

Compatibility of a severe climate target with *ad hoc* intermediate emission quotas

A PLANETS study via ETSAP-TIAM

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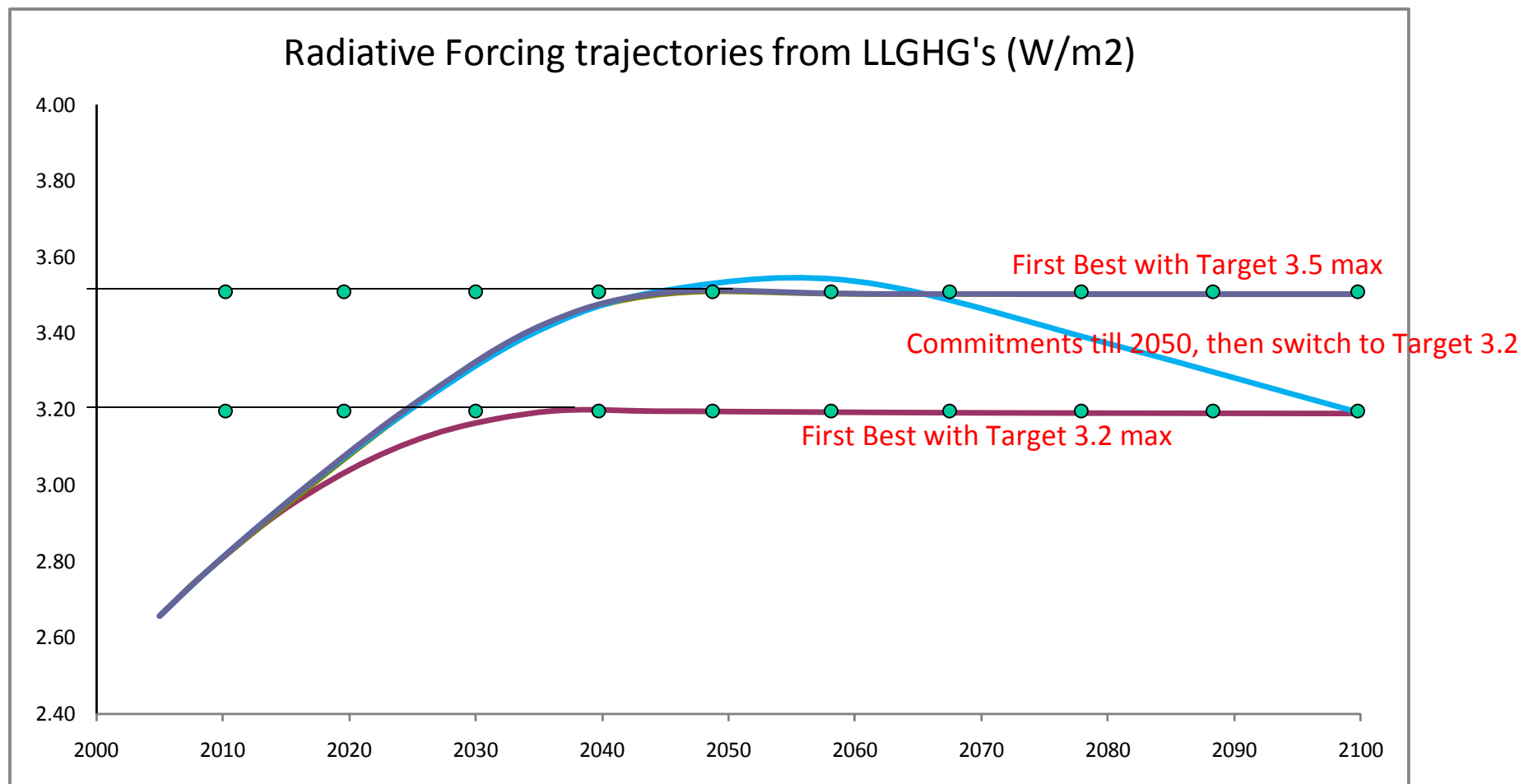
IEW, Venezia, June 17-19, 2009

I. Objectives and scenarios

Issues

- PLANETS scenarios: long-term climate objective and intermediate (2050) *ad hoc* Commitments (emission quotas).
- Long term targets:
 - Radiative Forcing value of 3.2 W/m² **or** 3.5 W/m² in 2100, from all LLGHG's
- Intermediate commitments
 - Two alternative sets of emission commitments
 - Differentiated by country groupings
 - each set is globally compatible with the long-term 3.5 W/m² forcing target
- Thus the questions are:
 - Can the World switch from a 3.5 W/m² course (till 2050) to a 3.2 W/m² target (in 2100)? Or, is 2050 too late a date to do the switch?
 - What are the costs incurred by the various groups of countries ?
 - What are the best technological choices ?
 - Subsidiarity issue: can the switch be done while limiting emission trading?

Sketch of the PLANETS Global Forcings



Ten Scenarios

Scen	Summary	Targets	Codes
First Best (FB)	All regions cooperate fully (and trade) from 2012 onward to achieve the target(s) efficiently	Two targets: • 3.2 W/m ² • 3.5 W/m ²	FB-3p2 FB-3p5
Second Best (SC)	• Global ETS starts in 2020 • 4 groups of countries: OECD, Energy EXporters, DEveloping Asia, ROW • Each group of countries has an emission commitment until 2050, with different starting date of commitment, and then all countries join the global climate coalition • Two different series of commitments (SC1 and SC2)	Until 2050: Fixed commitments After 2050: Two targets • 3.2 W/m ² in 2100 • 3.5 W/m ² in 2100	SC1-3p2 SC1-3p5 SC2-3p2 SC2-3p5
Variant (Var)	Same as Second Best, but Trading limited to 20% of reductions	Until 2050: Fixed commitments After 2050: Two targets • 3.2 W/m ² in 2100 • 3.5 W/m ² in 2100	Var1-3p2 Var1-3p5 Var2-3p2 Var2-3p5

The two alternate commitments

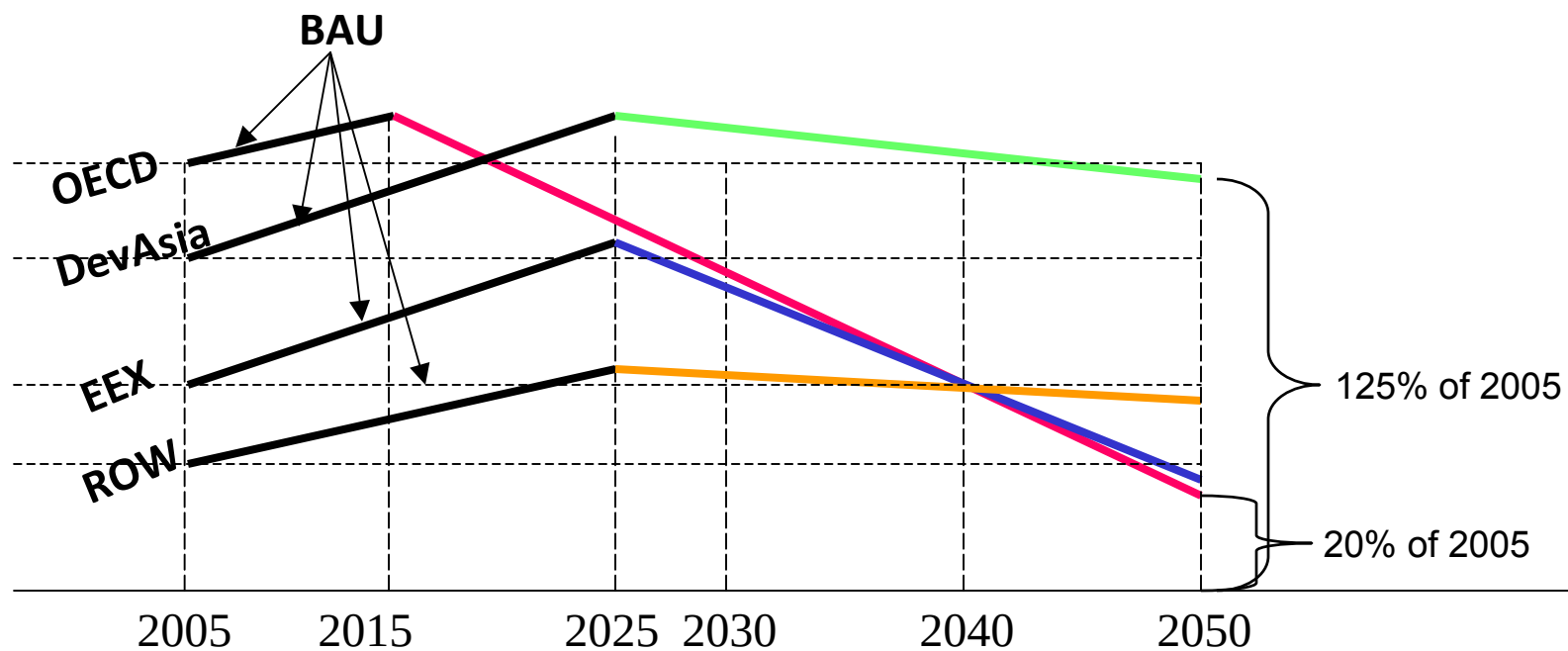
	STARTING DATE OF COMMITMENTS	COMMITMENTS SC1 & Var1 in 2050 wrt 2005	COMMITMENTS SC2 & Var2 in 2050 wrt 2005
OECD	2015	-80%	-90%
ENERGY EXPORTING EEX – Russia and Mid East	2025	-50%	0%
DEVELOPING ASIA	2025	25%	0%
ROW	2025	55%	100%
WORLD w.r.t. 2005		-27%	-27%

Note: EU implements some actions before 2020

Comments:

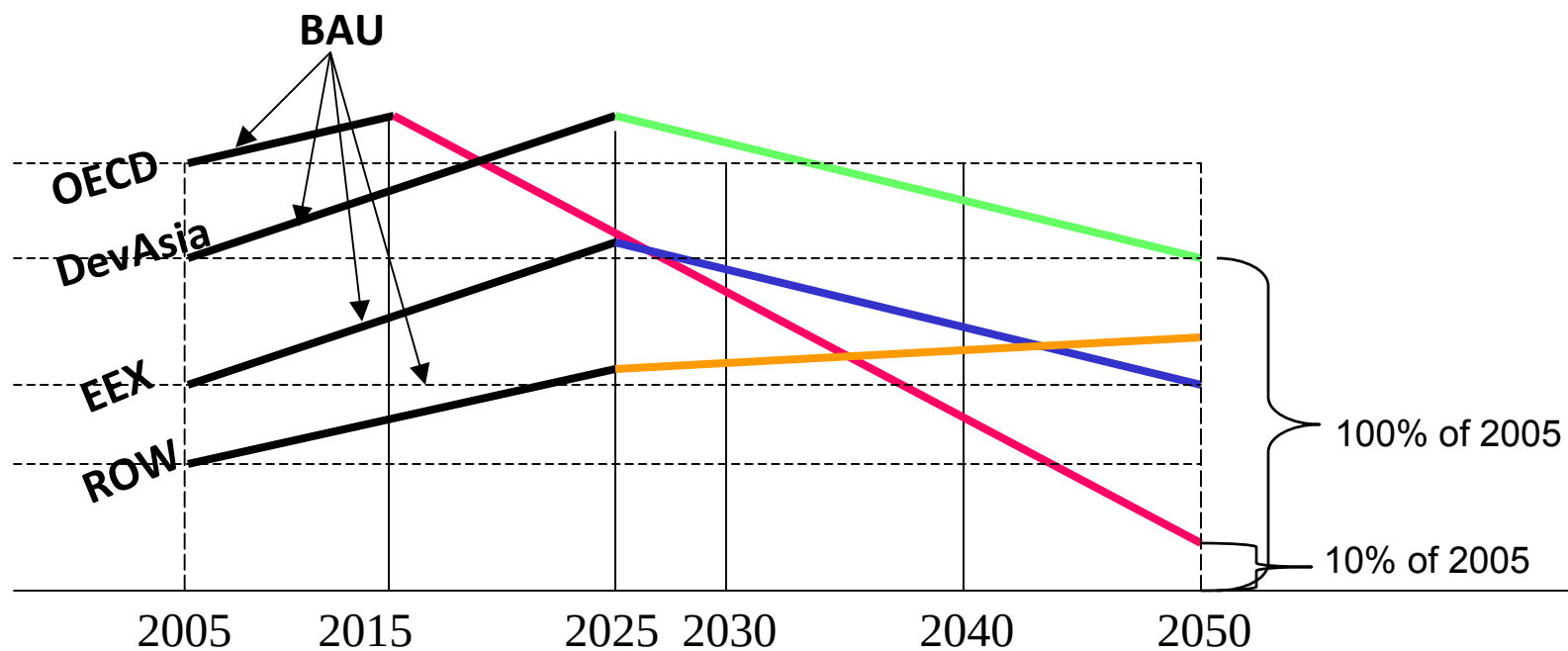
- SC1 and SC2 are very close globally, but regionally different
 - (SC2 is easier than SC1 for EEX and ROW but harder for DevAsia and OECD)
- VARx differs from SCx only due to limited trading. Hence, has higher global cost
- All commitments allow banking and borrowing (thus are cumulative commitments)

