The ETSAP-TIMES Integrated Assessment Model

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REACCESS

1

Objective

Present the ETSAP-TIMES Integrated Assessment Model (TIAM): multi-regional + integrated + TIMES model

Structure of the Reference Energy System
Data and organisation of the data (building the database)
Trade
Climate module
Examples of applications

2

ETSAP-TIMES Integrated Assessment Model (TIAM)

ETSAP-TIAM

- 15 region model
- Region-dependent technoeconomic data
- Trade of energy and emission between regions
- Long term horizon (up to 100 years)
- Demands are driven by drivers obtained from a global CGE model (GEM-E3 or GEMINI-E3)
- Global climate equations allowing climate targets

ETSAP-TIMES Integrated Assessment Model (TIAM)

ETSAP-TIAM

Among ETSAP, several researchers have greatly contributed to the development of TIAM, among them:

- Giancarlo Tosato (Italy), ETSAP operating agent
- The Canadian team at GERAD: Amit Kanudia, Maryse Labriet, Richard Loulou, Kathleen Vaillancourt;
- Uwe Remme, Markus Blesl, Peter Schaumann, Stuttgart University (Germany);
- Denise Van Regemorter, Catholic University of Leuwen (Belgium);
- Gary Goldstein, IRG Ltd (USA);
- Antti Lettila, VTT (Finland);
- and several others

The seed of TIAM was embodied in the initial version of the global models developed for:

US-EIA (System for the Analysis of Global Energy markets), IEA (Energy Technology Perspectives) and EFDA (European Fusion Development Agreement)

The users' interface is VEDA (FE and BE)

Special conditions for its access and use

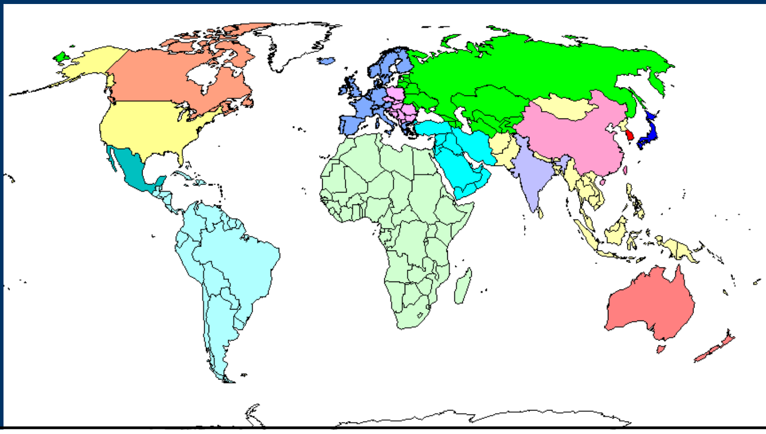
4

Overview of the Reference Energy System

15 regions + OPEC/Non-OPEC

Africa*	Eastern Europe	Middle-East*
Australia-New Zealand	Former Soviet Union	Other Developing Asia*
Canada	India	South Korea
Central and South America*	Japan	United States
China	Mexico	Western Europe

* *OPEC and Non-OPEC countries are separated in primary and secondary sectors ⇒ appropriate modelling of oil production strategies and oil price control by OPEC countries*



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], Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam
WEU	Austria, Belgium, Denmark, Finland, France[d], Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Italy[e], Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland[f], United Kingdom

[a] Included: Botswana, Burkina Faso, Burundi, Cape Verde, Central African Republic, Chad, Djibouti, Equatorial Guinea, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Niger, Reunion, Rwanda, 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.

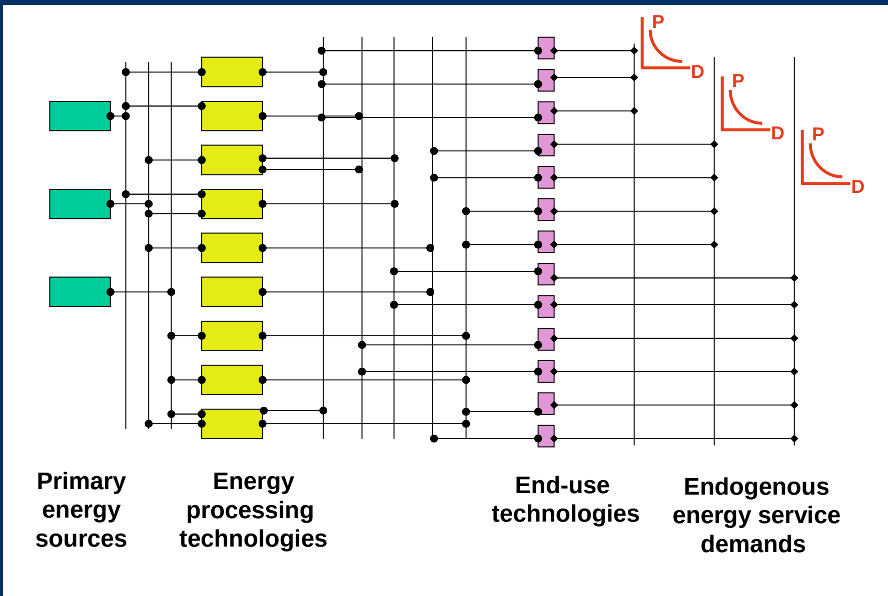
[d] Includes Monaco.

