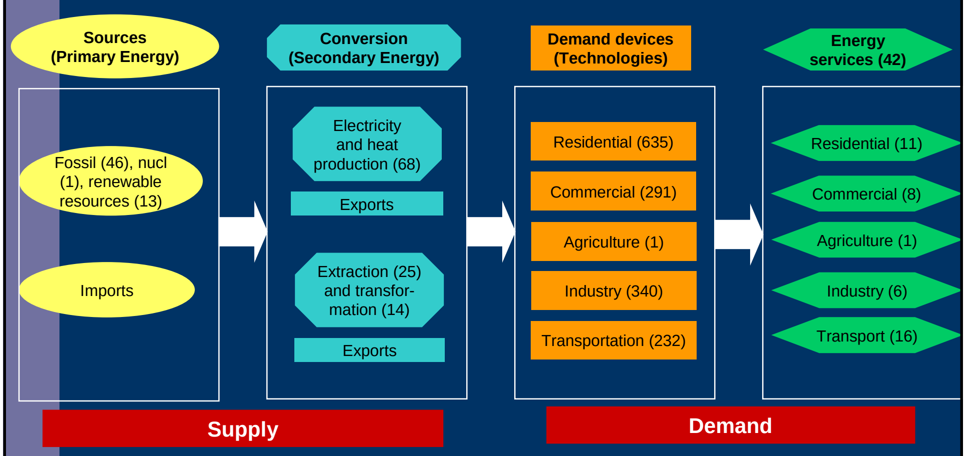
maryse.labriet@gerad.ca

Thank you

Appendix

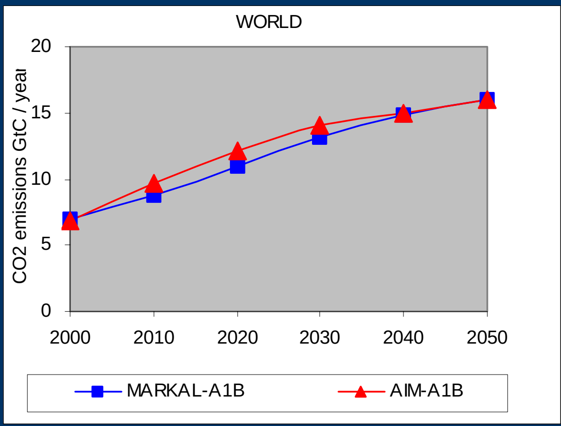
MARKAL

Structure of World Multi-Region MARKAL



MARKAL

Calibration of the base case



MARKAL

Cost analysis

Decrease in 2040 :
penetration of more advanced wind technologies available in 2040

US$2000 / t CO2	2000	2010	2020	2030	2040	2050
550-A1B	0	32.4	60.4	62.6	54.1	92.8
550-A1B not elastic	0	45.3	68.5	71.6	54.0	105.7
550-A1B no sink	0	42.6	119.0	148.9	139.8	191.8
550-FOS	0	36.9	60.9	63.6	55.0	113.2
550-FOS not elastic	0	51	68.8	81.2	67.9	124.5
550-FOS no sink	0	47.8	139.3	194.1	209.6	423.5

Comparison of carbon price between scenarios (more interesting than absolute values) :

- No elastic demands
=> price +14% and +10% in A1B and FOS in 2050
- No CO_2 sequestration
=> price multiplied by more than 2

Comparison with other studies related to the Kyoto Protocol with a global trading of carbon permits (4-44 $US\$_{2000}$ /tCO_2) :

- 2010 prices = high range of carbon prices

Integrated MARKAL

Damages and MARKAL coupling

Hypothesis : Damages depend only on total cumulative emissions, irrespective of the shape of the trajectory

?? $D_i = f_i(\text{CumEmi})$?? → Cum $D_i = a_i$ * Cum $\text{Emi}_{\text{world}} + b_i$

Empirical testing (Labriet *et al.*, 2003) with 30 contrasted emission trajectories (Nakicenovic, 2000), climate model and regional quadratic damage functions of ΔT (Nordhaus and Boyer, 1999)

$$\text{Cost}_i = C_i(X_i,E_i) + D_i\,(\Sigma_k E_k) = C_i(X_i,E_i) + a_i{*}\,\Sigma_k\,E_k + b_i$$

=> Cooperation: $\min \{\Sigma_i\, C_i(X_i,E_i) + (\Sigma_i\, a_i) * (\Sigma_k\, E_k)\}$ *Sum of damages*

=> No-coop (Nash) : $\min\ C_i(X_i,E_i) + a_i * E_i$ *Regional damages only*

- No-Coop = Local optimization problem
- Damages supported by each region i due to emissions of other countries are added *ex-post*
- Assumption of only one interdependency between regions : International trade of energy commodities is not affected by climate policies