Illustration of commitment SC1



Commitments may use Banking and Borrowing, so that only **Cumulative** Commitments matter

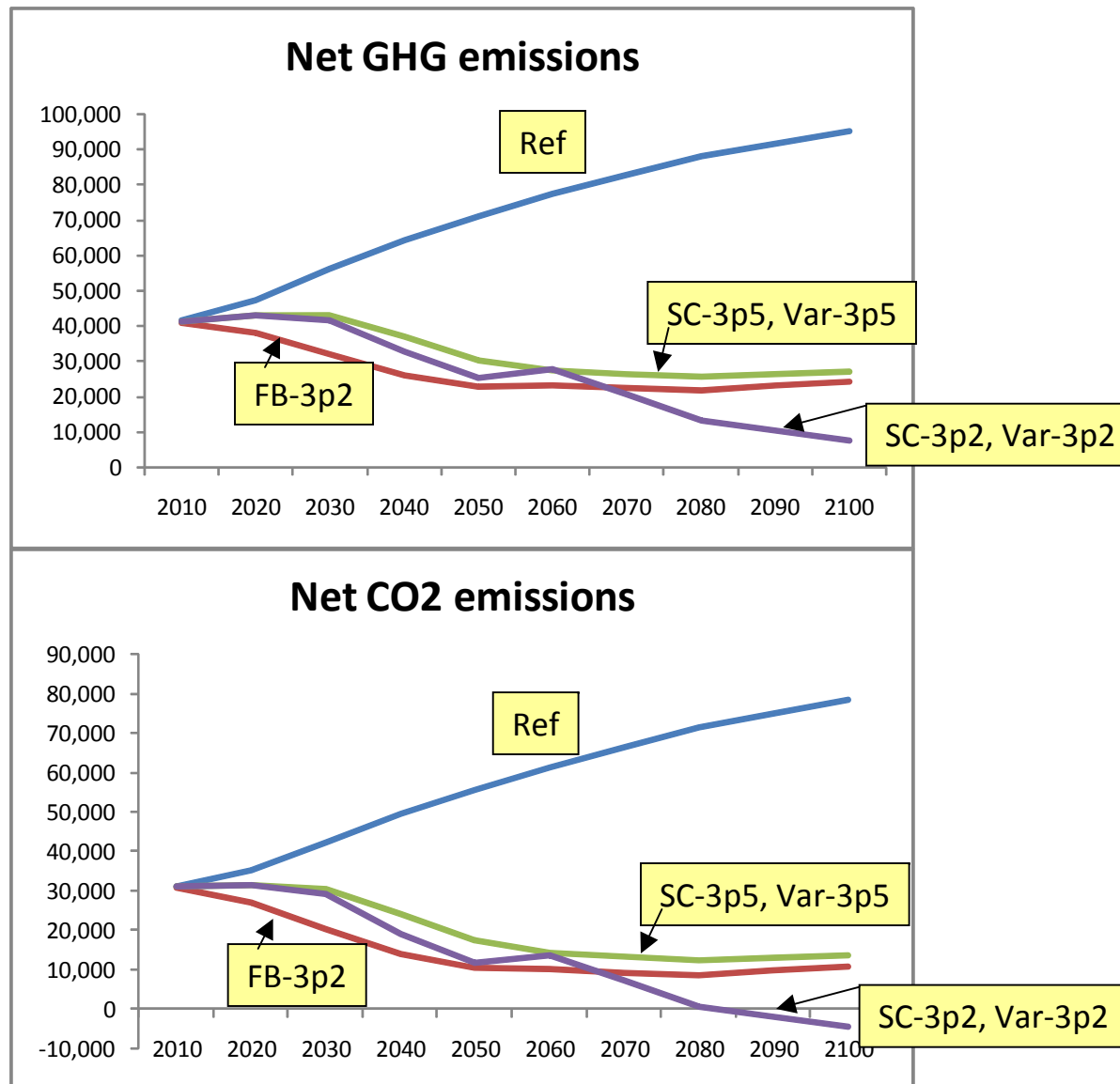
Illustration of commitment SC2



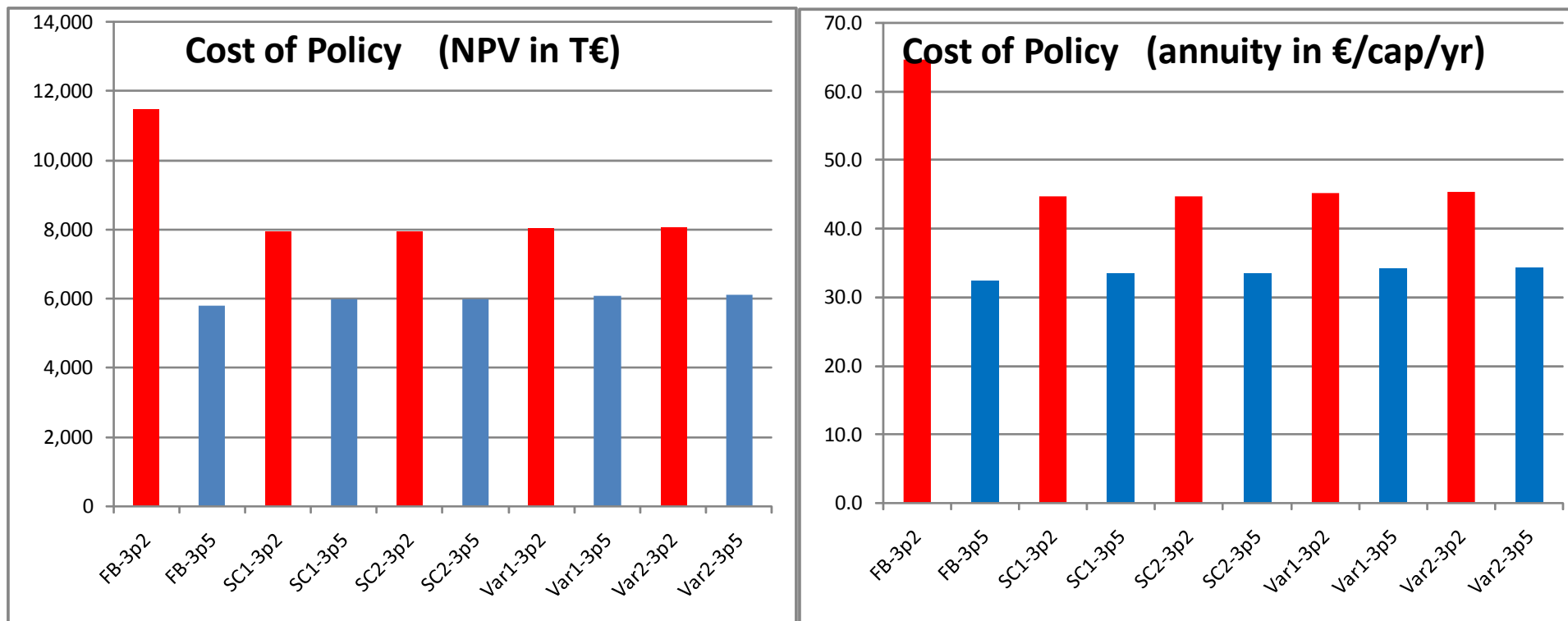
Commitments may use Banking and Borrowing, so that only **Cumulative** Commitments matter

II. Results and Analysis

Global Emissions (Mt CO₂-eq/yr)



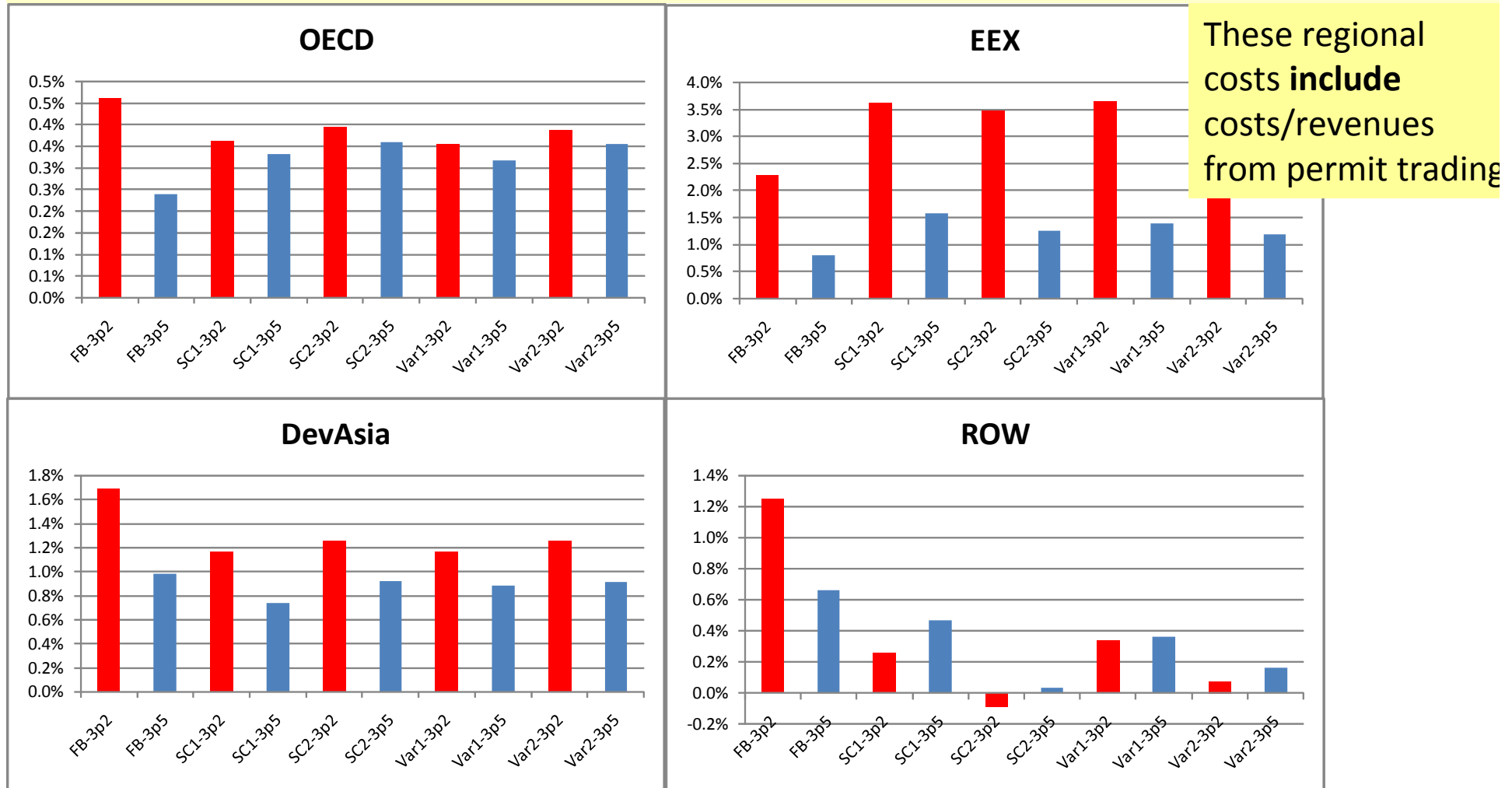
Global Costs of Policies



Comments

- Target has by far the largest influence on global policy cost
- Ranking: (1) 3p2 max, (2) 3p2 with commitments, (3) 3p5 --with or without commitments.
- Commitments influence cost of 3p5 target only very slightly
 - This has an important policy implication: timing of emissions before 2050 is relatively unimportant as long as cumulative emissions are respected.
- Limiting trading to 20% of reductions has a very small impact on global cost/

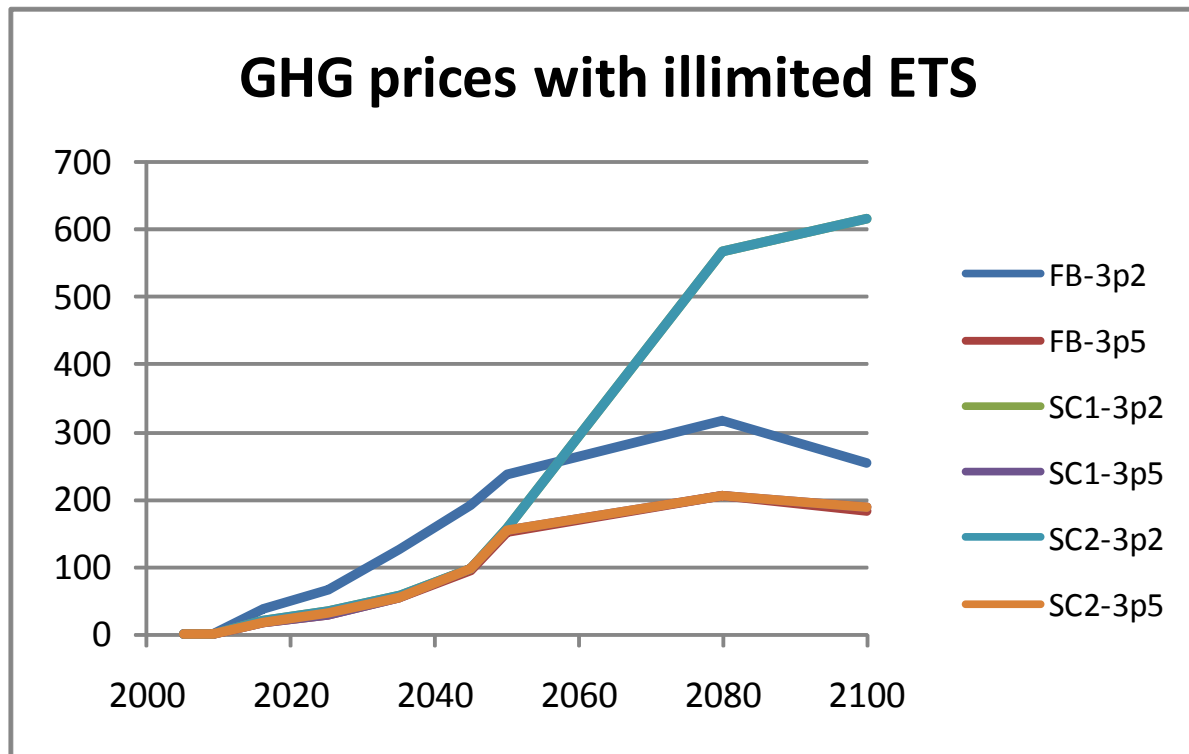
Regional policy costs as % of GDP



Comments:

