The TIMES Integrated Assessment Model (TIAM): An Introduction

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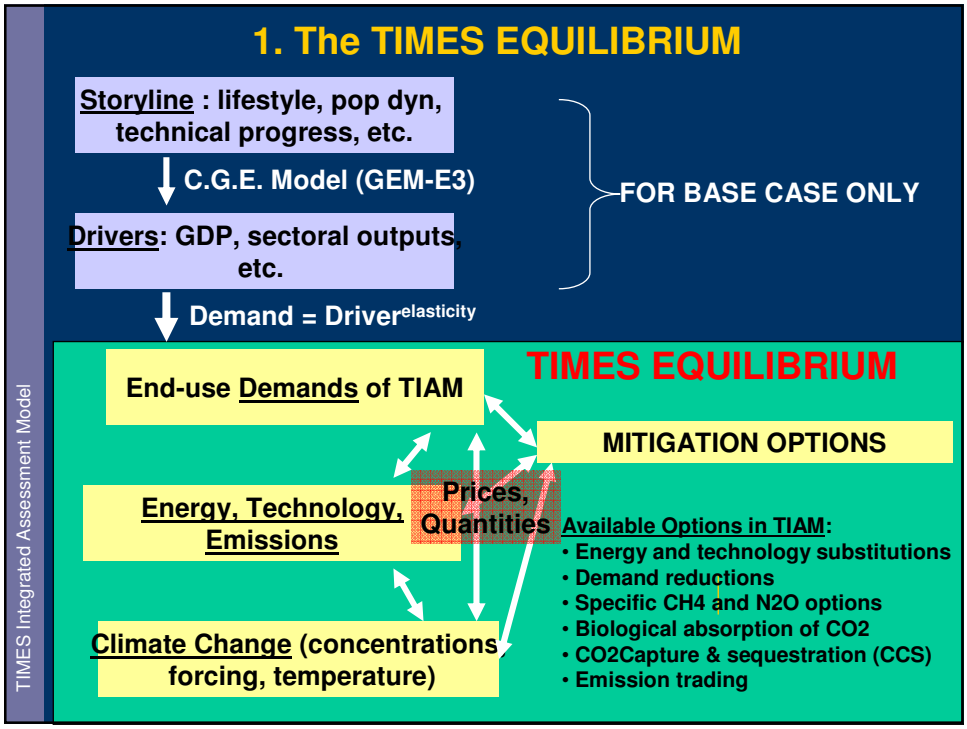
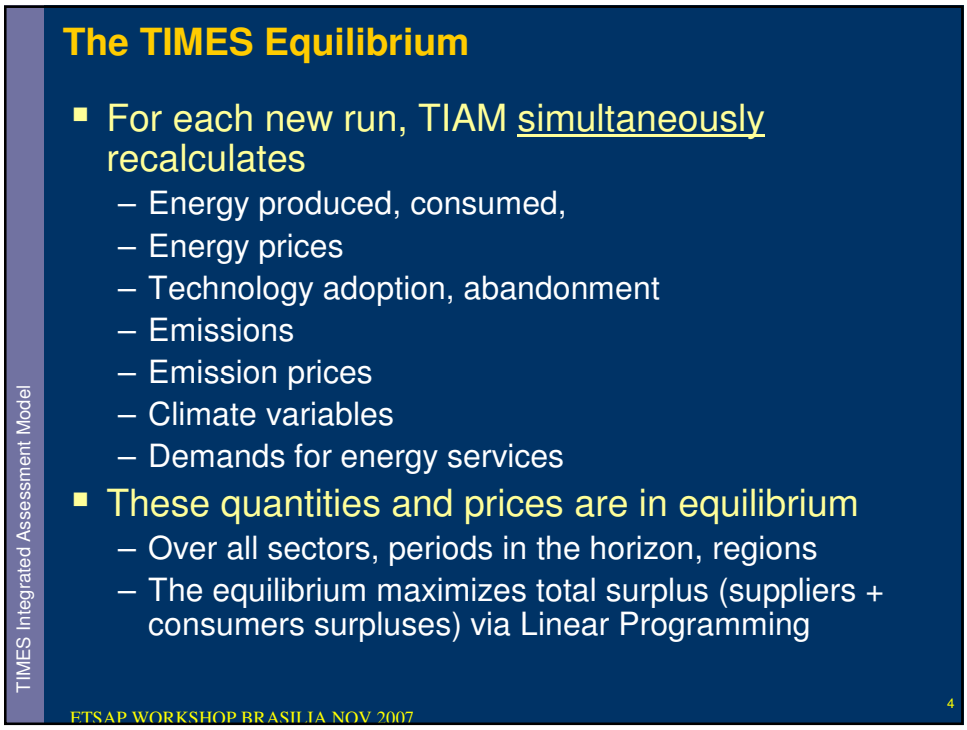
PLAN