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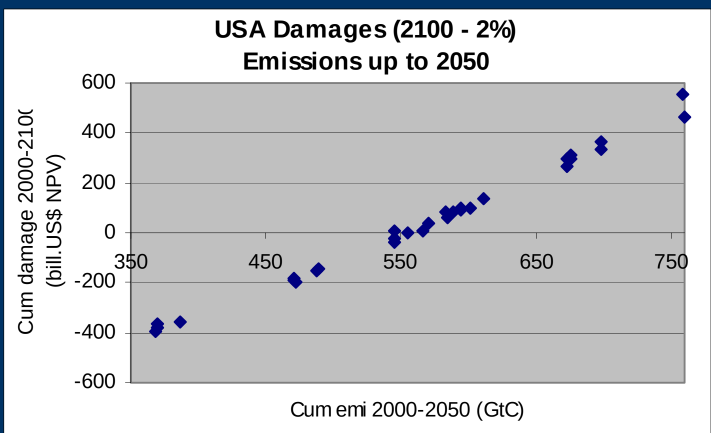
Integrated MARKAL

Damages and MARKAL coupling



Similar curve available for each region and for the world

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15 players

Damages scenarios

Damage factors (US$2000 / tCO2)	Mid damages (^2)	High damages (^3)	Mid damages (^2)	High damages (^3)
Share of damages	High share dev countries	High share dev countries	High share ind countries	High share ind countries
Name of scenario	Reference	High	Reverse	High & reverse
AFR	4.15	6.36	1.14	2.45
AUS	0.01	0.17	0.23	0.49
CAN	0.02	0.37	0.23	0.49
CHI	0.68	3.28	1.37	2.95
CSA	1.84	3.30	0.91	1.96
EEU	0.04	0.41	0.23	0.49
FSU	-0.03	1.89	1.59	3.44
IND	3.66	6.98	1.14	2.45
JPN	0.31	1.21	3.41	7.36
MEA	1.33	2.27	0.34	0.74
MEX	0.65	1.32	0.34	0.74
ODA	4.15	7.27	1.14	2.45
SKO	1.06	1.82	0.46	0.98
USA	0.79	2.78	5.01	10.80
WEU	4.10	9.69	5.23	11.29
Total	22.75	49.10	22.75	49.10
% GDP for 2.5°C	1.94%	4.16%	-	-
% GDP for 2xCO2 (2066)	1.34%	1.94%	-	-

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15 players

Loosers and winners (without transfers)

- Regions with low & intermediate damages: generally not interested in COOP
- FSU (neg dam but small absolute value) prefers BAU (highest emi). In NOCO, local increase of emi by FSU (+1%) is not high enough to compensate emi. reduction by other regions => FSU prefers BAU

PREFERED STRATEGY	Mid damages (^2) High share dev countries	Mid damages (^2) High share ind countries
	A1B-Reference	A1B-Reverse
AFR	COOP	COOP
AUS	NOCO	COOP
CAN	NOCO	COOP
CHI	NOCO	COOP
CSA	COOP	COOP
EEU	NOCO	NOCO
FSU	BAU	COOP
IND	COOP	COOP
JPN	COOP	COOP
MEA	NOCO	NOCO
MEX	COOP	NOCO
ODA	COOP	COOP
SKO	COOP	COOP
USA	NOCO	COOP
WEU	COOP	COOP
Total	COOP	COOP
Gain from full coop (bill.US$ DPV)	11274.82	11879.62

- AUS, CAN, CHI, FSU, USA: switch to COOP
- MEA : still prefers NOCO because of exports reduction under COOP
- EEU : damage factor still too low
- MEX: switch to NOCO

Remarks

- Preferred strategies depend on damage factors and available local options
- Limit of the analysis : Underlying assumption of COOP = all regions are engaged to respect their preferred strategies

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4 players

Results

A1B	Cum emi in base case	Marginal dam (US$$_{2000}$/t$CO_2$) and regional share (%)		% reduction wrt itself			% reduction wrt world reduction			Free rider index	
	A1B-BAU	REF	REV	COOP	NASH-REF	NASH-REV	COOP	NASH-REF	NASH-REV	REF	REV
USA	14.5%	0.78 (3.4%)	5.00 (22.0%)	-33.8%	-1.7%	-14.1%	11.9%	1.0%	11.9%	3.12	0.48
WEU	10.0%	4.10 (18.0%)	5.23 (23.0%)	-40.0%	-17.1%	-20.2%	9.7%	6.6%	9.7%	0.49	0.38
DC	57.8%	16.45 (72.3%)	6.37 (28.0%)	-43.6%	-39.7%	-26.5%	61.3%	88.7%	61.3%	0.77	1.90
OCD+	17.7%	1.40 (6.1%)	6.14 (27.0%)	-39.6%	-5.5%	-23.7%	17.1%	3.7%	17.1%	2.50	0.55
World	100.0%	22.75 (100%)	22.75 (100%)	-41.1%	-25.9%	-23.6%	100.0%	100.0%	100.0%	-	-