- EEX is most affected by Commitments
- ROW benefits from Commitments, especially from SC2
- Limited trading is detrimental to ROW only for SC2
- Developing Asia has higher costs per GDP than OECD

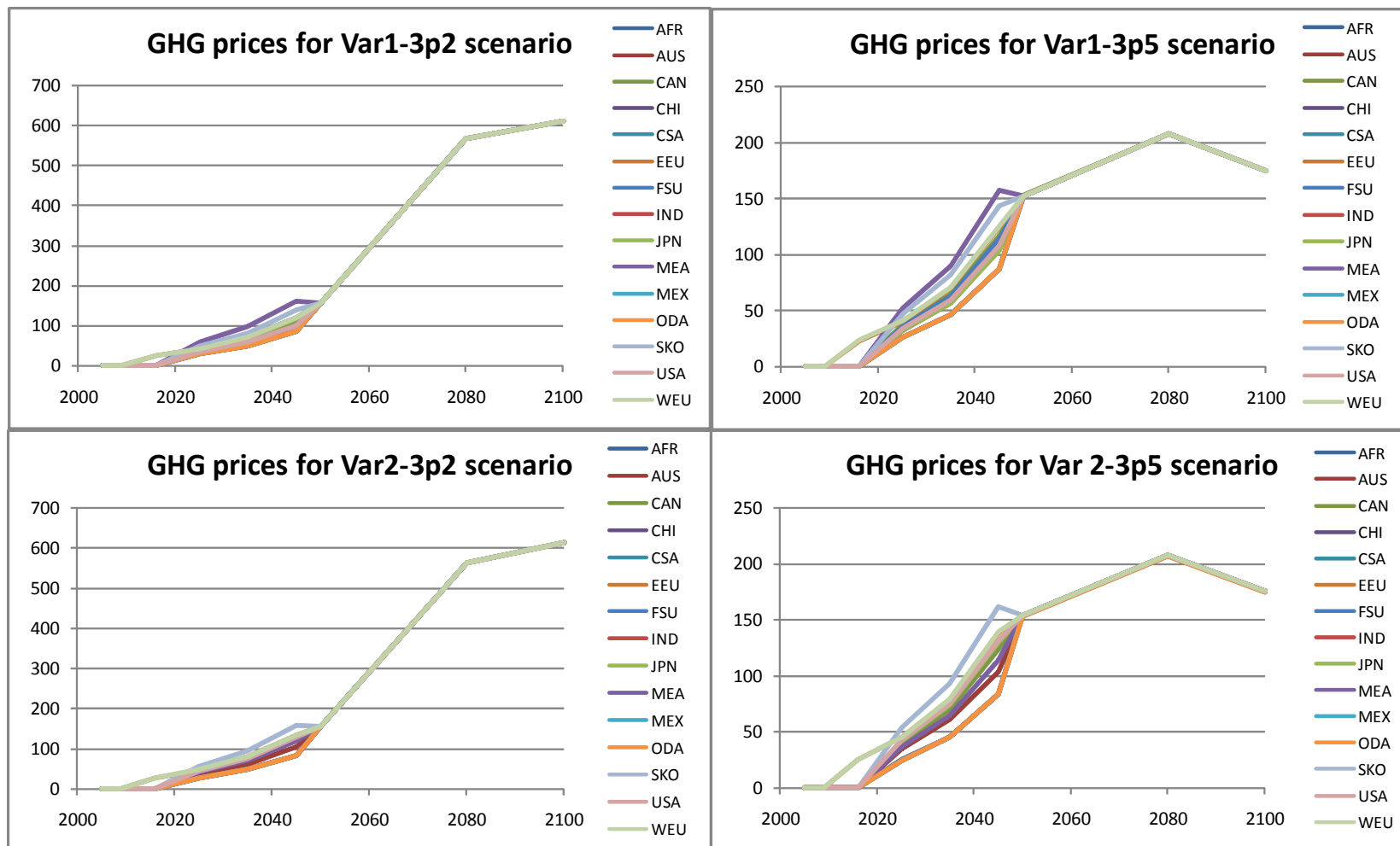
GHG prices with unlimited trading (€/t CO₂eq)



Comments:

- Large price increase when switching from 3p5 to 3p2 target after 2050
- Confirms earlier cost results

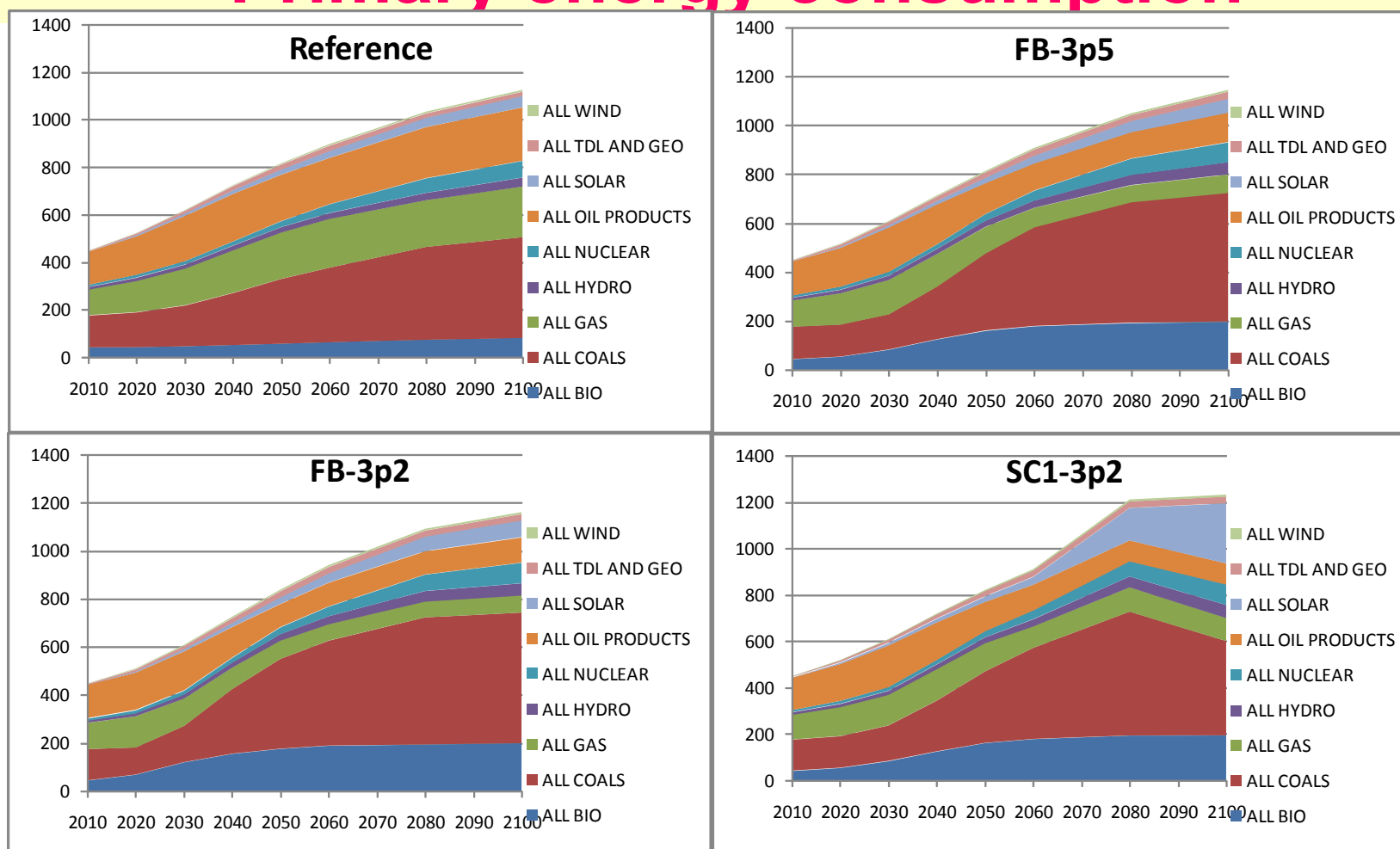
GHG prices with limited trading (fragmented regime)



Comments:

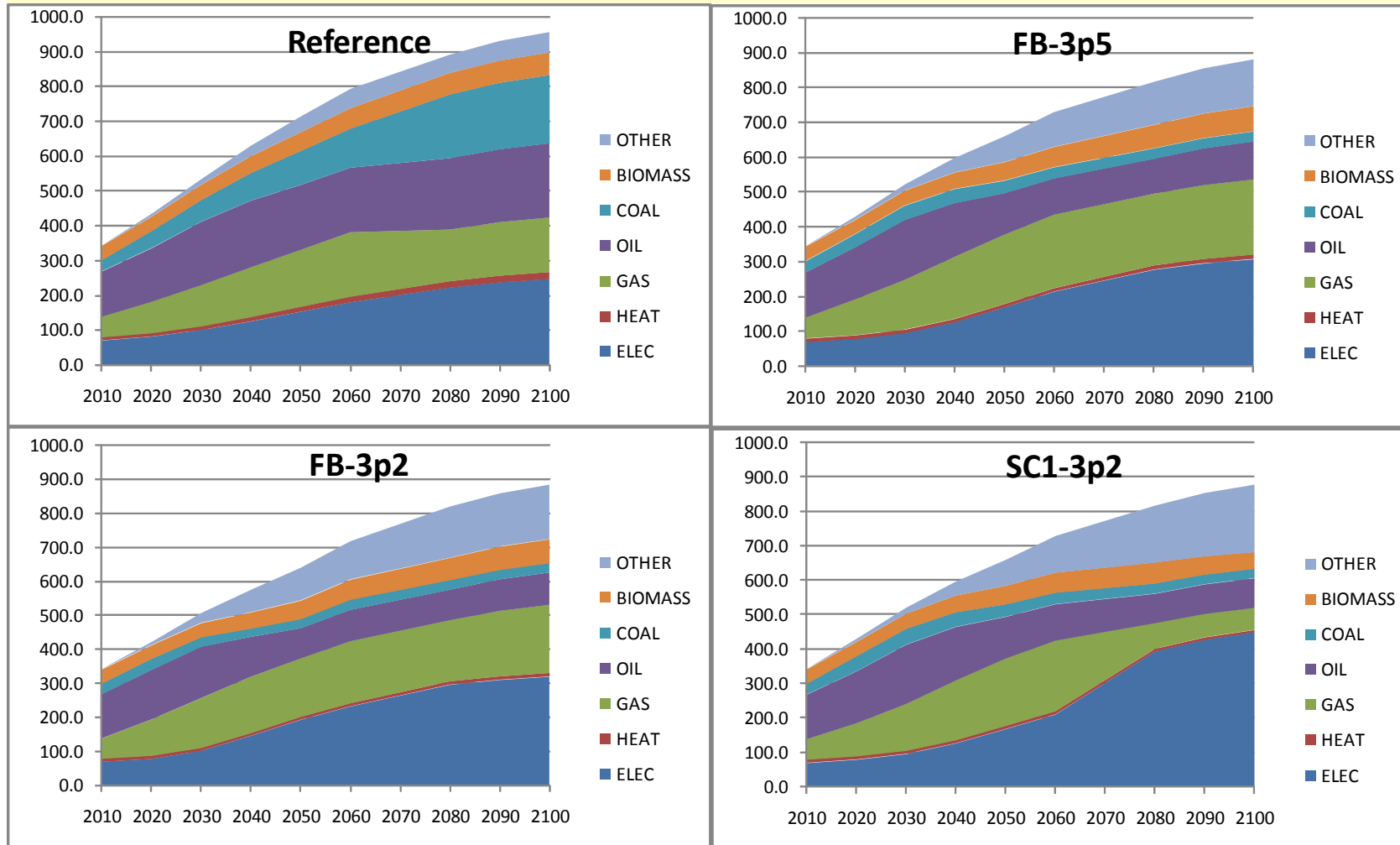
- Regions that had more than 20% permit imports are now penalized with higher carbon prices:
 - EU, FSU, Canada, Australia, MidEast, Japan, So. Korea
- Regions that were large exporters of permits now have lower prices but are also losers in terms of overall cost