1. The TIMES Equilibrium (reminder)
2. TIAM sectors: some details
    1. Demands
    2. Technologies
    3. Trade
    4. Emissions, abatement options
3. The TIAM Climate Module
4. The VEDA Interface


TIMES Integrated Assessment Model
1. The TIMES EQUILIBRIUM
Storyline : lifestyle, pop dyn, technical progress, etc.
C.G.E. Model (GEM-E3)
Drivers: GDP, sectoral outputs, etc.
Demand = Driver elasticity
FOR BASE CASE ONLY
TIMES EQUILIBRIUM
End-use Demands of TIAM
MITIGATION OPTIONS
Energy, Technology, Emissions
Prices, Quantities
Climate Change (concentrations forcing, temperature)
Available Options in TIAM:
• Energy and technology substitutions
• Demand reductions
• Specific CH4 and N2O options
• Biological absorption of CO2
• CO2Capture & sequestration (CCS)
• Emission trading


TIMES Integrated Assessment Model
The TIMES Equilibrium
For each new run, TIAM simultaneously recalculates
– Energy produced, consumed,
– Energy prices
– Technology adoption, abandonment
– Emissions
– Emission prices
– Climate variables
– Demands for energy services
These quantities and prices are in equilibrium
– Over all sectors, periods in the horizon, regions
– The equilibrium maximizes total surplus (suppliers + consumers surpluses) via Linear Programming
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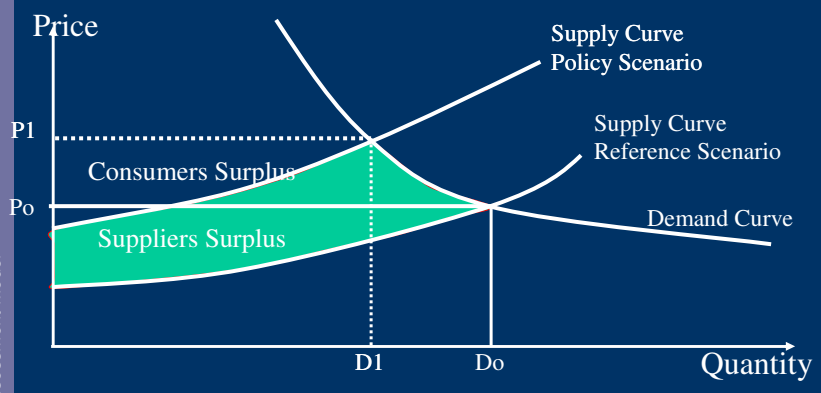
(Max) Total Surplus =
Consumer Surplus + Suppliers Surplus



- Supply curves are implicitly constructed by TIMES
- Demand curves are implicitly constructed by TIMES
  - except for energy service demands

2. TIAM: TIMES INTEGRATED ASSESSMENT MODEL

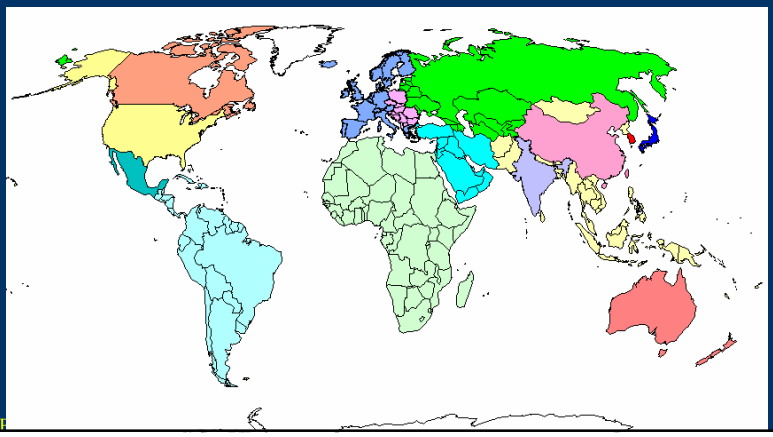
- TIAM is an incarnation of TIMES with the following characteristics:
  - 15 region global model
  - Region-dependent technoeconomic data
  - Trade of energy and emission rights between regions
  - Long term horizon (up to 100 years)
  - Demands are driven by drivers obtained from a global CGE model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