FOS	Cum emi in base case	Marginal dam (US$$_{2000}$/t$CO_2$) and regional share (%)		% reduction wrt itself			% reduction wrt world reduction			Free rider index	
	FOS-BAU	REF	REV	COOP	NASH-REF	NASH-REV	COOP	NASH-REF	NASH-REV	REF	REV
USA	14.7%	0.78 (3.4%)	5.00 (22.0%)	-44.2%	-1.1%	-23.4%	13.3%	0.5%	13.3%	4.88	0.77
WEU	9.7%	4.10 (18.0%)	5.23 (23.0%)	-46.8%	-21.3%	-26.1%	9.3%	6.7%	9.3%	0.65	0.51
DC	58.0%	16.45 (72.3%)	6.37 (28.0%)	-50.9%	-47.2%	-33.7%	60.4%	89.4%	60.4%	1.06	2.75
OCD+	17.7%	1.40 (6.1%)	6.14 (27.0%)	-47.2%	-5.8%	-29.1%	17.1%	3.4%	17.1%	3.52	0.81
World	100.0%	22.75 (100%)	22.75 (100%)	-48.9%	-30.6%	-30.7%	100.0%	100.0%	100.0%	-	-

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4 players

Computation of side-payments

- Shapley value
  - Each player obtains a share of the gain that reflects its average contribution to each sub-coalition => merit equity rule, always exists
- CORE
  - Set of imputations that insure that any sub-coalition gains more in the grand coalition than it could secure on its own => certain form of stability, but may be empty
- Nucleolus
  - Minimizes the maximum excess of the coalitions (minimizes the highest dissatisfaction) => unique
- GTT transfers (Germain, Toint and Tulkens, 1997)
  - Takes away, for every region, the diff between costs under Nash and coop + divides the surplus in proportion to marginal damages
- Equalisation of abatement cost / GDP
  - Horizontal equity principle of comparable burdens: all regions should be affected “similarly”

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4 players

Results

bill. US$-NPV2000		Player 1	Player 2	Player 3	Player 4	World
A1B-Reference						
Allocation of the gain	Nucleolus	862	924	1690	1160	4635
	Shapley	774	833	1930	1099	4635
	GTT	161	836	3353	286	4635
	Mitigation cos	889	1052	1799	895	4635
A1B-Reverse						
Allocation of the gain	Nucleolus	972	934	1111	1111	4127
	Shapley	874	857	1305	1091	4127
	GTT	908	949	1156	1114	4127
	Mitigation cos	792	936	1602	797	4127
FOS-Reference						
Allocation of the gain	Nucleolus	1559	1342	2639	1847	7386
	Shapley	1412	1177	3058	1739	7386
	GTT	256	1332	5342	456	7386
	Mitigation cos	1417	1676	2867	1427	7386
FOS-Reverse						
Allocation of the gain	Nucleolus	1335	1335	1335	1335	5338
	Shapley	1193	1188	1687	1270	5338
	GTT	1174	1228	1495	1441	5338
	Mitigation cos	1024	1211	2072	1031	5338

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4 players

Results

bill. US$-NPV2000		Player 1	Player 2	Player 3	Player 4	World
A1B-Reference						
Transfer to receive/give wrt COOP	Nucleolus	1493	-28	-3078	1613	3106
	Shapley	1405	-120	-2838	1552	2957
	GTT	792	-117	-1415	740	1532
	Mitigation cos	1521	99	-2968	1348	2968
A1B-Reverse						
Transfer to receive/give wrt COOP	Nucleolus	-424	-770	1591	-397	1591
	Shapley	-523	-846	1786	-416	1786
	GTT	-489	-755	1637	-393	1637
	Mitigation cos	-605	-767	2083	-711	2083
FOS-Reference						
Transfer to receive/give wrt COOP	Nucleolus	2379	-102	-4630	2353	4732
	Shapley	2232	-266	-4211	2245	4477
	GTT	1076	-112	-1926	963	2038
	Mitigation cos	2236	232	-4401	1933	4401
FOS-Reverse						
Transfer to receive/give wrt COOP	Nucleolus	-372	-859	1822	-591	1822
	Shapley	-513	-1006	2174	-655	2174
	GTT	-532	-966	1982	-484	1982
	Mitigation cos	-683	-982	2559	-894	2559

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