[e] Includes San Marino and Vatican City

[f] Includes Liechtenstein

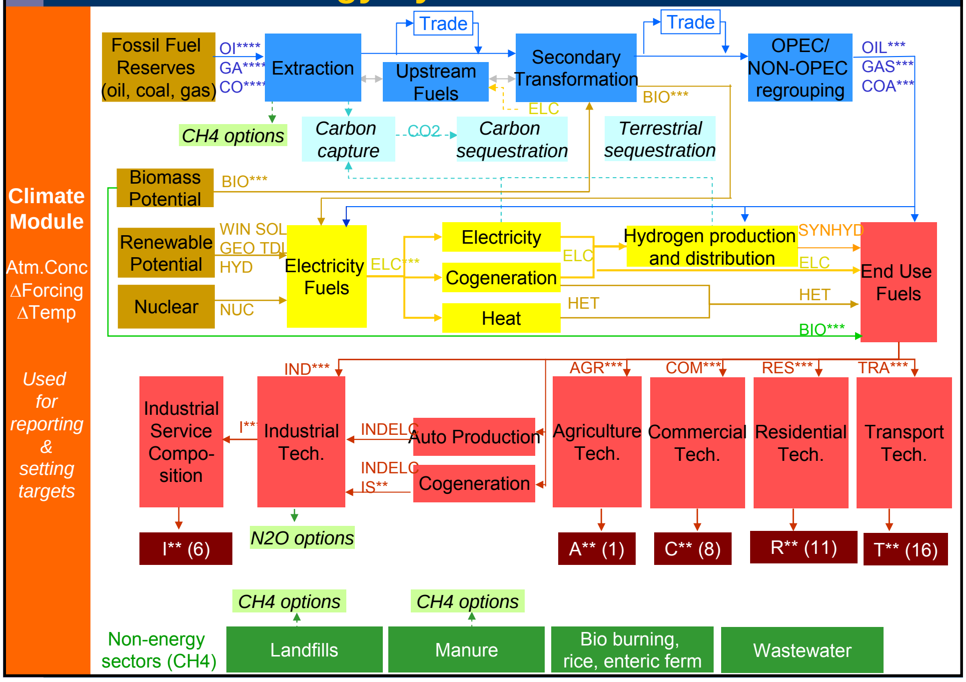
7

Reference Energy System

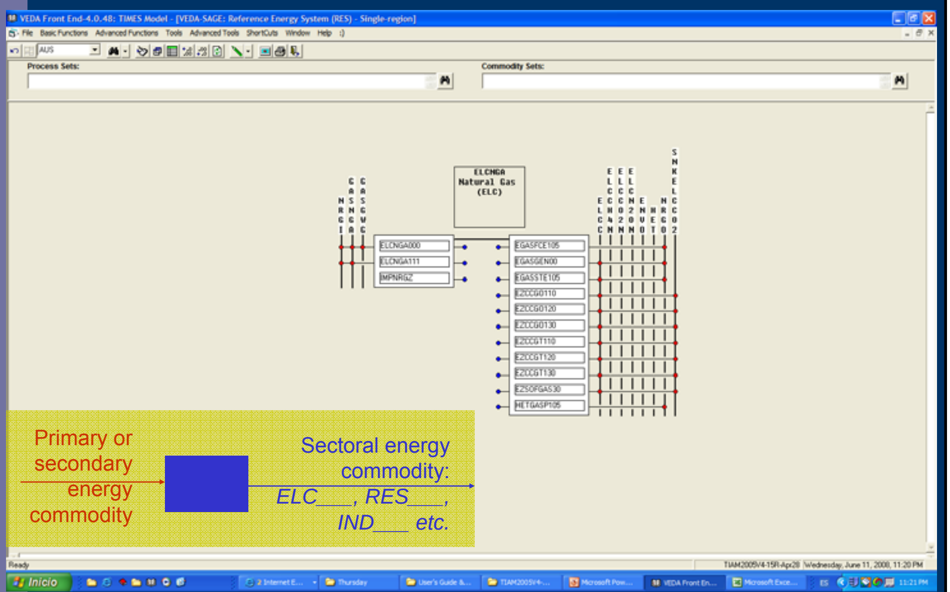


8

Reference Energy System

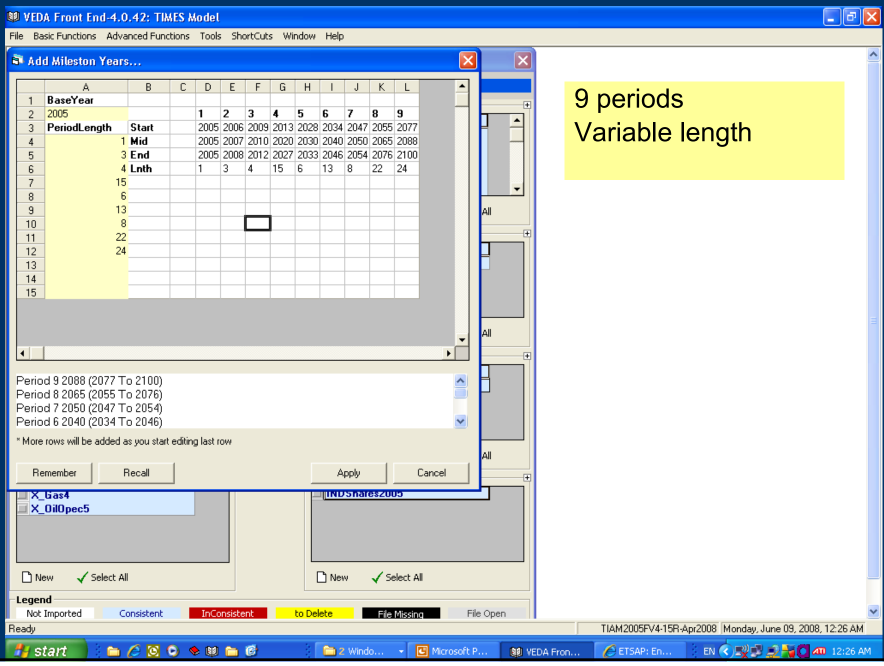


« Fuel technologies »: easier accounting



10

Periods



9 periods
Variable length

Energy resources (upstream sector)

Fossil resources

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

Oil: 20 (conventional, oil sands, bitumen, located, enhanced recovery, new discovery…)
Gas: 19 (conventional, aquifer, tight, coalbed, not connected…)
Coal: 4 (browncoal, hardcoal, located, new discovery)

Recently reviewed by IER (Uwe Remme)
http://www.etsap.org/Workshop/Stuttgart_11_2006/tiam_review.pdf

Nuclear

Uranium is not (yet) modelled as a resource, and cost of the resource is included in the varom.

Need for a user´s constraint (*up*) since the decision depends more on social values than economic rationality

13

Renewables

Geothermal: Shallow, deep and very deep

Hydro: Dam and run-of-river
WEC technical potential + extra potential more expensive

Wind: Four types of plants (different caracteristics): 2 onshore, 1 offshore, 1 backstop (high potential, high cost)
Equivalent to 10% of the potential provided by IPCC-TAR
~ WEC assuming 4% of the land area

Solar : PV, thermal, centralized and decentralized

Biomass: Industrial wastes, municipal wastes, solid biomass, biogas from landfills, liquids from biomass (IEA categories)
Under review (differences between different types of crops, sustainability issues)

Sources of data

World Energy Council, IPCC-TAR, US Geological Survey, IEA-ETP, many specialized papers and reports, etc.