TIMES Integrated Assessment Model

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*



TIMES Integrated Assessment Model

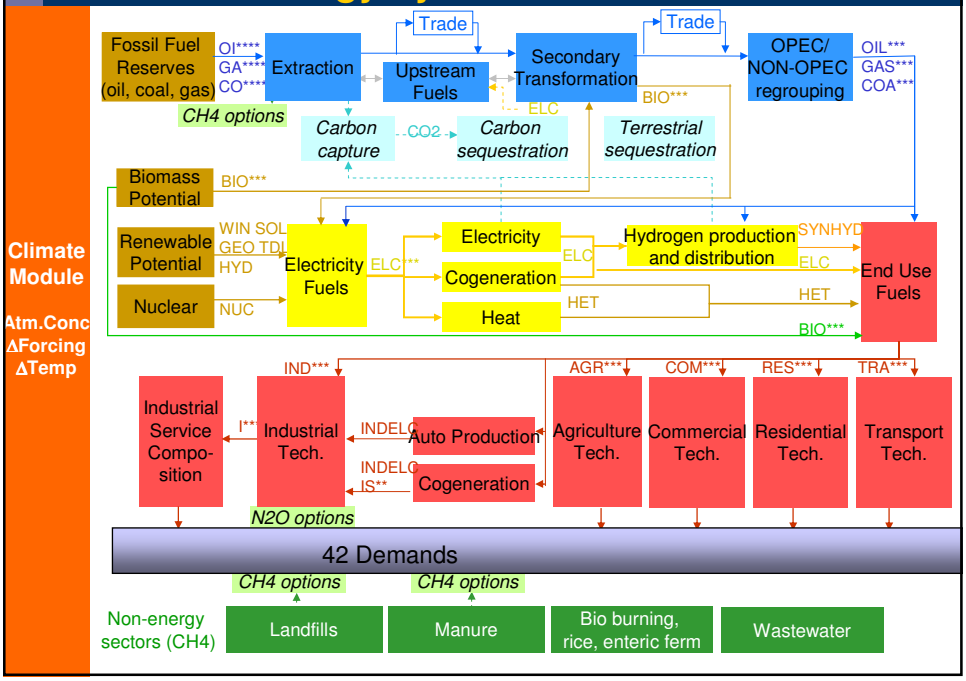
List of countries in multi-country regions

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, d, e, f]

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

2. TIAM SECTORS: some details

Reference Energy System



TIMES Integrated Assessment Model

A. Demand projections

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

↓ **GEM-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 elasticitiesafter 2050
- convergence of developing and industrialized countries around 2050

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End-use demands

	Code		Unit
Transportation segments (15)			
Autos	TRT		Billion vehicle-km/year
Buses	TRB		Billion vehicle-km/year
Light trucks	TRL		Billion vehicle-km/year
Commercial trucks	TRC	**Road**	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
Residential segments (11)*			
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

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	
*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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LIST OF DRIVERS USED WITH GEM-E3

- POP= population
- HOU: Number of households
- GDP: Total regional GDP
- SPROD-I: output from energy intensive industries
- SPROD-O: output from other industries
- SPROD-S: output from service industries
- SPROD-A: agricultural output
- GDPP: GDP per capita

$$DEM = K * DRIVER^{elasticity}$$

Association of Drivers to Demands

DEMAND	DRIVER	
Transportation	**All regions**	
Automobile travel	GDP/capita	
Bus travel	POP	
2 & 3 wheelers	POP	
Rail passenger travel	POP	
Domestic aviation travel	GDP	
International Aviation travel	GDP	
Trucks	GDP	
Fret rail	GDP	
Domestic Navigation	GDP	
Bunkers	GDP	
Residential	**All regions after 2050 + Non-OECD before 2050**	**OECD regions before 2050**
Space heating	HOU	HOU
Space Cooling	HOU	GDPP
Water Heating	POP	POP
Lighting	GDPP	GDPP
Cooking	POP	POP
Refrigeration and Freezing	HOU	GDPP
Washers	HOU	GDPP
Dryers	HOU	GDPP
Dish washers	HOU	GDPP
Other appliances	GDPP	GDPP
Other	HOU	GDPP

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Association of Drivers to Demands