Primary energy consumption



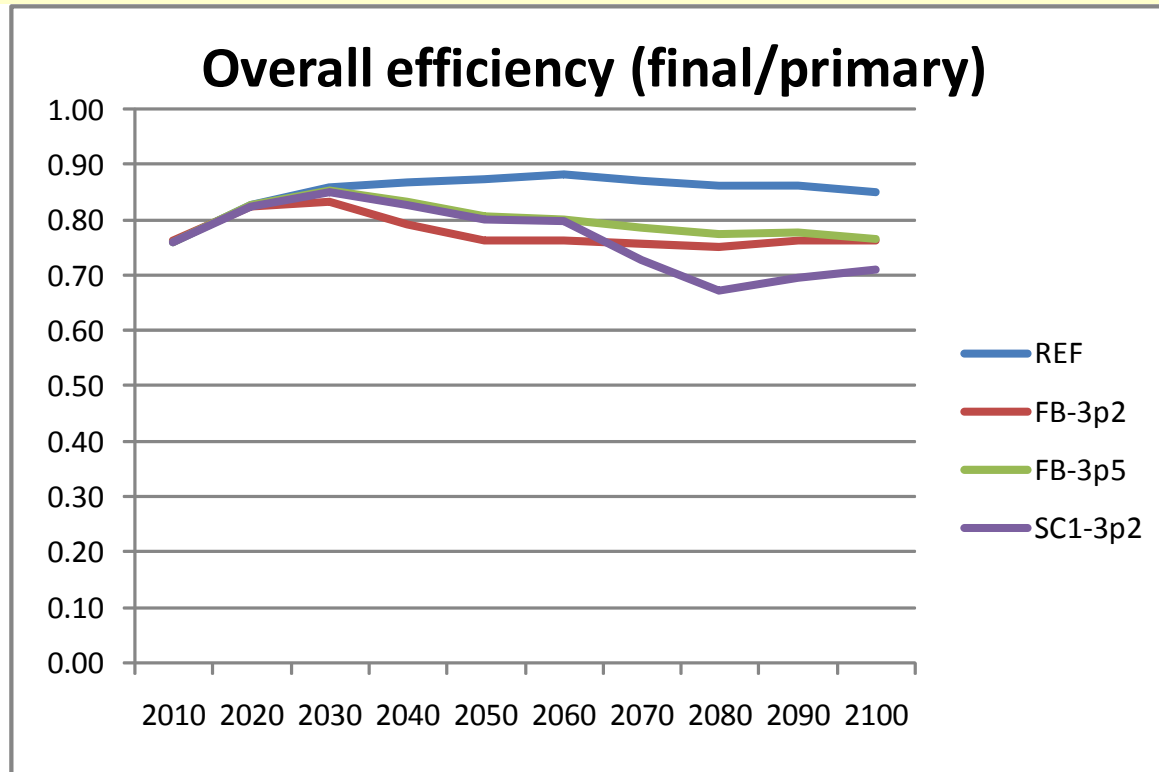
- **Total Primary consumption** is larger in Policy scenarios than in Reference, due to more wood and coal use in electricity sector (with CCS)
- **Oil and gas** decrease drastically
- **Coal, Biomass** increase strongly, **nuclear and solar** moderately (solar strong in SC-3p2 scenario)

Final energy in four scenarios EJ/yr



- Around 9 to 11% **final energy savings** in policy scenarios, relative to Reference
- **Coal and oil** products decrease drastically in end-uses, replaced by **electricity** and direct **solar** heat.
- **Gas** increases too, except in worst case scenario

Overall system efficiency

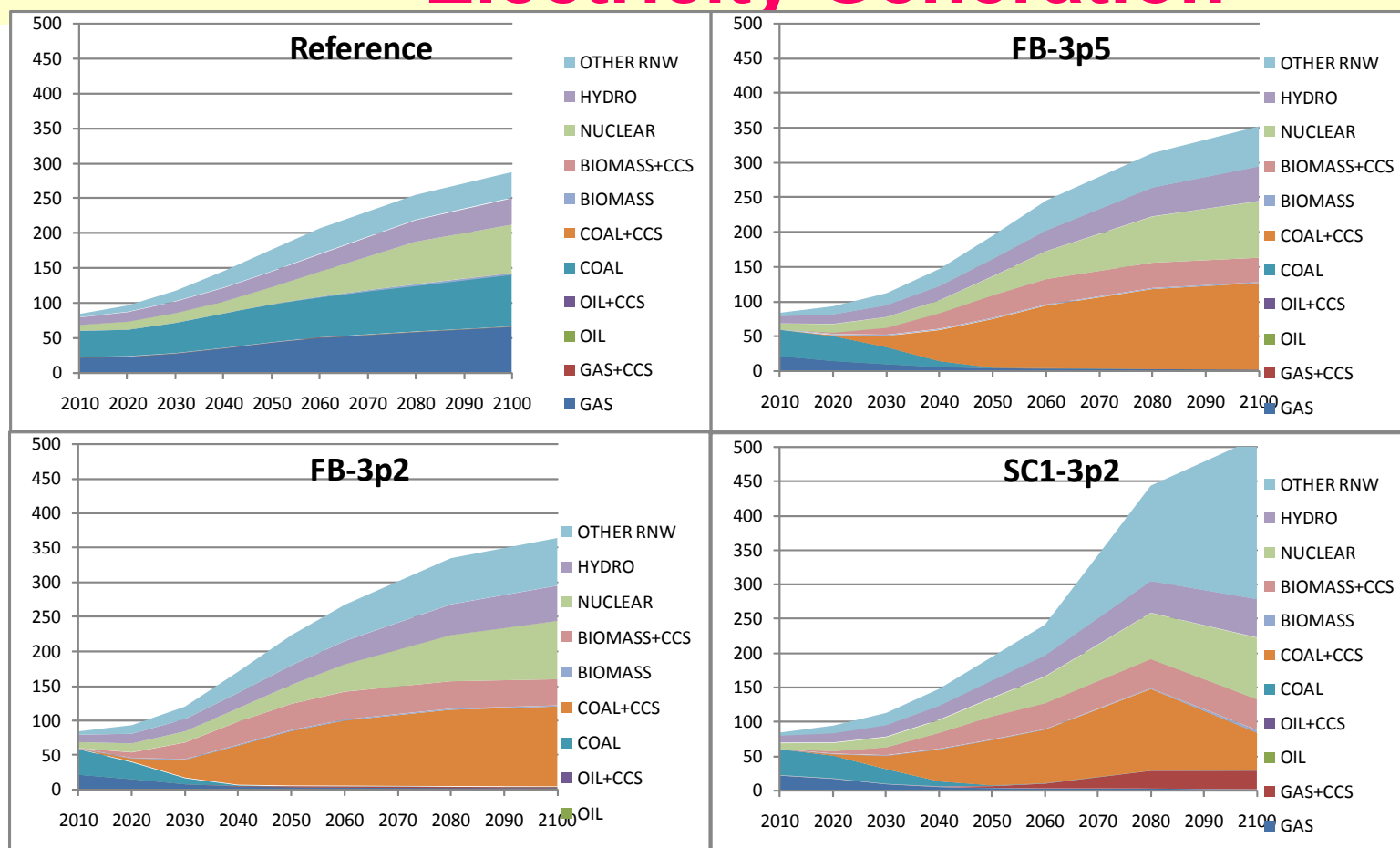


1. **Overall efficiency** (i.e. final/primary energy) **decreases** with Climate policies, **WHY ?**

- Biomass and coal plants with CCS are less efficient than gas plants
- Electricity end-uses increase (and elec production less efficient)
- **Lesson:** Climate objectives are not always congruent with Energy Efficiency

2. However, **end-use efficiency** does increase, as expected (previous slide)

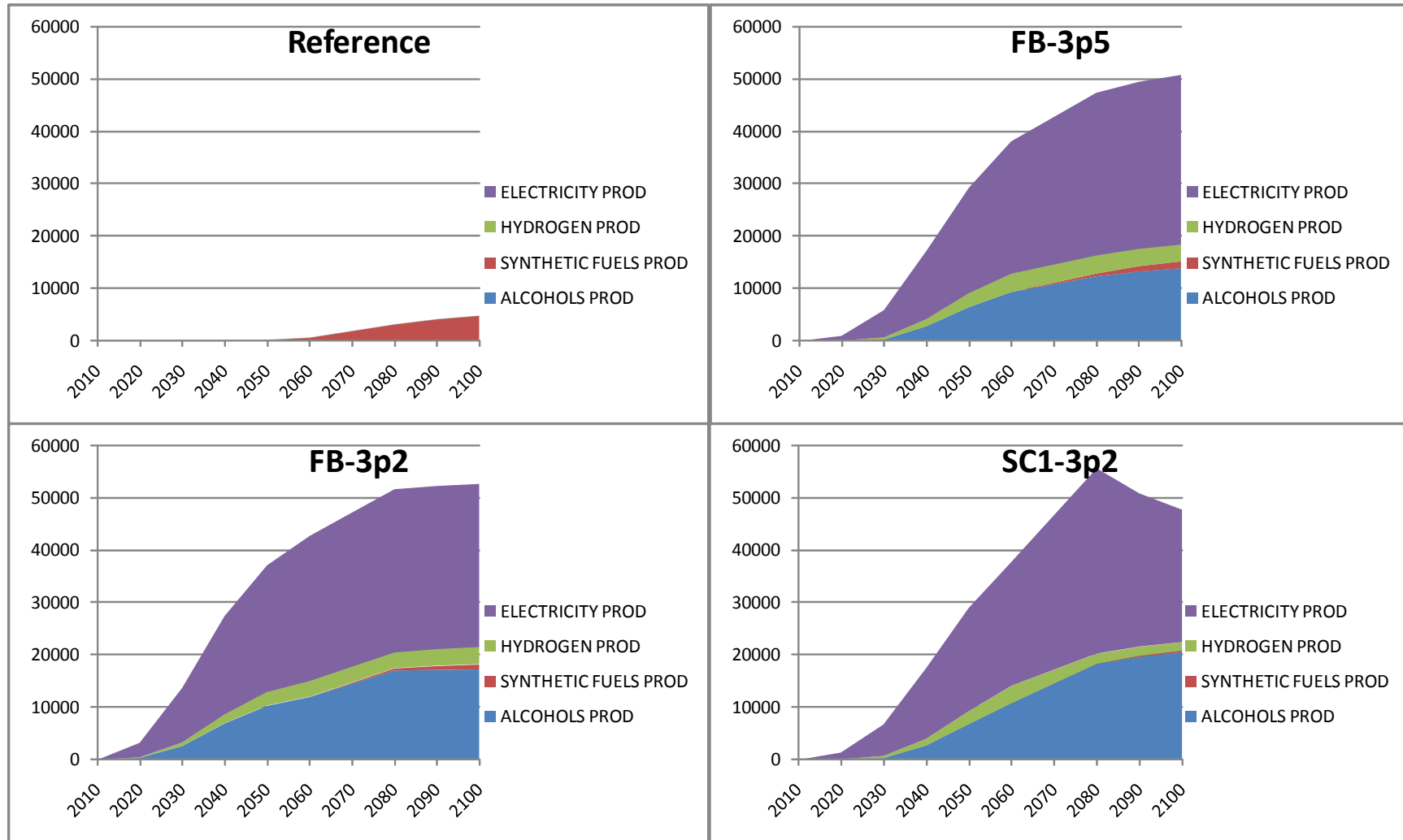
Electricity Generation



Comments

- Increased **electricity** production (from RNW and/or fossil + CCS) is a strategy to reduce emissions via substitution of end-use fossil fuels in buildings and industry
- **Biomass** plants with CCS result in negative emissions
- In SC1-3p2, **RNW** enter massively in late century (zero emission)
- **Nuclear** increases too, but has limited potential in several regions

CO2 sequestered from various processes Mt/yr



- **CCS** plays a large role in climate scenarios:
 - **Elec production:** Coal+CCS, Biomass+CCS, Gas+CCS
 - **Alcohols production:** Coal+CCS (but also from Biomass w/o CCS)
 - **Hydrogen production:** Gas+CCS, Coal+CCS
 - **Synthetic fuels production:** Coal+CCS