14

Also included in Upstream

Extraction and treatment technologies
Flaring and venting
Refinery
Blast furnace
Coke and Coke oven gas production
Specific cogeneration for upstream sector
(See template)

And also Declaration for Global Warming Potentials *~COMAGG* (commodity aggregation)

15

Trade

16

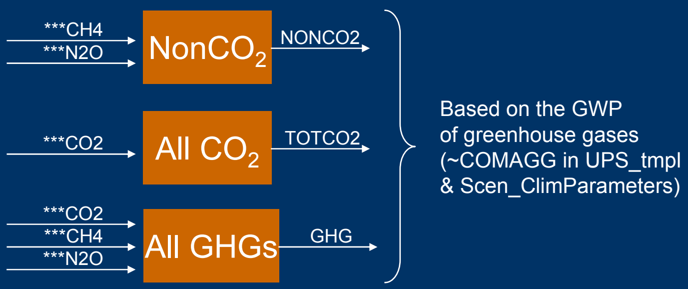
Endogenous trade

Endogenous trade of coal, crude oil, oil refined products, gas, liquefied gas
⇒ price and amount of traded energy are endogenous
⇒ the impact on trade of environmental policies is taken into account

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)

This also allows a World limit of emissions (GBL region)



17

Power plant / hydrogen / sequestration

18

Electricity sector (cogen and autoprod not shown)

Regional templates	8 existing power plants
SubRes NewTech	51 new power plants
SubRes Sequestration	17 power plants with CO_2 capture

The price of electricity generated by power plants with CO_2 capture ~ 50% higher than the electricity price generated by power plants without capture.

Remarks

Limited share of coal plants in the total electricity produced by fossil fuel power plants (local air quality requirements)

Examples of results

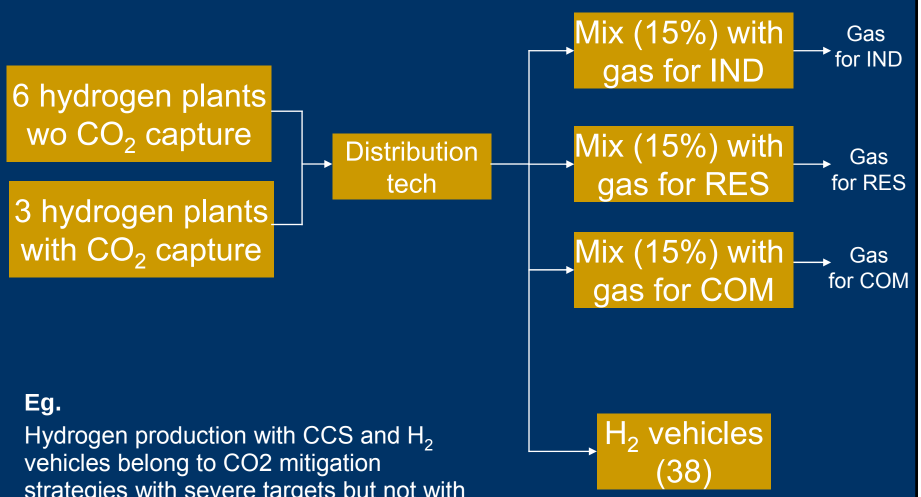
CCGT bridges the transition to more advanced fossil and zero-carbon plants

Primary consumption of coal may increase in the long term when associated with CCS and with the removal of the coal power plants limit (assuming new coal power plants are "clean" plants)

19

Hydrogen sector

SubRes Hydrogen & SubRes Sequestration

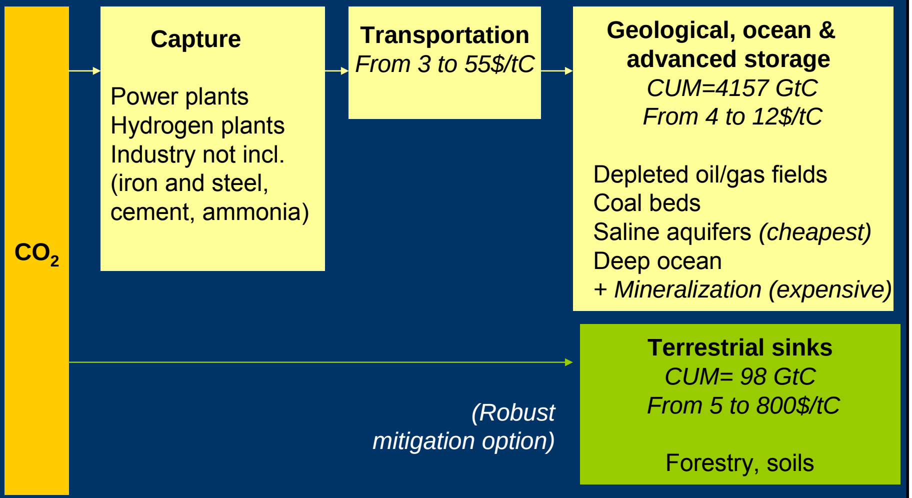


Eg.

Hydrogen production with CCS and H_2 vehicles belong to CO2 mitigation strategies with severe targets but not with moderate targets

20

CO_2 sequestration *SubRes Sequestration*



Remarks

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

Of course, many uncertainties (reservoirs and biological processes), risk of leakage, permanence

Non-CO2 emissions

(Subres NonCO2 emissions, CH4options and N2Ooptions)

CH_4 and N_2O (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*

(regional variations)

Examples of options

Catalytic oxidation of methane in coal mines, anaerobic digestion of wastes (with gas recovery), flaring instead of venting (oil extraction), etc.

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

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

EMF 21 - *Multi-Gas Mitigation and Climate Change*

CH4 options (1/2)

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 options (2/2)

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)

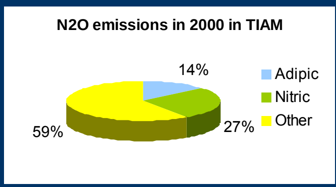
25

N2O 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)

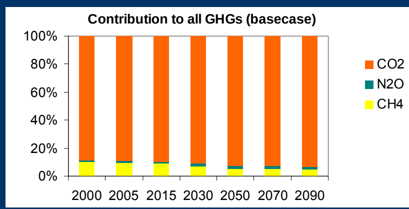
26

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



Examples of options for N2O

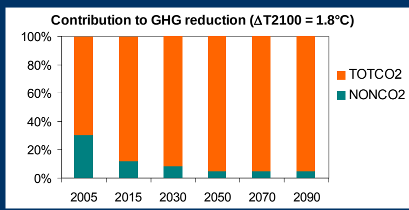
Different types of catalytic reduction, thermal destruction