DEMAND	DRIVER
Commercial	**All regions**
Space heating	SPROD-Services
Space Cooling	SPROD-Services
Water Heating	SPROD-Services
Lighting	SPROD-Services
Cooking	SPROD-Services
Refrigeration and Freezing	SPROD-Services
Other electric demands	SPROD-Services
Other	SPROD-Services
Agriculture	SPROD-Agriculture
Industry	**All regions**
Iron and steel	SPROD-I
Non ferrous metals	SPROD-I
Chemicals	SPROD-I
Pulp and paper	SPROD-O
Non metal minerals	SPROD-O
Other industries	SPROD-O

HOU: households GDPP: GDP per capita
POP: population SPROD-X: production of sector X related to GDP
GDP: gross domestic product

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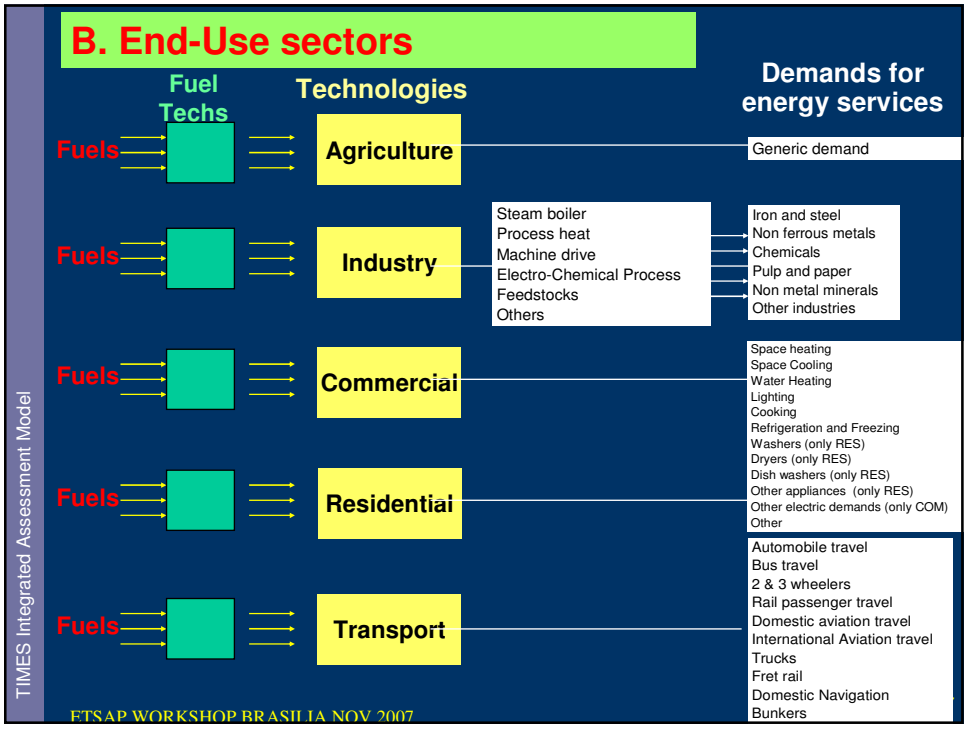
B. End-Use sectors
Fuel Techs
Technologies
Demands for energy services
Fuels
Agriculture
Generic demand
Industry
Steam boiler
Process heat
Machine drive
Electro-Chemical Process
Feedstocks
Others
Iron and steel
Non ferrous metals
Chemicals
Pulp and paper
Non metal minerals
Other industries
Commercial
Space heating
Space Cooling
Water Heating
Lighting
Cooking
Refrigeration and Freezing
Washers (only RES)
Dryers (only RES)
Dish washers (only RES)
Other appliances (only RES)
Other electric demands (only COM)
Other
Residential
Transport
Automobile travel
Bus travel
2 & 3 wheelers
Rail passenger travel
Domestic aviation travel
International Aviation travel
Trucks
Fret rail
Domestic Navigation
Bunkers
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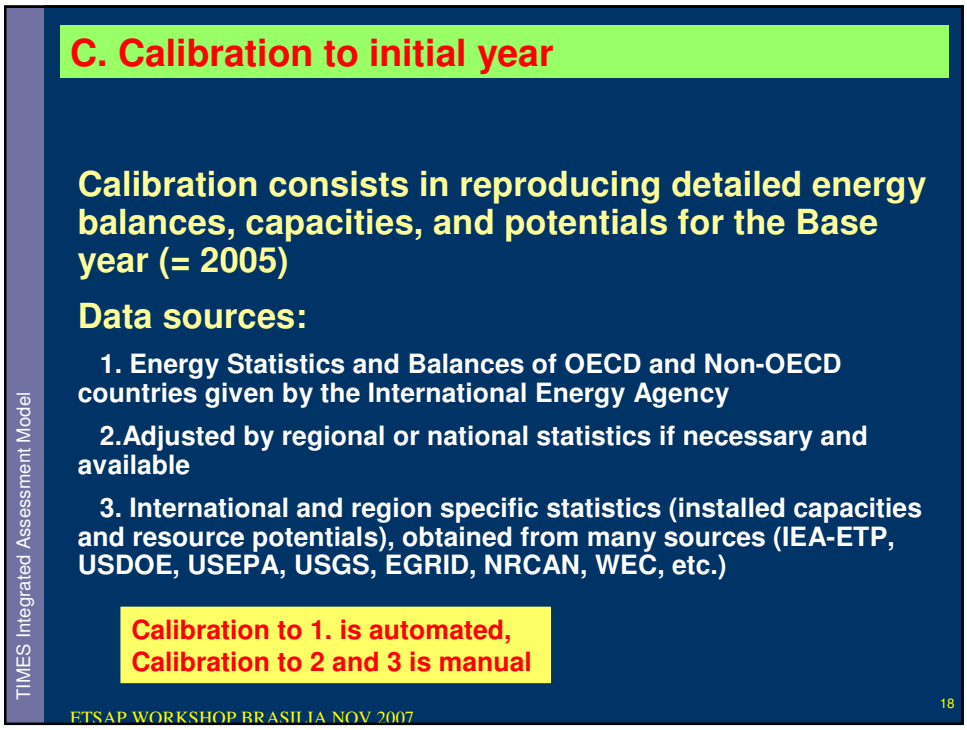
C. Calibration to initial year
Calibration consists in reproducing detailed energy balances, capacities, and potentials for the Base year (= 2005)
Data sources:
1. Energy Statistics and Balances of OECD and Non-OECD countries given by the International Energy Agency
2.Adjusted by regional or national statistics if necessary and available
3. International and region specific statistics (installed capacities and resource potentials), obtained from many sources (IEA-ETP, USDOE, USEPA, USGS, EGRID, NRCAN, WEC, etc.)
Calibration to 1. is automated,
Calibration to 2 and 3 is manual
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D. Primary and secondary energy sectors