Conclusions so far

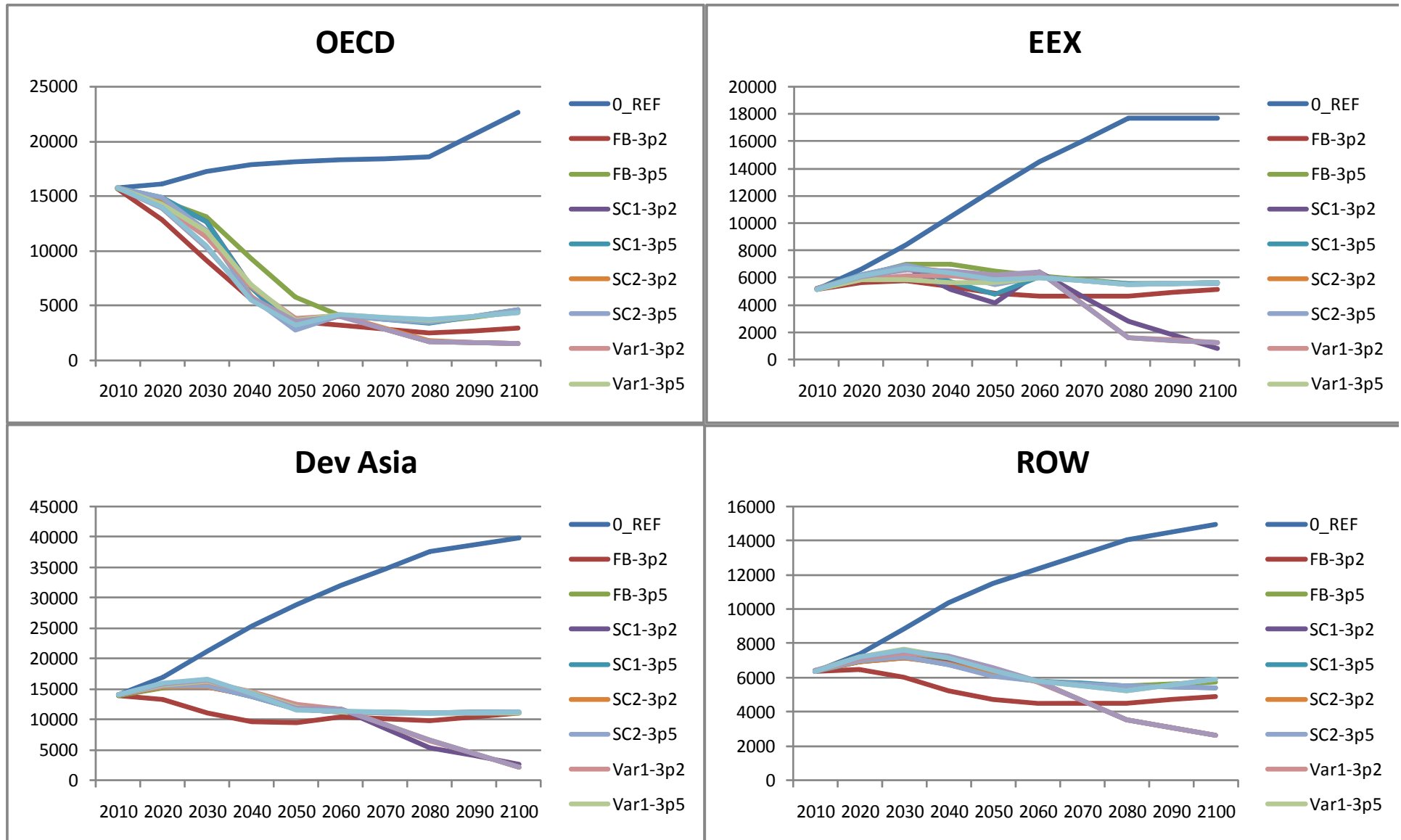
- The 3p5 target is reachable at moderate global costs
 - Commitments till 2050 do not make a large difference, but this is no surprise, since Commitments were **designed** to be compatible with 3p5 optimal trajectory
- The 3p2 target is much more demanding:
 - With First Best: global costs are 2x to 3x larger than 3p5 costs
 - With Commitments: global costs are 3x to 5x larger
- Why?
 - With SC-3p2, the World is on a 3.5 path till 2050, but must then “catch-up” in order to reach 3.2 in 2100.
 - This is a **costly but perhaps realistic** scenario: agreements are made till 2050 but must be then revised if and when a severe climate threat materializes.
- Regional costs not quite equitable with our choice of quotas:
 - EEX countries incur highest costs per GDP for SC and VAR scenarios
 - Followed by: Developing Asia, OECD, and ROW

Conclusions (cont'd)

- Carbon capture and storage a key technology in several sectors
 - Electric Power plants
 - Hydrogen, alcohols and synthetic fuels production, for the transportation sector
- A few Policy insights:
 - Availability of CCS highly desirable, and would reduce policy costs considerably
 - Rapid global diffusion of key technologies is important, especially in EPG sector (CCS, RNW, Nuclear)
 - The policy of restricted permit trading does not affect significantly the cost of the scenarios
- Further work should focus on:
 - new sets of quotas (equitable quotas)
 - different date for commitments (2030?)
 - More detail on allocation of emission rights **after** end of regional quotas.

III. Additional results

GHG emissions (Mt CO₂eq/yr)



Global Costs of Policies

	NPV in B\$	NPV in B\$			
	Cost of Policy (vs. REF)	extra cost of commitment vs First Best	extra cost of 3.2 target vs 3.5 target	extra cost of permit limitation	extra cost of SC2 vs SC1
FB-3p2	11,484		5,712		
FB-3p5	5,773				
SC1-3p2	7,933		1,963		
SC1-3p5	5,971	198			
SC2-3p2	7,935		1,963		1
SC2-3p5	5,971	199			1
Var1-3p2	8,036		1,970	102	
Var1-3p5	6,065	293		95	
Var2-3p2	8,058		1,960	123	22
Var2-3p5	6,098	326		127	33

	\$/cap/yr	\$/cap/yr			
	Cost of Policy (vs. REF)	extra cost of commitment vs First Best	extra cost of 3.2 target vs 3.5 target	extra cost of permit limitation	extra cost of SC2 vs SC1
FB-3p2	64.6		32.1		
FB-3p5	32.5				
SC1-3p2	44.6		11.0		
SC1-3p5	33.6	1.1			
SC2-3p2	44.6		11.0		0.007
SC2-3p5	33.6	1.1			0.004
Var1-3p2	45.2		11.1	0.57	
Var1-3p5	34.1			0.53	
Var2-3p2	45.3		11.0	0.69	0.13
Var2-3p5	34.3			0.71	0.18

Comments

Target 3.2max is much more costly than 3.5max or 3.2 with commitments
 Extra global cost due to commitments is small (about 4 to 6% of FB policy cost)
 Extra global cost due to limited permit trading is even smaller (about 2%)
 Extra global cost of SC2 vs SC1 is negligible

IV. TIAM: Model description

TIAM: TIMES INTEGRATED ASSESSMENT MODEL

- TIAM is an incarnation of TIMES with the following characteristics:
 - 15 region global model
 - Region-dependent technoeconomic data
 - Trade of energy and emission rights between regions
 - Long term horizon (up to 100 years)
 - Demands are driven by drivers obtained from a global CGE model (GEM-E3)
 - Global climate equations allowing climate targets

15 regions + OPEC/Non-OPEC

Africa*

Australia-New Zealand

Canada

Central and South America*

China

Eastern Europe

Former Soviet Union

India

Japan

Mexico

Middle-East*

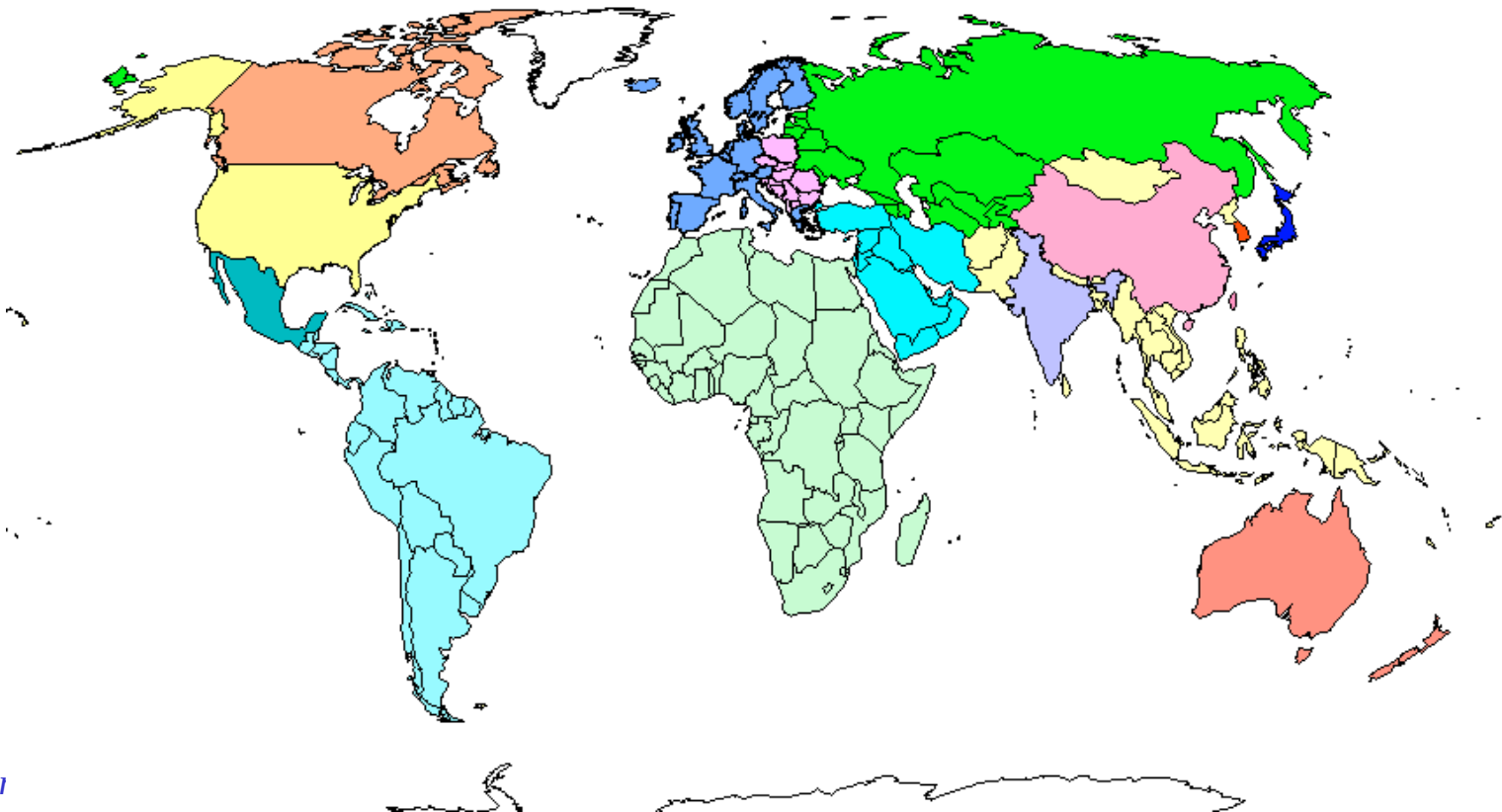
Other Developing Asia*

South Korea

United States

Western Europe

* In these four regions, the energy supply sector is further disaggregated into OPEC and Non-OPEC supplies



List of countries in multi-country regions

Region	Country
AFR	Algeria, Angola, Benin, Cameroon, Congo, Congo Republic, Egypt, Ethiopia, Gabon, Ghana, Ivory Coast, Kenya, Libya, Morocco, Mozambique, Nigeria, Other Africa ^a , Senegal, South Africa, Sudan, Tanzania, Tunisia, Zambia, Zimbabwe
CSA	Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Other Latin America ^b , Panama, Paraguay, Peru, Trinidad-Tobago, Uruguay, Venezuela
EEU	Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Macedonia, Poland, Romania, Slovakia, Slovenia, Yugoslavia
FSU	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
MEA	Bahrain, Cyprus, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, Yemen
ODA	Bangladesh, Brunei, Chinese Taipei, Indonesia, North Korea, Malaysia, Myanmar, Nepal, Other Asia ^c

Sao Tome and Principe, Seychelles, Sierra Leone, Somalia, Swaziland, Togo, Uganda. Excluded due to lack of data: Comoros, Namibia, St. Helena, Western Sahara.

^b Included: Antigua and Barbuda, Bahamas, Barbados, Belize, Bermuda, Dominica, French Guiana, Grenada, Guadeloupe, Guyana, Martinique, St. Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, Suriname. Excluded due to lack of data: Aruba, British Virgin Islands, Cayman Islands, Falkland Island, Montserrat, St. Pierre and Miquelon, Turks and Caicos Islands.