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

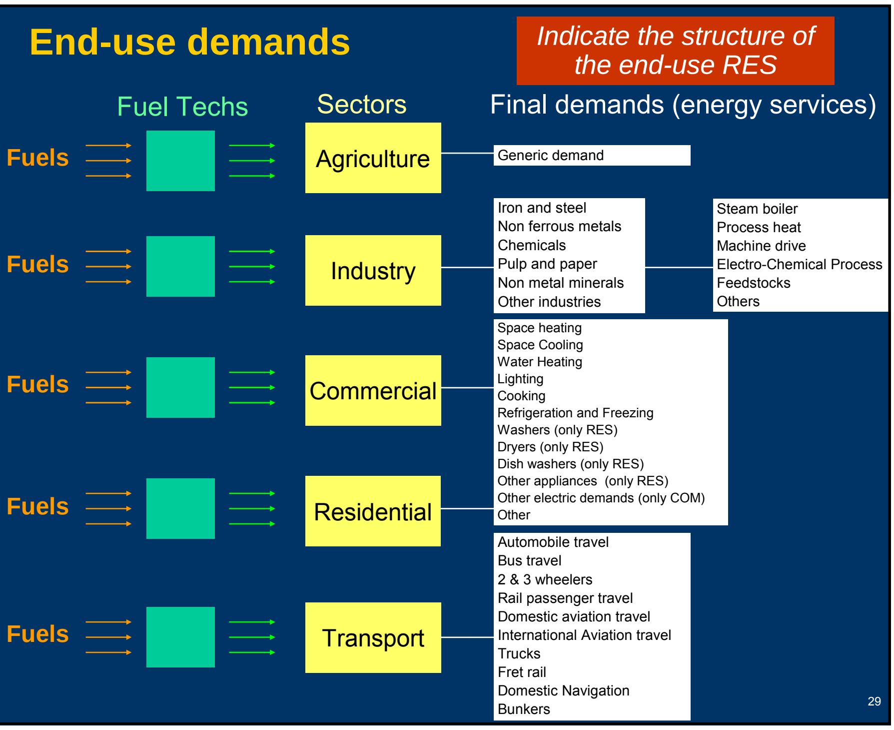


27

Energy service demands

28

End-use demands



29

List and units of end-use demands (1/2)

	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	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

30

List and units of end-use demands (2/2)

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

31

Each model has its own structure (RES)

TRA demands in TIAM

- Automobile travel
- Bus travel
- 2 & 3 wheelers
- Rail passenger travel
- Domestic aviation travel
- International Aviation travel
- Trucks
- Fret rail
- Domestic Navigation
- Bunkers

TRA demands in TIMES-Spain

Road.Car.Short Distance.	Million_Pkm
Road.Car.Long Distance.	Million_Pkm
Road.Freight.	Million_Tkm
Road.Bus.Urban.	Million_Pkm
Road.Bus.Intercity.	Million_Pkm
Road.Moto.	Million_Pkm
Rail.Freight.	Million_Tkm
Rail.Passengers.Light.	Million_Pkm
Rail.Passengers.Heavy.	Million_Pkm
Aviation Generic.	PJ
Navigation.Generic.	PJ
Navigation.Generic.Bunker	PJ
Aviation International	PJ

32

Demands: Link between a Computable General Equilibrium model and TIAM

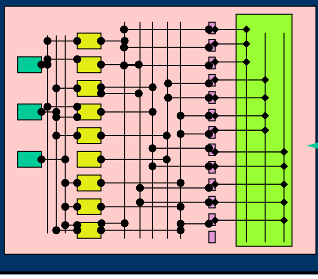
Storyline
Lifestyle, pop dyn, technical progress, etc.

CGE model

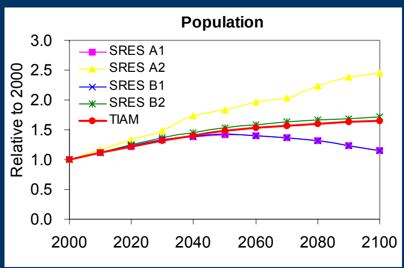
Drivers
(GDP, Sector outputs, Households, etc.)

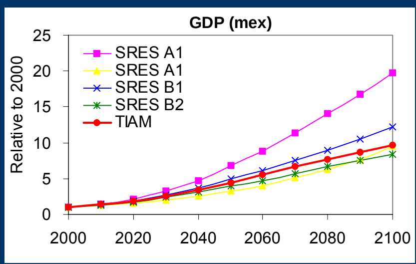
- **Associate** demands and drivers
- **Chose elasticities** of demands to drivers

Compute service demands
Demand = Driver^{elasticity}



GDP and POP





ANNUAL CHANGE		2000-2010	2010-2020	2020-2030	2030-2040	2040-2050	2050-2060	2060-2070	2070-2080	2080-2090	2090-2100	2000-2050	2050-2100	2000-2100
AFR	GDP	4.8%	4.2%	3.9%	3.9%	3.7%	3.2%	2.7%	2.2%	1.7%	1.3%	4.1%	2.2%	3.2%
AUS	GDP	2.5%	2.2%	2.1%	1.8%	1.5%	1.3%	1.1%	1.0%	0.9%	0.8%	2.0%	1.0%	1.5%
CAN	GDP	2.4%	2.1%	1.4%	1.5%	1.2%	1.1%	1.0%	0.9%	0.9%	0.8%	1.7%	0.9%	1.3%
CHI	GDP	10.4%	6.2%	6.0%	4.9%	4.4%	3.5%	2.6%	1.9%	1.6%	1.2%	6.4%	2.2%	4.2%
CSA	GDP	3.8%	3.6%	3.6%	3.6%	3.6%	3.1%	2.5%	2.0%	1.6%	1.3%	3.6%	2.1%	2.9%
EEU	GDP	2.3%	2.2%	2.1%	2.0%	1.9%	1.5%	1.2%	1.0%	0.9%	0.8%	2.1%	1.0%	1.6%
FSU	GDP	5.5%	3.8%	3.3%	3.0%	2.7%	2.2%	1.7%	1.3%	1.1%	0.8%	3.6%	1.4%	2.5%
IND	GDP	7.4%	8.0%	7.4%	5.7%	4.3%	3.4%	2.5%	1.8%	1.5%	1.2%	6.5%	2.1%	4.3%
JPN	GDP	1.8%	1.4%	1.0%	1.2%	1.3%	1.2%	1.1%	1.0%	0.9%	0.8%	1.3%	1.0%	1.2%
MEA	GDP	5.1%	4.0%	3.8%	3.5%	3.2%	2.8%	2.3%	2.0%	1.7%	1.3%	3.9%	2.0%	3.0%
MEX	GDP	3.5%	4.2%	4.3%	4.1%	3.7%	3.1%	2.5%	2.0%	1.6%	1.2%	4.0%	2.1%	3.0%
ODA	GDP	4.5%	3.9%	3.6%	3.3%	2.9%	2.5%	2.1%	1.7%	1.5%	1.2%	3.6%	1.8%	2.7%
SKO	GDP	2.8%	2.4%	1.9%	2.0%	1.8%	1.5%	1.4%	1.2%	1.0%	0.8%	2.2%	1.2%	1.7%
USA	GDP	3.1%	3.0%	2.8%	2.2%	1.7%	1.5%	1.2%	1.0%	0.9%	0.8%	2.6%	1.1%	1.8%
WEU	GDP	2.1%	2.2%	2.1%	1.9%	1.7%	1.5%	1.2%	1.0%	0.9%	0.8%	2.0%	1.1%	1.5%
WORLD	GDP	3.3%	3.1%	3.1%	2.9%	2.7%	2.3%	1.9%	1.5%	1.3%	1.0%	3.0%	1.6%	2.3%

Drivers used to build energy service demands (1/2)

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

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

35

Drivers used to build energy service demands (1/2)

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-X
Non ferrous metals	SPROD-X
Chemicals	SPROD-X
Pulp and paper	SPROD-X
Non metal minerals	SPROD-X
Other industries	SPROD-X

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

36

Elasticities of service demands to their driver

These elasticities reflect changing patterns in energy service demands in relation to socio-economic growth, such as :

- Shift away from public transport (<1) towards private car (>1) with increasing income, with however a certain saturation level after 2050 (<1); the greater urbanization would also contribute to a lesser increase in the passenger-km demand.
- For residential basic needs, the drivers are either the number of households or the population; for the other demand categories, the evolution of income is the dominant factor. In the long run, a certain saturation and changes in consumption patterns will lessen this link.
- Etc.

