Analysis of climate policies under uncertainty

with TIAM and the new Climate Module

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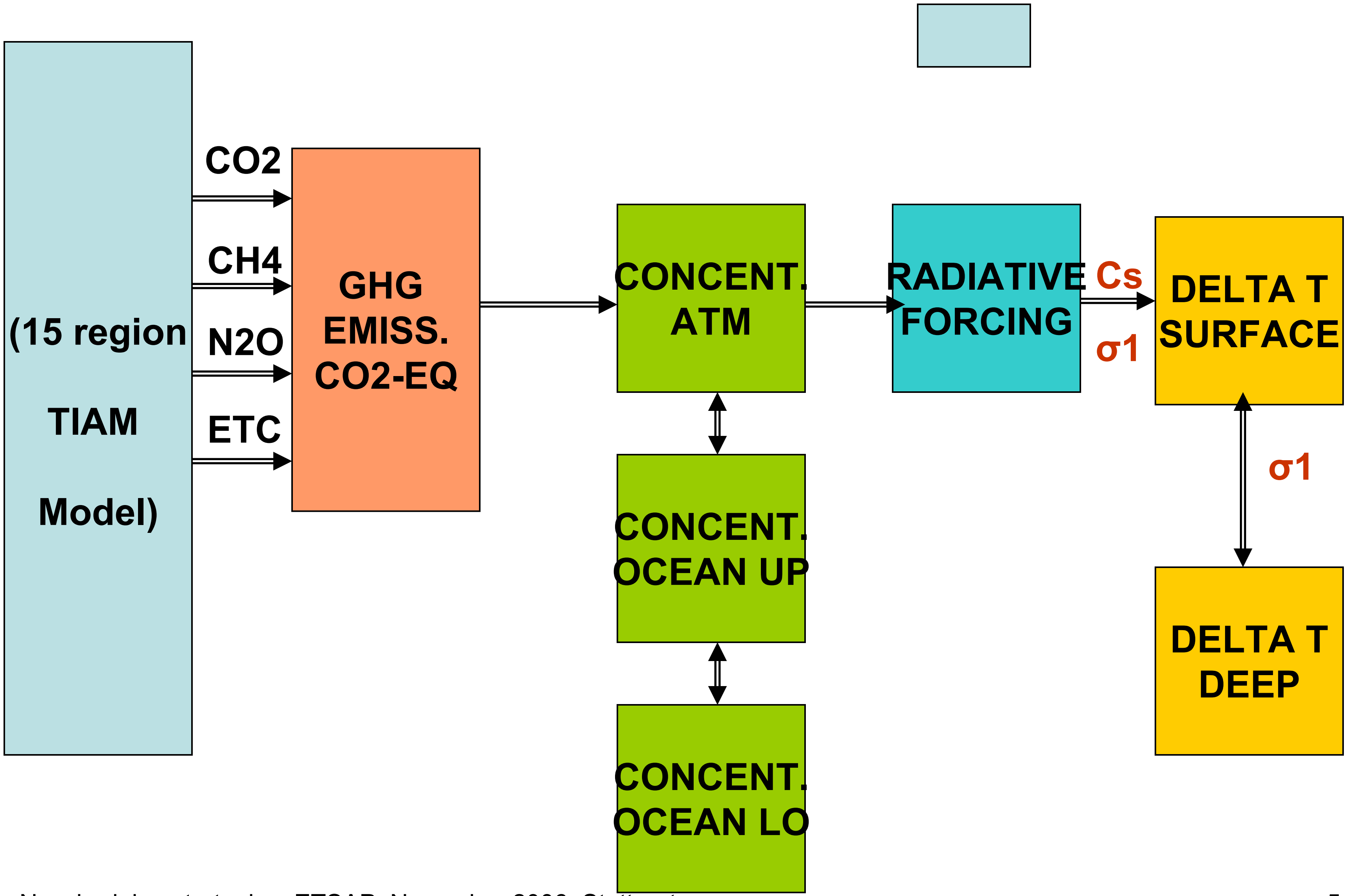
I: OBJECTIVE

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

II: METHODOLOGY

Schematics of TIAM Climate Module



Original Climate equations (adapted from Nordhaus and Boyer, 1999)

Concentrations of GHG (in CO2-equivalent) (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 forcing

4. $\Delta F(t) = \gamma/\ln 2 * \ln [CO2_{atm}(t)/CO2_{atm} (\text{pre-ind})] + O(t)$

Temperatures (2 layers)

Lag parameter

Climate sensitivity

5. $\Delta T_{up}(t) = \Delta T_{up}(t-1) + \sigma_1 * \{ \Delta F(t) - 3.7/C_s * \Delta T_{up}(t-1) - \sigma_2 [\Delta T_{up}(t-1) - \Delta T_{lo}(t-1)] \}$
6. $\Delta T_{lo}(t) = \Delta T_{up}(t-1)* \sigma_3 + \Delta T_{lo}(t-1)* g_{22}$