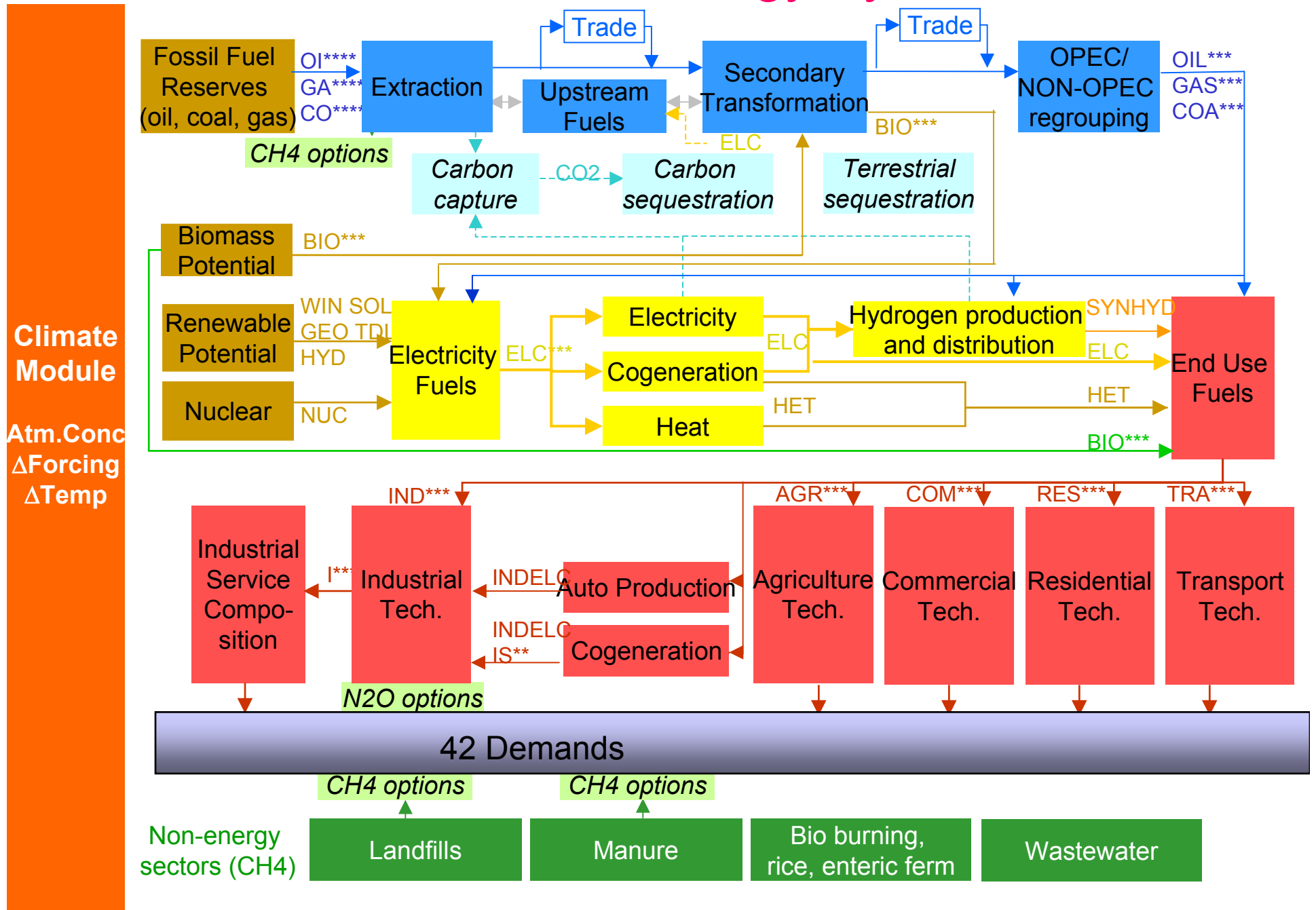
^c Included: Afghanistan, Bhutan, Fiji, French Polynesia, Kiribati, Maldives, New Caledonia, Papua-New-Guinea, Samoa, Solomon Islands, Vanuatu. Excluded due to lack of data: American Samoa, Cambodia, Christmas Island, Cook Islands, Laos, Macau, Mongolia, Nauru, Niue, Pacific Islands, Tonga, Wake Island.

^d Includes Monaco.

^e Includes San Marino and Vatican City

^f Includes Liechtenstein

Reference Energy System



A. Demand projections

Storyline (BASE CASE) : population dynamics, technical progress, etc.

GEMINI-E3

Drivers: GDP, sectoral outputs, Population, Households

GDP: medium annual growth (2.4%)

$GDP(2100) = 12 * GDP(2000)$

POP: grows to 9 billions (2000-2100)

$DEM = K * (Driver)^{elasticity}$

End-use demands of TIAM

Elasticities:

- saturation in the long term
⇒ lower elasticities after 2050
- convergence of developing and industrialized countries around 2050

End-use demands

	Code	Unit
<i>Transportation segments (15)</i>		
Autos	TRT	Billion vehicle-km/year
Buses	TRB	Billion vehicle-km/year
Light trucks	TRL	Billion vehicle-km/year
Commercial trucks	TRC	Billion vehicle-km/year
Medium trucks	TRM	Billion vehicle-km/year
Heavy trucks	TRH	Billion vehicle-km/year
Two wheelers	TRW	Billion vehicle-km/year
Three wheelers	TRE	Billion vehicle-km/year
International aviation	TAI	PJ/year
Domestic aviation	TAD	PJ/year
Freight rail transportation	TTF	PJ/year
Passengers rail transportation	TTP	PJ/year
Internal navigation	TWD	PJ/year
International navigation (bunkers)	TWI	PJ/year
Non-energy uses in transport	NEU	PJ/year
<i>Residential segments *(11)</i>		
Space heating	RH1, RH2, RH3, RH4	PJ/year
Space cooling	RC1, RC2, RC3, RC4	PJ/year
Hot water heating	RWH	PJ/year
Lighting	RL1, RL2, RL3, RL4	PJ/year
Cooking	RK1, RK2, RK3, RK4	PJ/year
Refrigerators and freezers	RRF	PJ/year
Cloth washers	RCW	PJ/year
Cloth dryers	RCD	PJ/year
Dish washers	RDW	PJ/year
Miscellaneous electric energy	REA	PJ/year
Other energy uses	ROT	PJ/year

Road

End-use demands

*Commercial segments *(8)*

Space heating	CH1, CH2. CH3, CH4	PJ/year
Space cooling	CC1, CC2. CC3. CC4	PJ/year
Hot water heating	CHW	PJ/year
Lighting	CLA	PJ/year
Cooking	CCK	PJ/year
Refrigerators and freezers	CRF	PJ/year
Electric equipments	COE	PJ/year
Other energy uses	COT	PJ/year

Agriculture segment (1)

Agriculture	AGR
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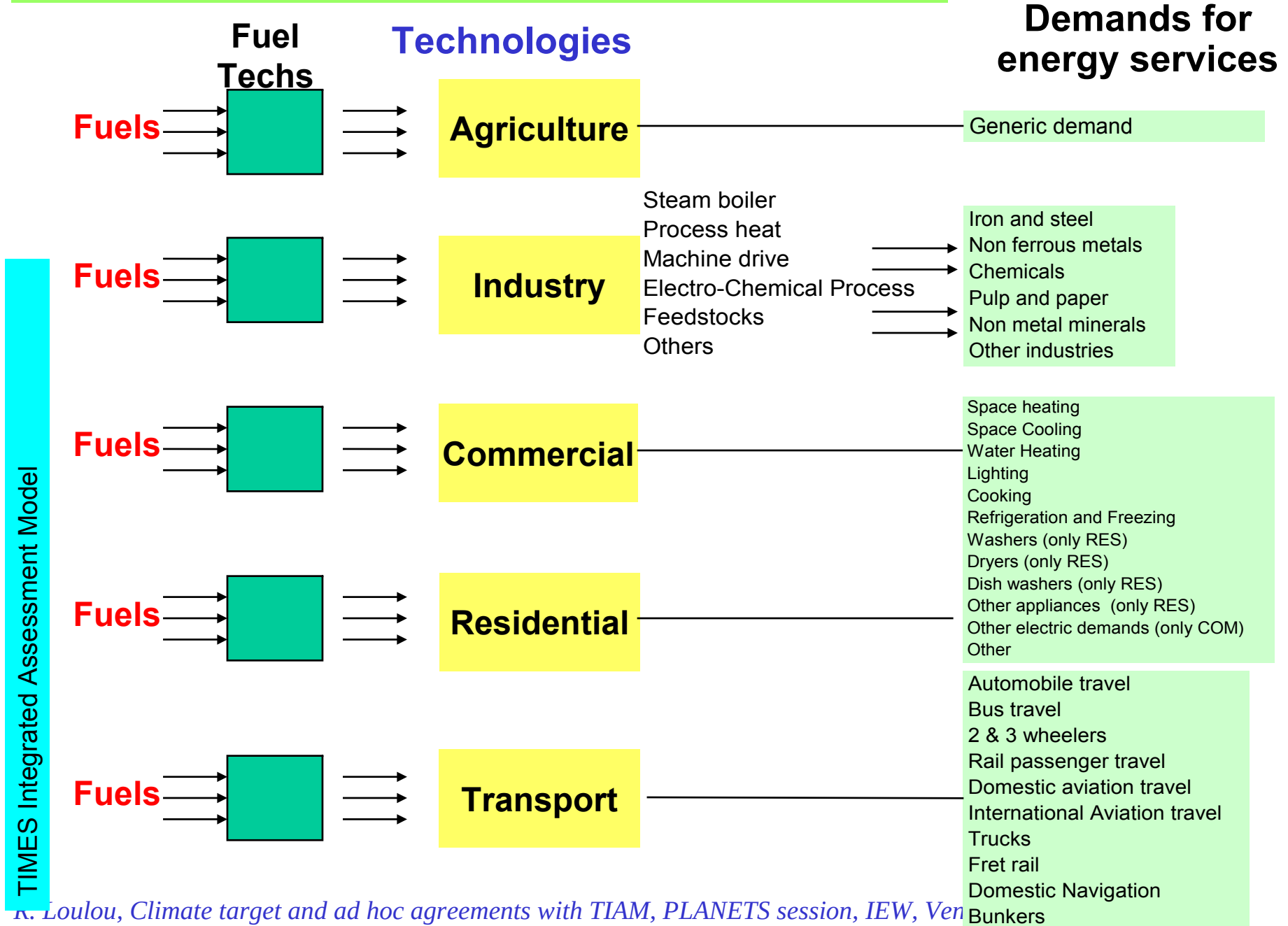
*Industrial segments ** (6)*

Iron and steel	IIS	Millions tonnes
Non ferrous metals	INF	Millions tonnes
Chemicals	ICH	PJ
Pulp and paper	ILP	Millions tonnes
Non metal minerals	INM	PJ
Other industries	IOI	PJ

Other segment (1)

Other non specified energy consumption	ONO	PJ/year
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B. End-Use sectors



C. Primary and secondary energy sectors

Fossil resources and extraction

Different types of reserves (characteristics of the resource, cumulative potential, cost)

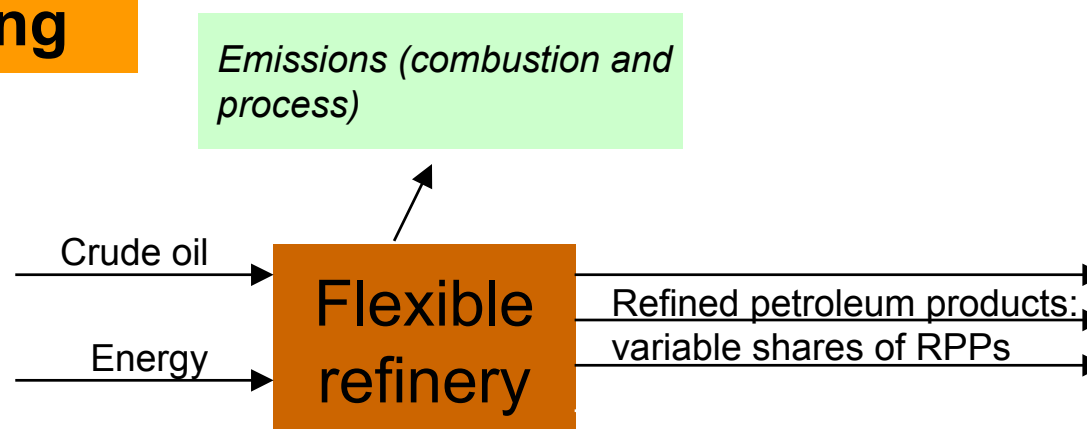
Eg. Oil: 21 (conventional, oil sands, located, enhanced recovery, new discovery...)