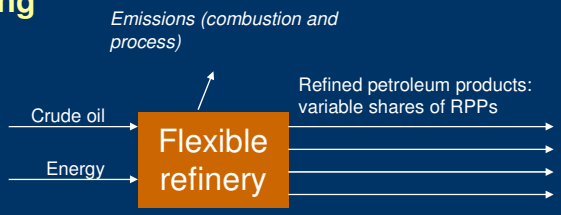
Fossil resources and extraction

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



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Nuclear and Renewable resources (being revised 2007-08)

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, ..

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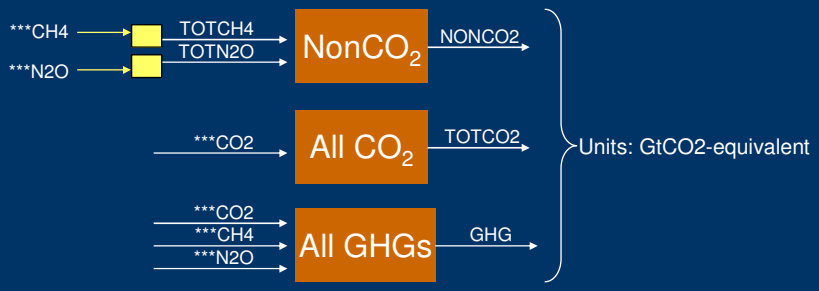
E. Energy and emission trade

- Endogenous trade of coal, crude oil, gas, liquefied gas, and RPP's *(revised 2006)* ⇒ prices and amounts of traded energy are endogenous ⇒ the impact of environmental policies on energy trade is simulated
- Endogenous trade of CO_2 (or GHG) permits
- The user can choose which gases/energy commodity and which regions are included in trade (eg. only CO_2, all GHGs, only some countries, etc.)