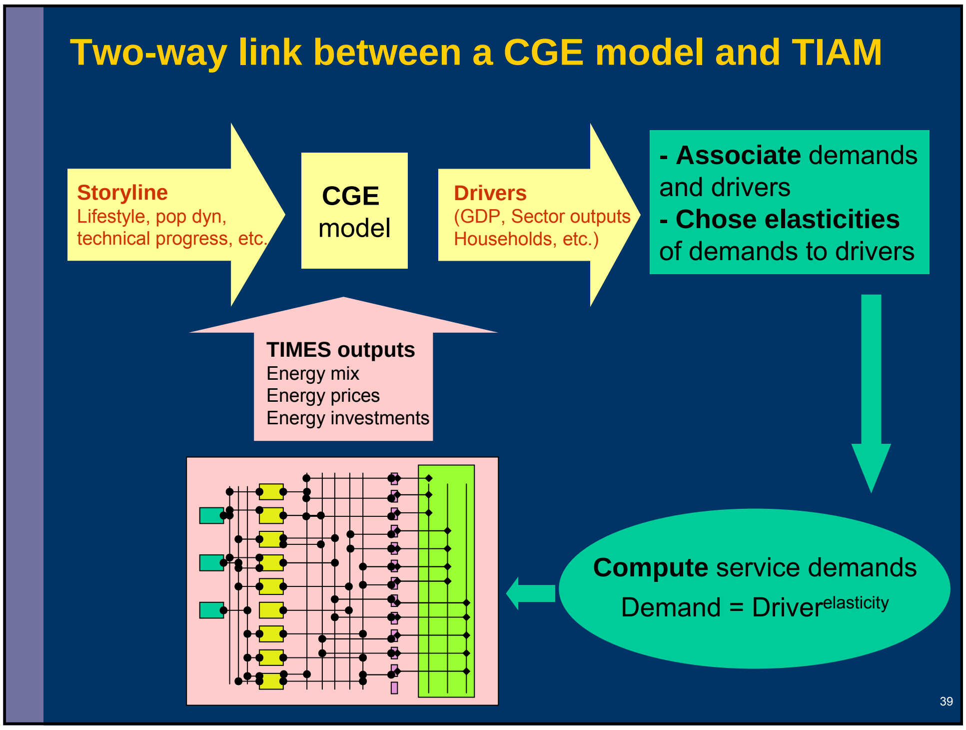
Long term convergence of the elasticities between developing and industrialized countries

37

Example of elasticities of service demands to their driver

Demand Category	Driver		Driver Elasticity of Demands		
			Before 2050		After 2050
Transportation demand	All regions		OECD	Non-OECD	All regions
Autos	GDPP		1.2	1.5	0.5
Buses	POP		0.7	0.8	0.8
Two/three wheelers	POP		0.7	0.7	0.7
Passengers rail transportation	POP		0.8	0.8	0.7
Domestic aviation	GDP		1.3	1.5	0.6
International aviation	GDP		1.3	1.5	0.6
Freight transport	GDP		1	1.2	0.4
Trucks	GDP		0.7	0.9	0.4
Freight rail transportation	GDP		1	1.2	0.4
Internal navigation	GDP		1	1.2	0.4
International navigation (bunkers)	GDP		1	1.2	0.4
Residential demand	All regions >2050	OECD < 2050			
Space heating	HOU	HOU	0.8	1/0.7*	0.5
Space cooling	HOU	GDPP	1	1	0.5
Hot water heating	POP	POP	1	1.1	0.8
Lighting	GDPP	GDPP	1	1.2	0.7
Cooking	POP	POP	0.7	0.8	0.5
Refrigerators and freezers	HOU	GDPP	1	1.2	0.8
Cloth washers	HOU	GDPP	1	1.2	0.8
Cloth dryers	HOU	GDPP	1	1.2	0.8
Dish washers	HOU	GDPP	1	1.2	0.8
Miscellaneous electric energy	GDPP	GDPP	1	1.2	0.8
Other energy uses	HOU	GDPP	1	1.2	0.8

38



Calibration to initial year

40

Base year (2005) information

Calibration = matching detailed energy balances in initial period (2005)

❶ Energy Statistics and Balances of OECD and Non-OECD countries of the International Energy Agency

❷ Adjusted by regional or national statistics if necessary and available

❸ International and regional statistics (installed capacities and resource potentials)

➊ is automatic, ➋ & ➌ are manual

Calibration to any future projections?

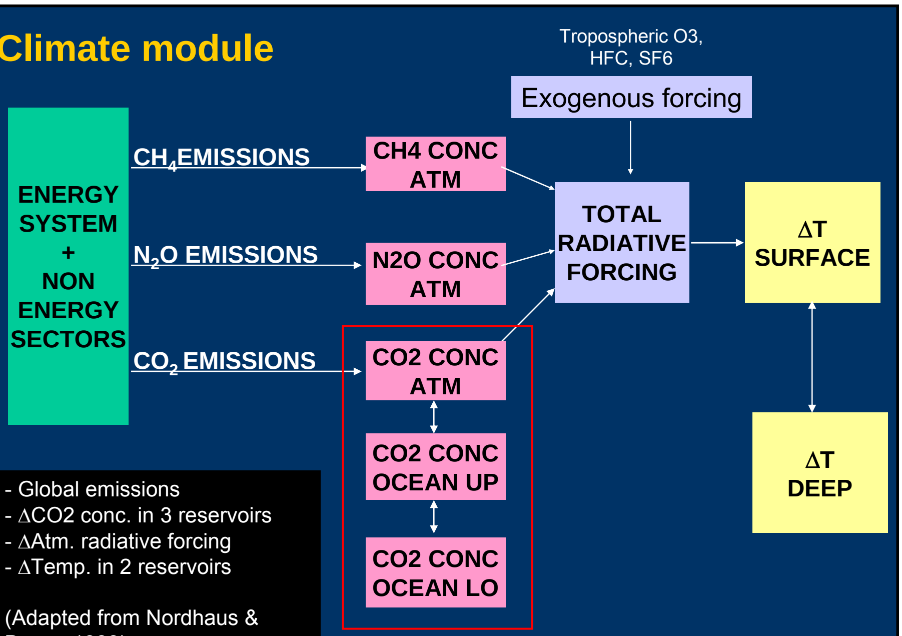
Time-consuming and… useless… and almost impossible