Gas: 9 (conventional, unconventional, not connected)

Coal: 4 (brown coal, hard coal, located, new discovery)

► *Reviewed and revised by IER (Stuttgart) in 2006*

Oil refining



Nuclear and Renewable resources

Geothermal: Shallow, deep and very deep

Hydro: Dam (5 levels) and run-of-river
WEC economic potential

Wind: Four plant-and-location combinations (different costs and AF)
Based on a fraction of the theoretical potential provided by IPCC-TAR ~ WEC assuming 4% of the land area

Solar: PV, thermal, centralized and decentralized

Nuclear: Basecase = maximum of 109 EJ/yr in 2100 (3500 GW)

Biomass: Includes industrial wastes, municipal wastes, solid biomass, biogas from landfills, liquids from biomass (IEA categories)
World potential = 238 EJ in 2100
Practical and technical constraints (distance of a biomass production site from demand centres, land-use conflicts)

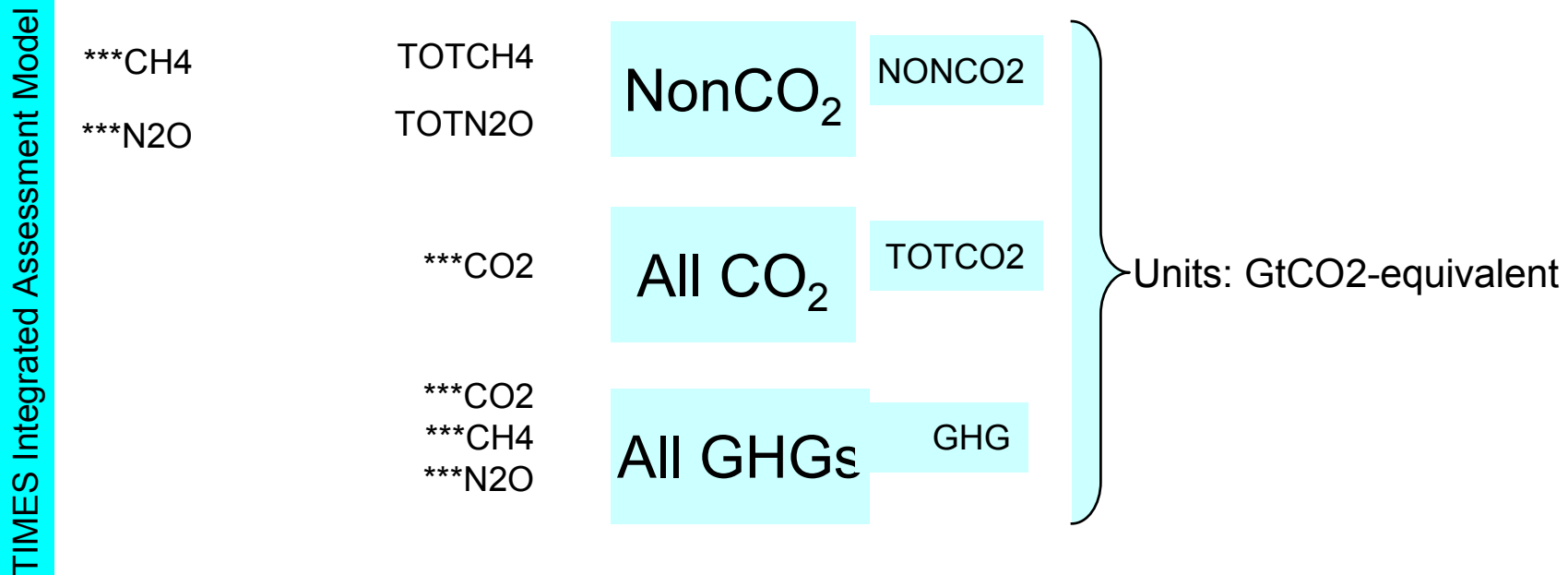
Methane capture and use for elec production (many measures)

Many sources of data

IEA-ETP, World Energy Council, IPCC-TAR, US Geological Survey, ..

D. Energy and emission trade

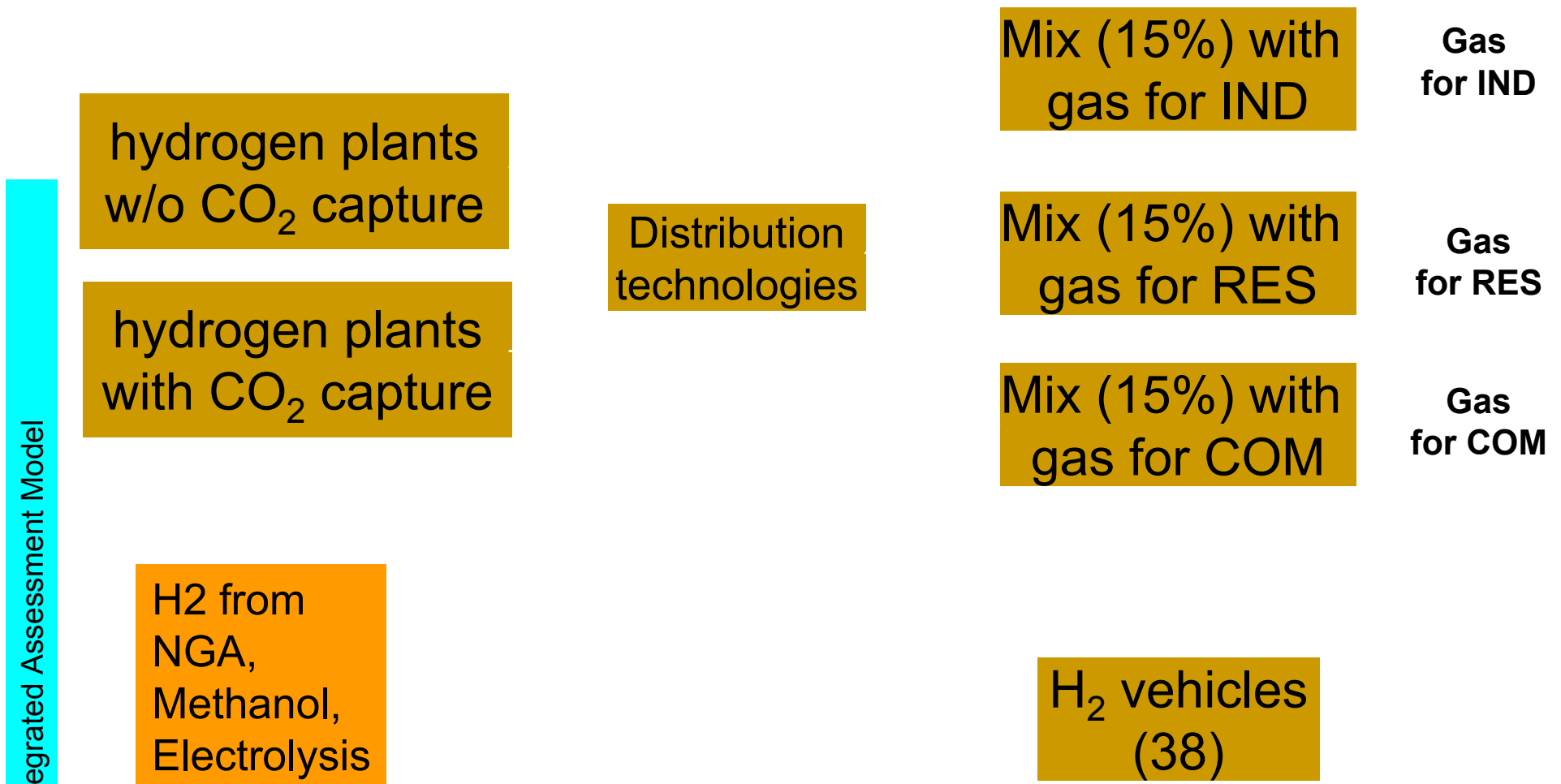
- Endogenous trade of coal, crude oil, gas, liquefied gas, and RPP's (*revised 2006*) $\Rightarrow$ prices and amounts of traded energy are endogenous $\Rightarrow$ the impact of environmental policies on energy trade is simulated
- Endogenous trade of CO₂ (or GHG) permits
- The user can choose which gases/energy commodity and which regions are included in trade (eg. only CO₂, all GHGs, only some countries, etc.)



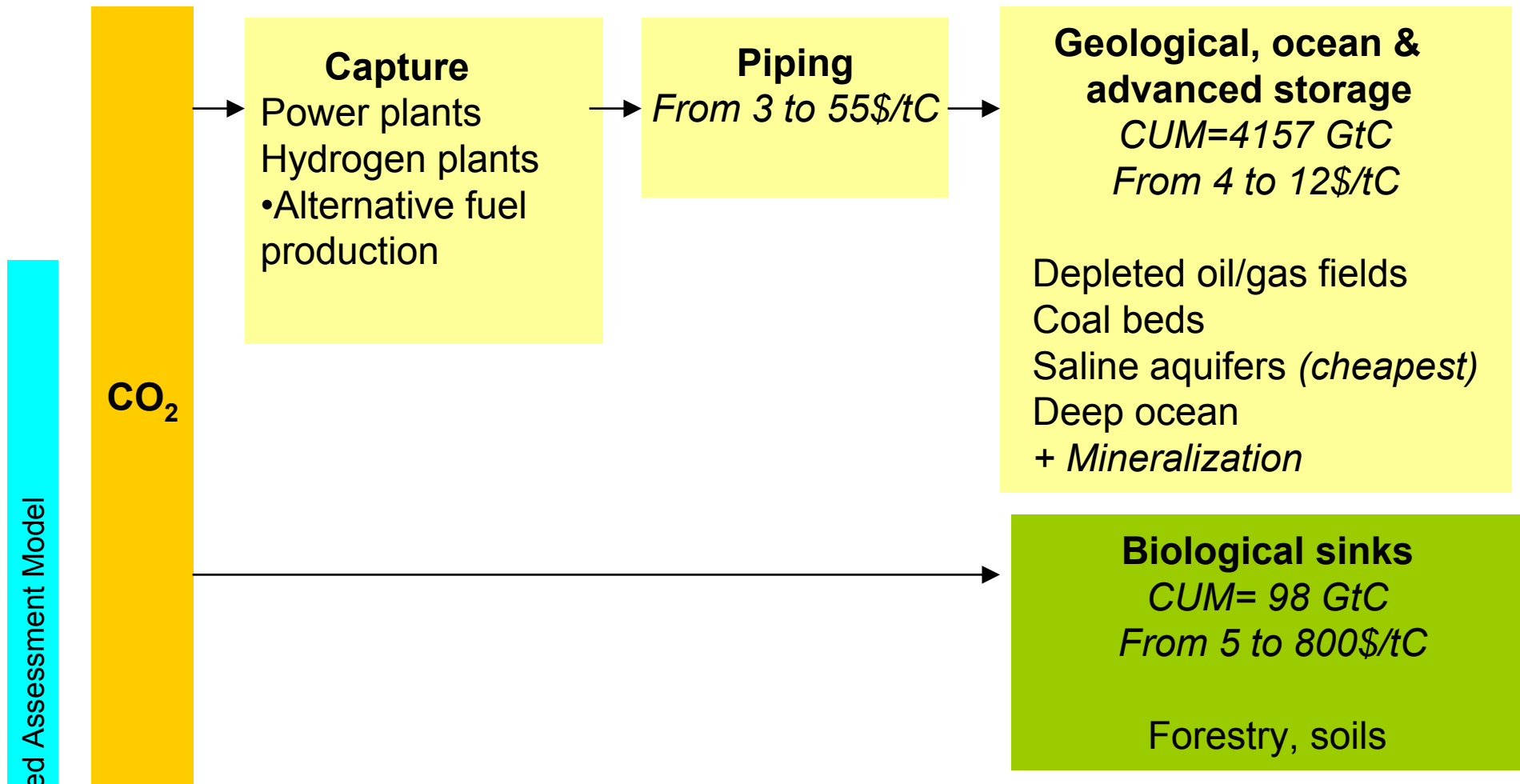
E. Electricity sector (cogen and autoprod not shown)

<i>Regional templates</i>	existing power plants
<i>SubRes NewTech</i>	many new power plants
<i>SubRes Sequestration</i>	Many power plants with CO ₂ capture

F. Hydrogen sector, revised 2007



G. CO₂ capture and sequestration revised 2005



Remark

Sources of data: IEA-ETP, EMF-22 (EPA), literature, IPCC,

K. Loulou, Climate target and ad hoc agreements with TIAM, PLANETS session, IEW, Venezia, June 18 2009

H. CH₄ emissions and abatement options (energy and non-energy – EMF21&22)

	% modeled CH4 emissions in 2000 TIAM	Abatement technologies EMF TIAM	
<i>Non-energy emissions</i>			
Manure	4%	5	4
Landfill	13%	11	11
Wastewater	10%	0	0
Biomass burning, Enteric Fermentation, Rice	46%	0	0
<i>Energy emissions</i>			
Primary oil	2%	4	4
Coal mining	7%	8	8
Gas production, transmission and distribution	13%	35	14
Biofuel combustion	4%	-	Many
Fuel combustion (stationary and mobile)	1%	-	Many
<i>Total</i>	<i>100 %</i>	<i>63</i>	<i>41</i>

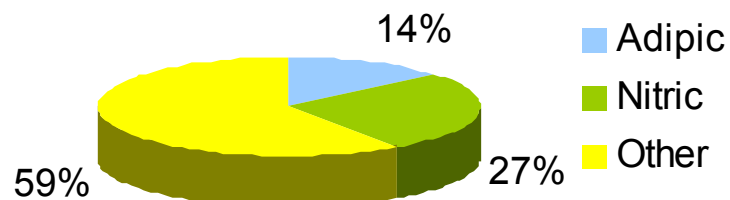
CH₄ abatement options

Some EMF options were not modeled due to very high cost or very small potential (eg. some options related to gas pipelines)

Combustion (energy sectors): many options available in TIAM (energy substitution or penetration of more efficient technologies)

CH₄ and N₂O (energy and non-energy)

N₂O emissions in 2000 in TIAM



Examples of options for N₂O

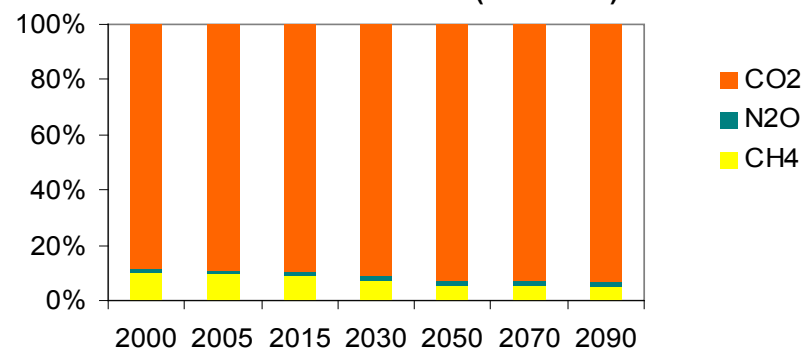
Different types of catalytic reduction, thermal destruction