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E. Oil pricing, Gas Pricing

- **Oil market is not competitive. Cartel (OPEC) fixes production, other producers top-up to satisfy demand.**
- **Modeled as follows**:
  1. Fix upper bound on OPEC oil production
  2. Run model: observe (from model results) the market response by other producers and by consumers, as well as world price
  3. Modify upper bound if desired, goto step 1
  4. Repeat steps 1,2,3, until OPEC profits are maximised (or until oil price target is reached)

- **Nat Gas markets are regional. TIAM assumes competitive markets: price = marginal value in each region**
- **LNG market is global**

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F. Electricity sector (cogen and autoprod not shown) revised 2007

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Regional templates	existing power plants
SubRes NewTech	many new power plants
SubRes Sequestration	Many power plants with CO_2 capture

G. Hydrogen sector, revised 2007

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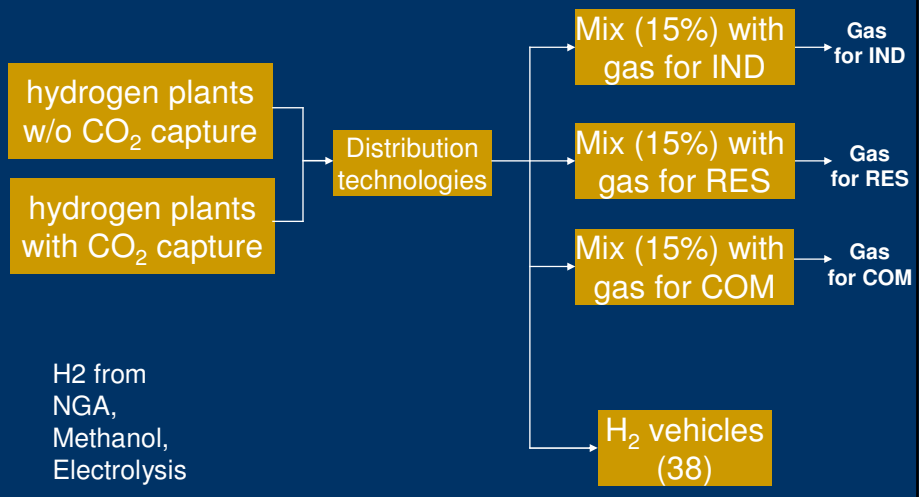
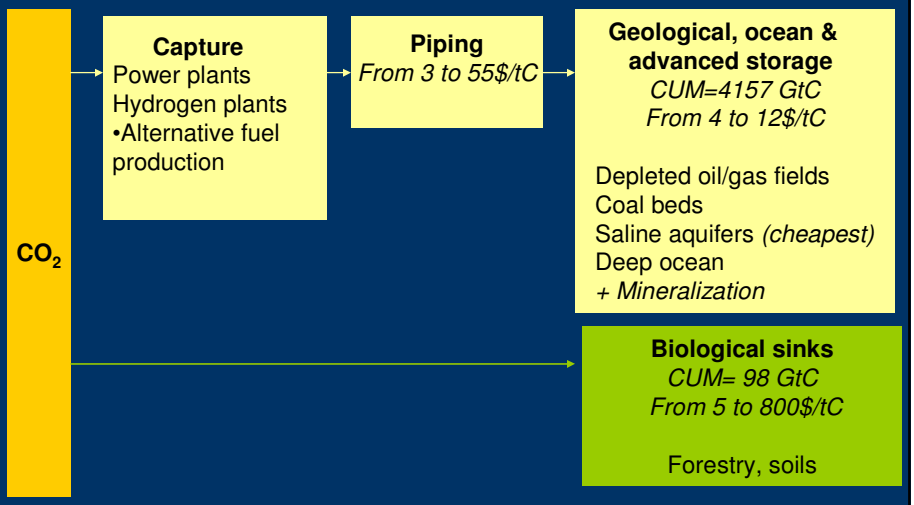


H2 from NGA, Methanol, Electrolysis

H. CO_2 capture and sequestration revised 2005



Remark

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

I. CH_4 emissions and abatement options (energy and non-energy – EMF21&22)

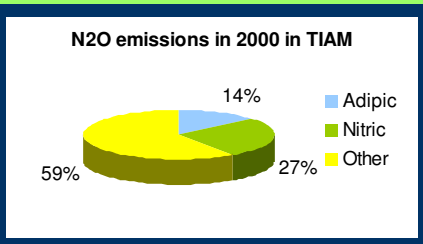
	% modeled CH4 emissions in 2000 TIAM	Abatement technologies EMF	TIAM
Non-energy emissions			
Manure	4%	5	4
Landfill	13%	11	11
Wastewater	10%	0	0
Biomass burning, Enteric Fermentation, Rice	46%	0	0
Energy emissions			
Primary oil	2%	4	4
Coal mining	7%	8	8
Gas production, transmission and distribution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