41

Climate module (scenario Scen_ClimParameters)

42

Climate module



- Global emissions
- ΔCO2 conc. in 3 reservoirs
- ΔAtm. radiative forcing
- ΔTemp. in 2 reservoirs

(Adapted from Nordhaus & Boyer, 1999)

Climate equations: CO2 concentration

CO2 accumulation is represented as the linear three-reservoir model below: the atmosphere, the quickly mixing upper ocean + biosphere, and the deep ocean. CO2 flows in both directions between adjacent reservoirs. The 3-reservoir model is represented by the following 3 equations when the step of the recursion is equal to one year:

$$M_{atm}(y) = E(y\text{-}1) + (1 - \varphi_{atm\text{-}up})\, M_{atm}(y\text{-}1) + \varphi_{up\text{-}atm}\, M_{up}(y\text{-}1) \qquad (1)$$

$$M_{up}(y) = (1 - \varphi_{up\text{-}atm} - \varphi_{up\text{-}lo})\, M_{up}(y\text{-}1) + \varphi_{atm\text{-}up}\, M_{atm}(y\text{-}1) + \varphi_{lo\text{-}up}\, M_{lo}(y\text{-}1) \qquad (2)$$

$$M_{lo}(y) = (1 - \varphi_{lo\text{-}up})\, M_{lo}(y\text{-}1) + \varphi_{up\text{-}lo}\, M_{up}(y\text{-}1) \qquad (3)$$

with

- $M_{atm}(y)$, $M_{up}(y)$, $M_{lo}(y)$: masses of CO_2 in atmosphere, in a quicly mixing reservoir representing the upper level of the ocean and the biosphere, and in deep oceans (GtC), respectively, at period *t* (GtC)
- $E(y\text{-}1)$ = CO_2 emissions in previous year (GtC)
- φ_{ij}, transport rate from reservoir *i* to reservoir *j* (*i, j = atm, up, lo*) from year *y-1* to *y*

Climate equations: CH4 and N2O

Have their own concentration equations

Climate equations: Radiative forcing

The relationship between GHG accumulations and increased radiative forcing, $\Delta F(t)$, is derived from empirical measurements and climate models.

$$\Delta F(t) = \gamma * \frac{\ln (M_{atm}(t)/M_0)}{\ln 2} + O(t) \qquad (4)$$

where:

- M_0 (i.e.CO2ATM_PRE_IND) is the pre-industrial (circa 1750) reference atmospheric concentration of CO2 = 596.4 GtC
- γ is the radiative forcing sensitivity to atmospheric CO_2 concentration doubling = 4.1 W/m^2
- $O(t)$ (i.e. EXOFORCING(t)), is the increase in total radiative forcing at period t relative to pre-industrial level due to anthropogenic GHG's not accounted for in the computation of CO2 emissions. Units = W/m^2. In Nordhaus and Boyer (1999), only emissions of CO2 were explicitly modeled, and therefore O(t) accounted for all other GHG's. In TIMES, N_2O and CH_4 are fully accounted for, but some are not (e.g. CFC's, aerosols, ozone)

45

Climate equations: Radiative forcing

$$\Delta F_{CH4}(t) = \beta(M^{1/2} - M_0^{1/2}) - [f(M,N_0) - f(M_0,N_0)]$$

$$\Delta F_{N2O}(t) = \varepsilon(N^{1/2} - N_0^{1/2}) - [f(M_0,N) - f(M_0,N_0)]$$

$$\Delta F_{TOT}(t) = \Delta F_{CO2}(t) + \Delta F_{CO2}(t) + \Delta F_{CO2}(t) + O(t)$$

- M is the atmospheric CH_4 concentration and M_0 is the natural reference concentration of CH_4
- β is the radiative forcing sensitivity to CH_4 concentration, $\beta = 0.036$
- N is the atmospheric N_2O concentration and N_0 is the natural reference concentration of N_2O
- ε is the radiative forcing sensitivity to N_2O concentration, $\varepsilon = 0.12$
- The function $f(M,N)$ takes into account the overlap of nitrous oxide and methane;
  $f(M,N) = 0.47 \cdot \ln[1 + 2.01 \cdot 10^{-5} \cdot (M \cdot N)^{0.75} + 5.31 \cdot 10^{-15} \cdot M(M \cdot N)^{1.52}]$

46

Climate equations: Temperature

In the TIMES Climate Module as in many other integrated models, climate change is represented by the global mean surface temperature. The idea behind the two-reservoir model is that a higher radiative forcing warms the atmospheric layer, which then quickly warms the upper ocean. In this model, the atmosphere and upper ocean form a single layer, which slowly warms the second layer consisting of the deep ocean.

$$\Delta T_{up}(y) = \Delta T_{up}(y\text{-}1) + \sigma_1\{F(y) - \lambda\,\Delta T_{up}(y\text{-}1) - \sigma_2\,[\Delta T_{up}(y\text{-}1) - \Delta T_{low}(y\text{-}1)]\} \quad (8)$$

$$\Delta T_{low}(y) = \Delta T_{low}(y\text{-}1) + \sigma_3\,[\Delta T_{up}(y\text{-}1) - \Delta T_{low}(y\text{-}1)] \quad (9)$$

with

- ΔT_{up} = globally averaged surface temperature increase above pre-industrial level,
- ΔT_{low} = deep-ocean temperature increase above pre-industrial level,
- σ_1 = 1-year speed of adjustment parameter for atmospheric temperature (also known as the *lag* parameter),
- σ_2 = coefficient of heat loss from atmosphere to deep oceans,
- σ_3 = 1-year coefficient of heat gain by deep oceans,
- λ = feedback parameter (climatic retroaction). It is customary to write λ as $\lambda = \gamma / C_s$, C_s being the *climate sensitivity* parameter, defined as the change in equilibrium atmospheric temperature induced by a doubling of CO_2 concentration.