Remarks

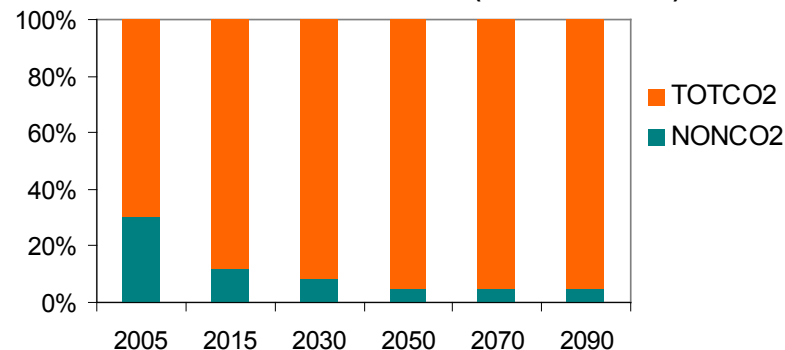
Some no-regret CH₄ mitigation options penetrate in base case (mostly production of “cheap” gas or electricity) - Also observed by US-EPA using MARKAL for the US

CH₄ and N₂O options help for GHG reduction in the short term

Contribution to all GHGs (basecase)



Contribution to GHG reduction (ΔT₂₁₀₀ = 1.8°C)



CH4 abatement options

Manure

ACH4MAN01	Farm Scale Digesters-A (cool climate)
ACH4MAN02	Farm Scale Digesters-A (warm climate)
ACH4MAN03	Farm Scale Digesters-B (cool climate)
ACH4MAN04	Farm Scale Digesters-B (warm climate)
<i>Not modeled</i>	<i>Centralized Digesters (cool climate)</i>

Landfill

RCH4WLF01	Anaerobic digestion 1 (AD1)
RCH4WLF02	Anaerobic digestion 2 (AD2)
RCH4WLF03	Composting (C1)
RCH4WLF04	Mechanical Biological Treatment
RCH4WLF05	Heat Production
RCH4WLF06	Increased Oxidation
RCH4WLF07	Direct Gas Use (profitable at base price)
RCH4WLF08	Electricity Generation
RCH4WLF09	Direct Gas Use (profitable above base price)
RCH4WLF10	Flaring
RCH4WLF11	Composting (C2)

Primary oil

UNCH4OIL01	Flaring instead of Venting (Offshore)
UNCH4OIL02	Flaring instead of Venting (Onshore)
UNCH4OIL03	Associated Gas (vented) Mix with Other Options
UNCH4OIL04	Associated Gas (flared) Mix with Other Options + Same options for OPEC

Coal mining

UNCH4COA01	Degasification and Pipeline Injection
UNCH4COA02	Enhanced Degasification, Gas Enrichment, and Pipeline Injection
UNCH4COA03	Catalytic Oxidation (US)
UNCH4COA04	Flaring
UNCH4COA05	Degasification and Power Production – A
UNCH4COA06	Degasification and Power Production – B
UNCH4COA07	Degasification and Power Production – C
UNCH4COA08	Catalytic Oxidation (EU) + Same options for OPEC

CH4 abatement options

Gas production, transmission and distribution

- UNCH4GAS01 P&T - Use gas turbines instead of reciprocating engines
- UNCH4GAS02 Prod-D I&M (Pipeline Leaks)
- UNCH4GAS03 Installation of Flash Tank Separators (Production)
- UNCH4GAS04 Replace high-bleed pneumatic devices with compressed air systems (Production)
- UNCH4GAS05 Replace high-bleed pneumatic devices with low-bleed pneumatic devices (Production)
- UNCH4GAS06 Dry Seals on Centrifugal Compressors (P&T)
- UNCH4GAS07 Catalytic Converter (P&T)
- UNCH4GAS08 Portable Evacuation Compressor for Pipeline Venting (P&T)
- UNCH4GAS09 Replace High-bleed pneumatic devices with compressed air systems (P&T)
- UNCH4GAS10 Replace high-bleed pneumatic devices with low-bleed pneumatic devices (P&T)
- UNCH4GAS11 D-D I&M (Distribution)
- UNCH4GAS12 D-D I&M (Enhanced: Distribution)
- UNCH4GAS13 Electronic Monitoring at Large Surface Facilities (D)
- UNCH4GAS14 Replacement of Cast Iron/Unprotected Steel Pipeline (D)

+ Same options for OPEC

- Not modeled*
- P&T - Compressors-Altering Start-Up Procedure during Maintenance*
 - Prod-D I&M (Chemical Inspection Pumps)*
 - Prod-D I&M (Enhanced)*
 - Prod-D I&M (Offshore)*
 - Prod-D I&M (Onshore)*
 - Installation of Electric Starters on Compressors (Production)*
 - Installing Plunger Lift Systems In Gas Wells*
 - Portable Evacuation Compressor for Pipeline Venting (Production)*
 - Reducing the Glycol Circulation Rates in Dehydrators (Production)*
 - Surge Vessels for Station/Well Venting (Production)*
 - Fuel Gas Retrofit for Blowdown Valve*
 - Reducing the Glycol Circulation Rates in Dehydrators (P&T)*
 - P&T-D I&M (Compressor Stations)*
 - P&T-D I&M (Compressor Stations: Enhanced)*
 - P&T-D I&M (Enhanced: Storage Wells)*
 - P&T-D I&M (Pipeline: Transmission)*
 - P&T-D I&M (Wells: Storage)*
 - Installation of Flash Tank Separators (P&T)*
 - Portable Evacuation Compressor for Pipeline Venting (P&T)*
 - Static-Pacs on reciprocating compressors (P&T)*
 - Surge Vessels for Station/Well Venting (P&T)*

N2O abatement options

Adipic Acid

ICH4ADI01 Thermal Destruction

Nitric Acid

ICH4INT01 Grand Paroisse - High Temperature Catalytic Reduction Method

ICH4INT02 BASF - High Temperature Catalytic Reduction Method

ICH4INT03 Norsk Hydro - High Temperature Catalytic Reduction Method

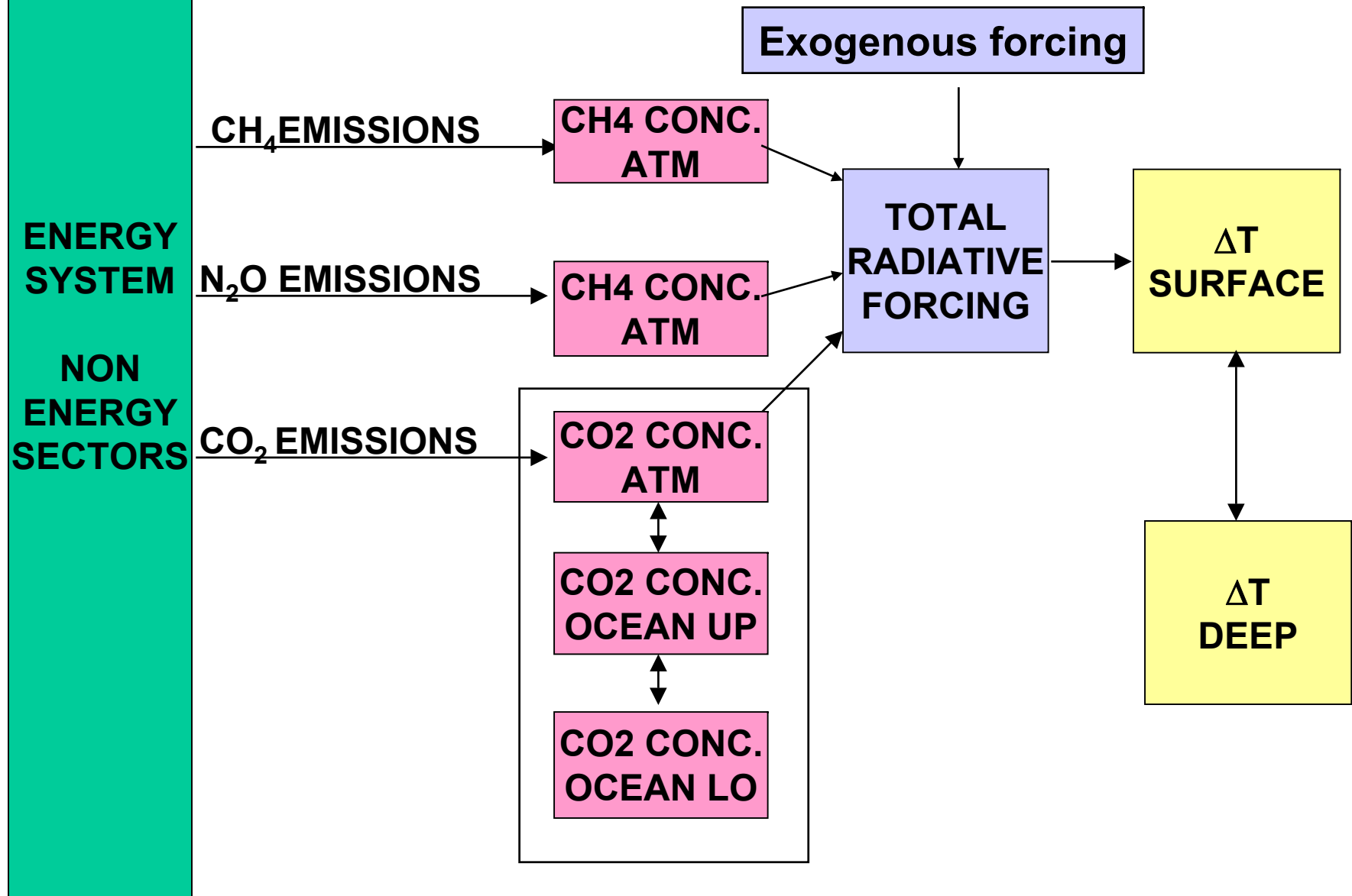
ICH4INT04 HITK - High Temperature Catalytic Reduction Method

ICH4INT05 Krupp Uhde - Low Temperature Catalytic Reduction Method

ICH4INT06 ECN - Low temperature selective catalytic reduction with propane addition

ICH4INT07 Non-Selective Catalytic Reduction (NSCR)

I. Climate module: Option 2 (2007)



Climate equations 1: concentrations

Concentrations of CO₂ (3 layer model)

- $\text{CO2}_{\text{atm}}(t) = \text{Emi}(t) + \text{CO2}_{\text{atm}}(t-1) \cdot (1 - f_{\text{atm,up}}) + \text{CO2}_{\text{up}}(t-1) \cdot f_{\text{up,atm}}$
- $\text{CO2}_{\text{up}}(t) = \text{CO2}_{\text{up}}(t-1) \cdot (1 - f_{\text{up,atm}} - f_{\text{up,lo}}) + \text{CO2}_{\text{lo}}(t-1) \cdot f_{\text{lo,up}} + \text{CO2}_{\text{atm}}(t-1) \cdot f_{\text{atm,up}}$
- $\text{CO2}_{\text{lo}}(t) = \text{CO2}_{\text{lo}}(t-1) \cdot (1 - f_{\text{lo,up}}) + \text{CO2}_{\text{up}}(t-1) \cdot f_{\text{up,lo}}$

Atmospheric Concentrations of CH₄ and N₂O (exponential decay models)

- $\text{CH4}_{\text{atm}}(t) = \text{CH4}_{\text{atm}}(t-1) \cdot (1 - \text{PHI}_{\text{CH4}})$
- $\text{N2O}_{\text{atm}}(t) = \text{N2O}_{\text{atm}}(t-1) \cdot (1 - \text{PHI}_{\text{N2O}})$

Climate equations 2: Forcings

Atmospheric forcings due to each gas (W/m²)

- $DF_{CO_2}(t) = \gamma / \ln 2 * \ln [CO_{2atm}(t) / CO_{2atm}(0)]$
- $DF_{CH_4}(t) = a * (\sqrt{CH_4(t)} - \sqrt{CH_4(0)}) - f(CH_4(t), N_2O(0))$
- $DF_{N_2O}(t) = b * (\sqrt{N_2O(t)} - \sqrt{N_2O(0)}) - f(CH_4(0), N_2O(t))$
- Exogenous forcing:

$$EXO(t) = -0.7 + 0.01 * (t - 2005) \quad \text{for } t \leq 2100$$

$$EXO(t) = 0.25 \quad \text{for } t > 2100$$

- Total forcing:

$$DF(t) = DF_{CO_2}(t) + DF_{CH_4}(t) + DF_{N_2O}(t) + EXO(t)$$

Climate equations 3: Global Temperatures

Temperatures (2 layers)

Climate sensitivity

$$\begin{aligned} \Delta T_{up}(t) = & \Delta T_{up}(t-1) + \sigma_1 * \{ \Delta F(t) - 3.7 / C_s * \Delta T_{up}(t-1) \\ & - \sigma_2 [\Delta T_{up}(t-1) - \Delta T_{lo}(t-1)] \} \end{aligned}$$

$$\Delta T_{lo}(t) = \Delta T_{up}(t-1) * \sigma_3 + \Delta T_{lo}(t-1) * g_{22}$$