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)

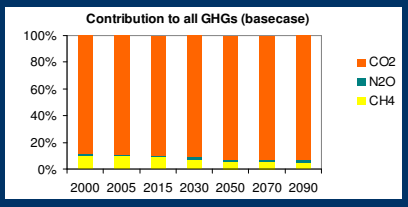
Combustion (energy sectors): many options available in TIAM (energy substitution or penetration of more efficient technologies)

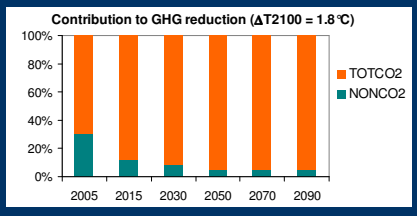
I. CH_4 and N_2O (energy and non-energy – EMF22)



Examples of options for N2O

Different types of catalytic reduction, thermal destruction





Remarks

Some no-regret CH_4 mitigation options penetrate in base case (mostly production of "cheap" gas or electricity) - Also observed by US-EPA using MARKAL for the US

CH_4 and N_2O options help for GHG reduction in the short term

CH4 abatement options

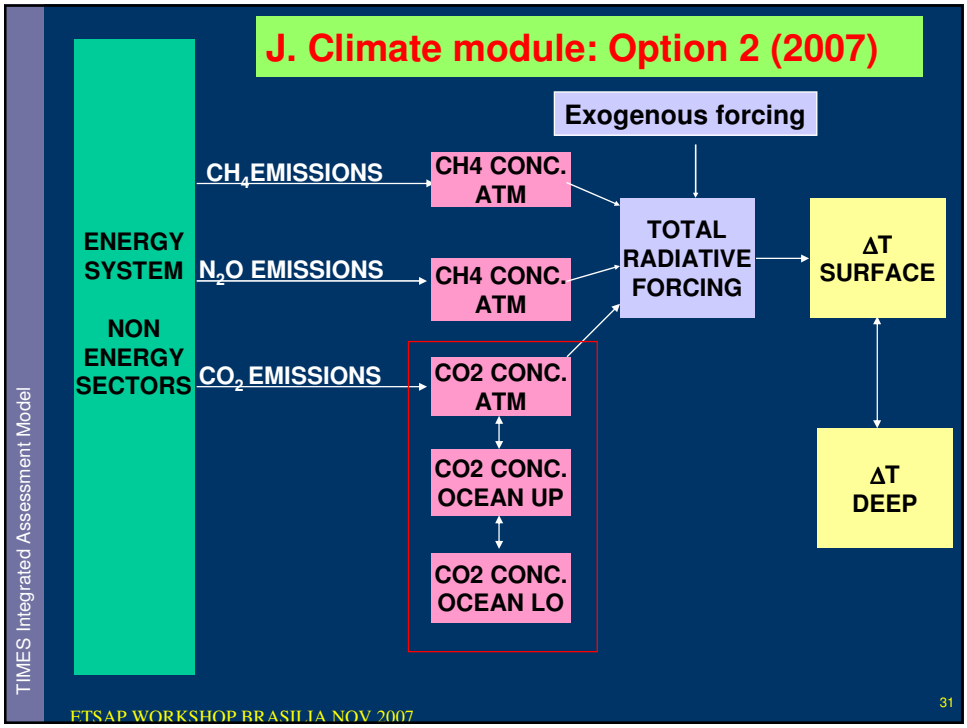
Manure	
ACH4MAN01	Farm Scale Digesters-A (cool climate)
ACH4MAN02	Farm Scale Digesters-A (warm climate)
ACH4MAN03	Farm Scale Digesters-B (cool climate)
ACH4MAN04	Farm Scale Digesters-B (warm climate)
Not modeled	*Centralized Digesters (cool climate)*
Landfill	
RCH4WLF01	Anaerobic digestion 1 (AD1)
RCH4WLF02	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	
ICH4NIT01	Grand Paroisse - High Temperature Catalytic Reduction Method
ICH4NIT02	BASF - High Temperature Catalytic Reduction Method
ICH4NIT03	Norsk Hydro - High Temperature Catalytic Reduction Method
ICH4NIT04	HITK – High Temperature Catalytic Reduction Method
ICH4NIT05	Krupp Uhde - Low Temperature Catalytic Reduction Method
ICH4NIT06	ECN - Low temperature selective catalytic reduction with propane addition
ICH4NIT07	Non-Selective Catalytic Reduction (NSCR)