47

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)

48

Example of applications

Examples of analyses

MARKAL previous version of the model

Integration of climate damages and analysis of World cooperative and non-cooperative strategies with game theory

Energy Modelling Forum (EMF-22)

1) Stochastic analysis of climate policies

Long term concentration / temperature targets

2) Transition policies

Simulate policies that could be applied in 2010-2040

Eg. *sectoral caps and trade, taxes and/or subsidies on commodities and/or technologies, technology standards (car efficiency, building shell efficiency), portfolio standards (emission per kWh of electricity produced)*

Exploratory analysis

Potential role of nuclear energy in climate policies by 2100

Examples of analyses

Other projects

1) GICC (Gestion et impacts du changement climatique)
Sponsored by the French Ministry of Ecology and Sustainable Development
Simulation of post-Kyoto strategies in a fragmented international climate framework / Study of the impact of oil pricing policies on climate mitigation

2) TOCSIN (Technology-Oriented Cooperation and Strategies in India and China: Reinforcing the EU dialogue with Developing Countries on Climate Change Mitigation)
Sponsored by the European Commission (Sixth Framework Program)
Analyses the role of large developing countries in the long term abatement of greenhouse gases, with particular focus on technology diffusion

51

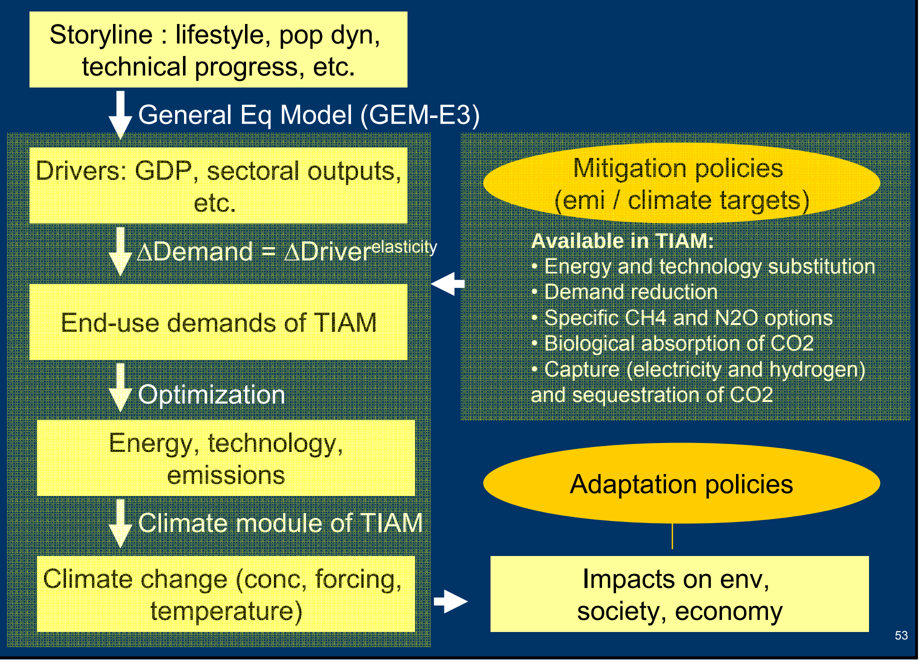
Examples of analyses

3) PLANETS (Probabilistic Long-Term Assessment of New Energy Technology Scenarios)
Sponsored by the European Commission (Seventh Framework Program)
To evaluate robust scenarios for the evolution of energy technologies in the next 50 years

4) REACCESS (Risk of Energy Availability: Common Corridors for Europe Supply Security)
Sponsored by the European Commission (Seventh Framework Program)
Evaluating technical, economical and environmental features of present and future energy corridors within Europe and between Europe and the ROW

52

Framework used for the analysis of climate policy



53

Application 1 of ETSAP-TIAM : Analysis of climate policies under uncertainty

54

Objective

Assess the feasibility, cost, and means of maintaining global temperature increase within the 2ºC to 3ºC range (long term), under high economic and climate uncertainty (EMF22)

Uncertainties

➊ Climate sensitivity C_s and lag parameter σ_1 (speed of adjustment parameter for atmospheric temperature)

➋ Economic growth and thus GHG emissions

➌ Technologies: nuclear, carbon sequestration

➊ & ➋ Stochastic programming

➌ Sensitivity analyses (scenarios)

55

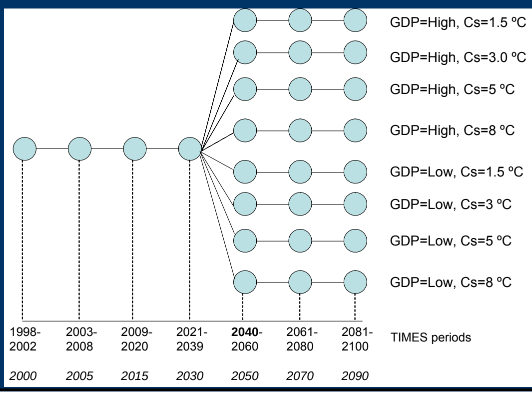
Stochastic optimisation

Define an event tree

Maximize the expected surplus subject to:

- All TIMES constraints must be satisfied <u>for each branch</u> of the event tree
- There is a <u>single</u> set of decisions prior to the resolution of uncertainty (while the decision maker does not yet know the outcome)

Optimal compromise between the negative effects of « guessing wrong »



56

Hedging

Hedging is deemed relevant if decisions *prior* the resolution of uncertainty are different from those in the base case.

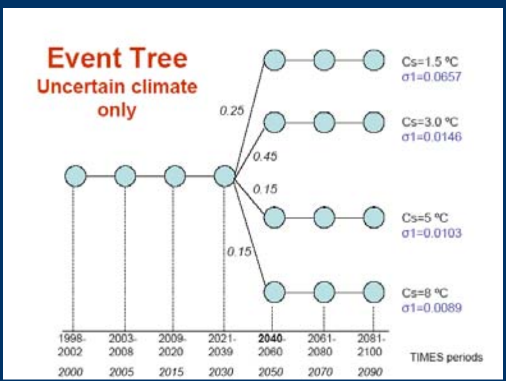
Otherwise, “*wait and see*” is a good policy.

Hedging is even more useful when it is not identical to *any* of the perfect forecast strategies, since such a situation clearly shows that the optimal technology and energy decisions are not easily predictable without an explicit treatment of uncertainty

57

Reduced tree of events

The impact of economic uncertainty on the hedging strategy before 2040 is negligible. In other words, the hedging decisions taken *before* 2040 are quite insensitive to the values of economic demands (and therefore the emission levels) *after* 2040 (there is no anticipation effect).