Climate equations 1: concentrations

Concentrations of CO2 (3 layer model)

1. $CO2_{atm}(t) = Emi(t) + CO2_{atm}(t-1)*(1-f_{atm,up}) + CO2_{up}(t-1)*f_{up,atm}$
2. $CO2_{up}(t) = CO2_{up}(t-1)*(1-f_{up,atm} - f_{up,lo}) + CO2_{lo}(t-1)* f_{lo,up} + CO2_{atm}(t-)*f_{atm,up}$
3. $CO2_{lo}(t) = CO2_{lo}(t-1)*(1-f_{lo,up}) + CO2_{up}(t-1)* f_{up,lo}$

Atmospheric Concentrations of CH4 and N2O (exponential deca
models)

4. $CH4_{atm}(t) = CH4_{atm}(t-1)*(1-PHI_{CH4})$

5. $N2O_{atm}(t) = N2O_{atm}(t-1)*(1-PHI_{N2O})$

Climate equations 2: Forcings

Atmospheric forcings due to each gas (W/m2)

6. $DF_{CO2}(t) = \gamma/\ln 2 * \ln [CO2_{atm}(t)/CO2_{atm}(0)]$
7. $DF_{CH4}(t) = a*(\sqrt{CH4}(t)- \sqrt{CH4}(0)) -f(CH4(t), N2O(0))$
8. $DF_{N2O}(t) = b*(\sqrt{N2O}(t)- \sqrt{N2O}(0)) -f(CH4(0), N2O(t))$
9. Exogenous forcing:

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

   $EXO(t) = 0.25$ for $t > 2100$
10. Total forcing:

    $DF(t) = DF_{CO2}(t) + DF_{CH4}(t) + DF_{N2O}(t) + EXO(t)$

Climate equations 3: Global Temperatures

Temperatures (2 layers)

Lag parameter

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

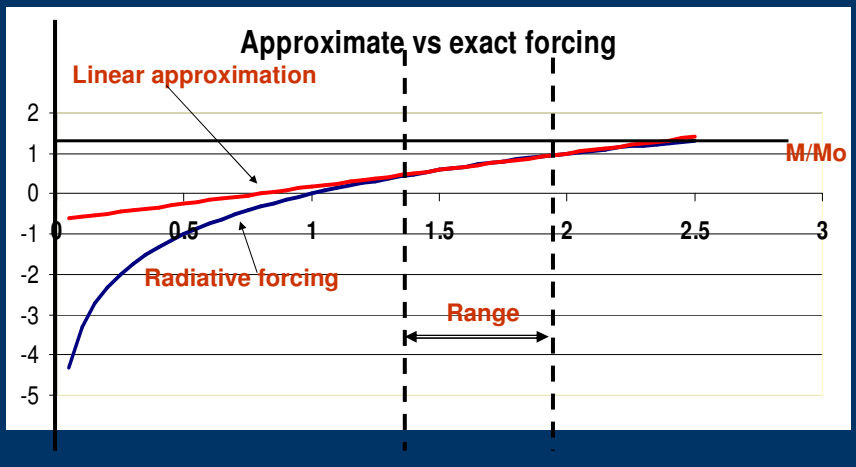
Climate sensitivity

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

Linear approximations of forcing equations

- The 3 non-linear forcing equations are replaced by (very good) linear approximations within the intervals of interest
  - For CO2: 375 ppm-550 ppmv
  - For CH4: 1750 to 3000 ppbv
  - For N2O: 310 to 450 ppbv
- Each approximation is halfway between the tangent and the chord of the exact forcing curve
- Within the selected ranges, the error made on Forcing never exceeds 2% (well within the inherent uncertainty of forcing values)

Example: linearized forcing equation for CO2



Relative error less than 2% in range (375 ppm; 550 ppm)

Computational Experience with TIAM

- Portable Computer, 2 GB memory, 2.5 GHz
  - Import complete new data into VEDA: 30 minutes
  - Run: from 15 minutes to 2 hours depending on # of periods, stochastic vs. Simple run (Optimizer: CPLEX)
  - Export solution to VEDA_Back End: 2 minutes