58

Declaration of stochastic parameters

Documentation: http://www.etsap.org/Docs/TIMES-Stochastic.pdf

2 stages: before and after information is known

4 possible states of the World (SOWs) after 2050

~scenario:SEMFCs
~TFM_INS

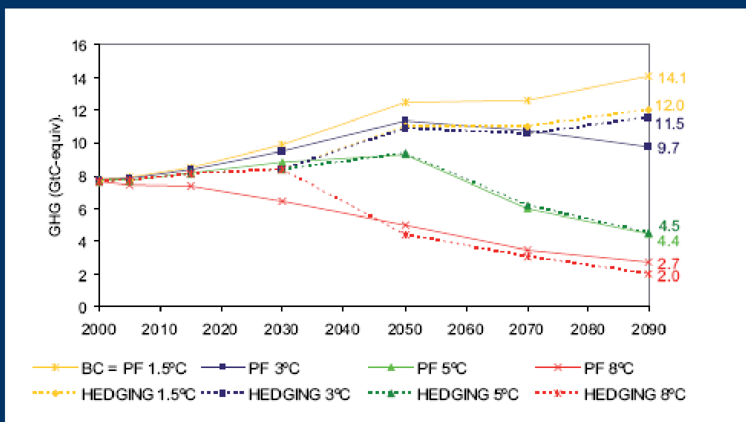
~include_comm

TS	BD	Stage	SOW	Prmtr	Yr	AllREG	AFR	AUS	CAN	Sets	Comm_Na
		1		SW_START		2000					
		2		SW_START		2050					
		1	1	SW_SUBS		4					
		2	1	SW_SPROB		0.25					
		2	2	SW_SPROB		0.45					
		2	3	SW_SPROB		0.15					
		2	4	SW_SPROB		0.15					
		2	1	S_CM_CONST			1.5				CS
		2	1	S_CM_CONST			0.06574				SIGMA1
		2	2	S_CM_CONST			3.0				CS
		2	2	S_CM_CONST			0.01461				SIGMA1
		2	3	S_CM_CONST			5.0				CS
		2	3	S_CM_CONST			0.01028				SIGMA1
		2	4	S_CM_CONST			8.0				CS
		2	4	S_CM_CONST			0.00886				SIGMA1

Probabilities for each branch

Values of Cs and σ_1 for each branch (stage 2)
Cs and are constant data (CM_CONST) of the climate module.

ΔT max (long term) = 2.5ºC



Perfect forecast strategies show diverse emission paths before 2040
When Cs=1.5, no emission reduction is needed
Hedging (before 2040) is close to PF5ºC

60

Robust (hedging) options

Table 5: Electricity production (EJ/year)

Plant Type		2000	2005	2015	2030	2050	2070	2090
NUCLEAR	BASE, PF Cs=1.5ºC	9	8	10	11	20	59	109
	PF Cs=3ºC	9	8	10	11	20	59	109
	PF Cs=5ºC	9	8	10	11	20	73	128
	PF Cs=8ºC	9	8	10	13	28	74	136
	HEDGING Cs=1.5ºC					20	59	109
	HEDGING Cs=3ºC					20	59	109
	HEDGING Cs=5ºC	9	8	10	11	20	73	128
	HEDGING Cs=8ºC					28	74	138
HYDRO	BASE, PF Cs=1.5ºC	9	9	10	11	13	22	26
	PF Cs=3ºC	9	9	10	11	19	26	38
	PF Cs=5ºC	9	9	10	15	30	39	44
	PF Cs=8ºC	9	9	12	25	35	42	49
	HEDGING Cs=1.5ºC					19	19	27
	HEDGING Cs=3ºC					19	24	28
	HEDGING Cs=5ºC	9	9	10	17	28	39	44
	HEDGING Cs=8ºC					35	44	53

Nuclear is not a robust technology

Hydro, Forestry sequestration, yes

Contribution of forestry sequestration to GHG (CO_2 equiv) reduction

Year	2005	2015	2030	2050	2070	2090
TIMES periods	2003–2008	2009–2020	2021–2039	2040–2060	2061–2080	2081–2100
HEDGING Cs=1.5°C				65%	99%	97%
HEDGING Cs=3°C				61%	85%	78%
HEDGING Cs=5°C	35%	53%	29%	31%	27%	21%
HEDGING Cs=8°C				12%	18%	16%
PF Cs=1.5°C	0%	0%	0%	0%	0%	0%
PF Cs=3°C	85%	86%	77%	53%	61%	41%
PF Cs=5°C	44%	65%	43%	29%	26%	20%
PF Cs=8°C	25%	27%	16%	13%	19%	17%

61

Super hedging options

A super-hedging action is an action that penetrates more in the hedging strategy than in any of the perfect forecast strategies.

Lies outside limits defined by the perfect forecast strategies

Ex:
Electricity production from renewables
Fuel substitution in industry
Geothermal in commercial buildings
Biomass in residential buildings

62

Expected Value of Information (EVI)

What is the expected gain in welfare if perfect information is available **earlier than 2040**?

- in 2005 (perfect foresight)? *EVPI = 210 B$*
- in 2020 (earlier knowledge)? *EVII = 159 B$ (3/4 of EVPI)*

$$EVPI = \sum_{s=1 \text{ to } S} p(s) \cdot [O_{PF(s)} - O_{HEDG}]$$

where

- $O_{PF(s)}$ is the surplus of the PFs strategy ($s = 1$ to S)
- O_{HEDG} is the expected surplus of the hedging strategy

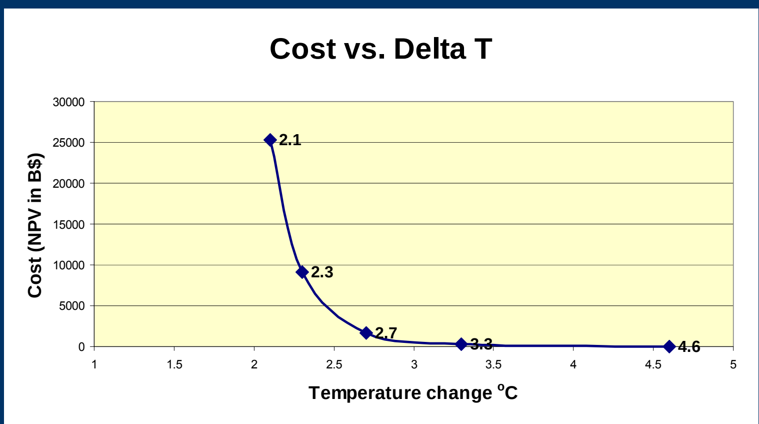
Table 2: Loss of surplus and expected value of perfect information

Strategy	Loss of surplus (NPV5% in B$)	Probability	Expected loss (NPV in B$ and annuity in B$/year)	EVPI (NPV in B$ and annuity in B$/year)
BASE	0	1	–	–
PF Cs=1.5°C	0	0.25	–	–
PF Cs=3°C	43	0.45	–	–
PF Cs=5°C	580	0.15	–	–
PF Cs=8°C	3353	0.15	–	–
Total PF			610 (31)	–
HEDGING	820		820 (41)	210 (11)

EPVI = Expected loss $_{\text{HEDGING}}$ – Expected loss $_{\text{PERFECT FORECAST}}$

63

Trade-off Cost / Temperature change



64

Application 2 of ETSAP-TIAM : Analysis of oil production strategies by OPEC

See IEW 2008

65