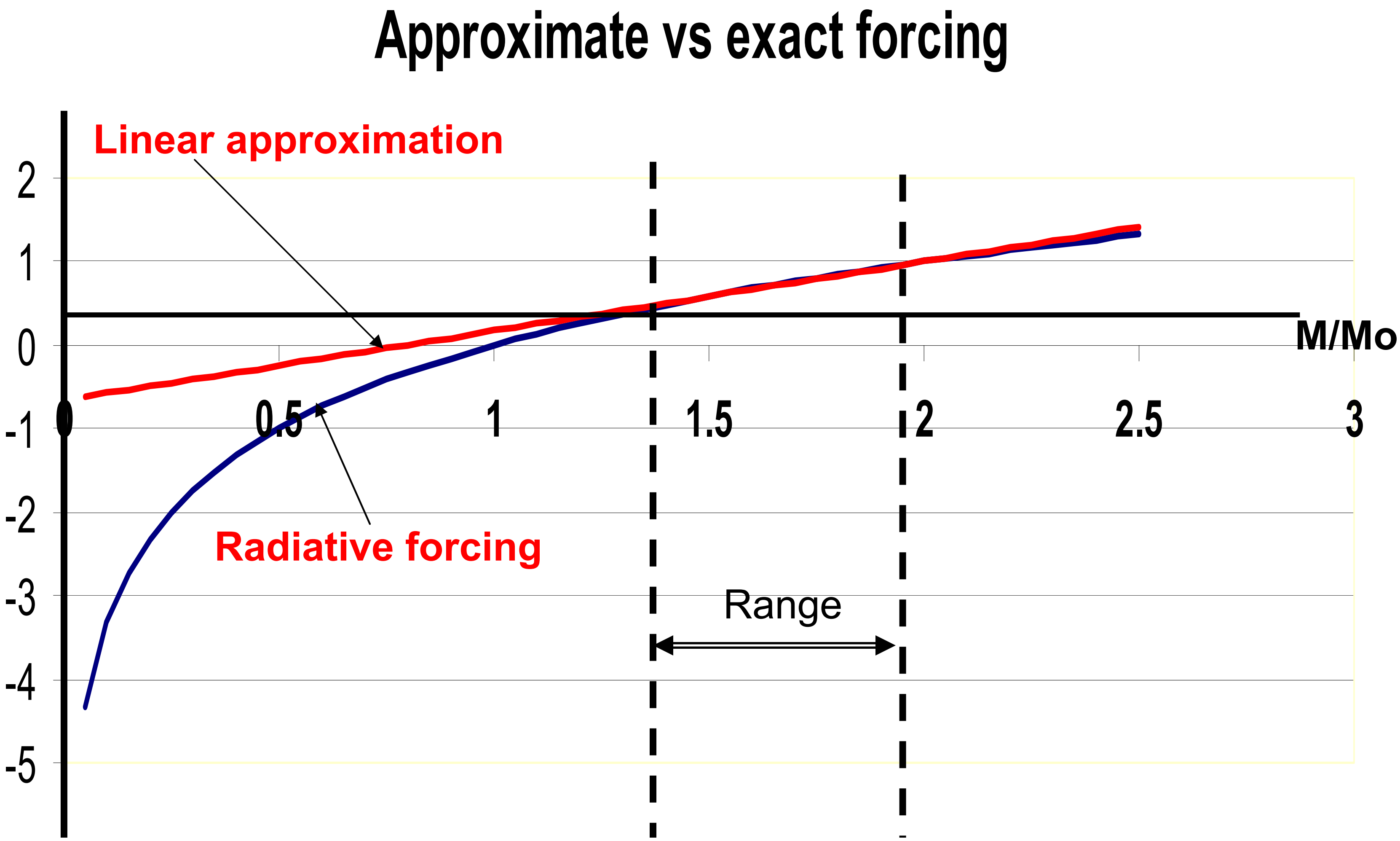
New version of the Climate Module

- The non-linear forcing equation is replaced by a linear approximation within the interval of interest For instance : (375 ppm-550 ppm)

- The approximation is halfway between the tangent and the chord of the exact logarithmic curve

- Within the selected range, the error made on Forcing never exceeds 2% (well within the inherent uncertainty on forcing values)

Linearized forcing equation



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

Procedure

- Impose an upper bound on $\Delta T_{atm}(2090)$
- Define the uncertainties
- Run the TIAM (stochastic mode)
- Observe atmospheric temperature $\Delta T_{atm}(t)$ in the long term (Excel sheet)
- Make additional runs if wanted, to explore additional temperature targets

Uncertainties in climate change

Uncertainty considered in this study

- Climate sensitivity C_s and Lag parameter σ_1

►**This uncertainty is treated explicitly via Stochastic Programming**

Other uncertainties, explored in the previous version of our work (Cape Town, 2006)

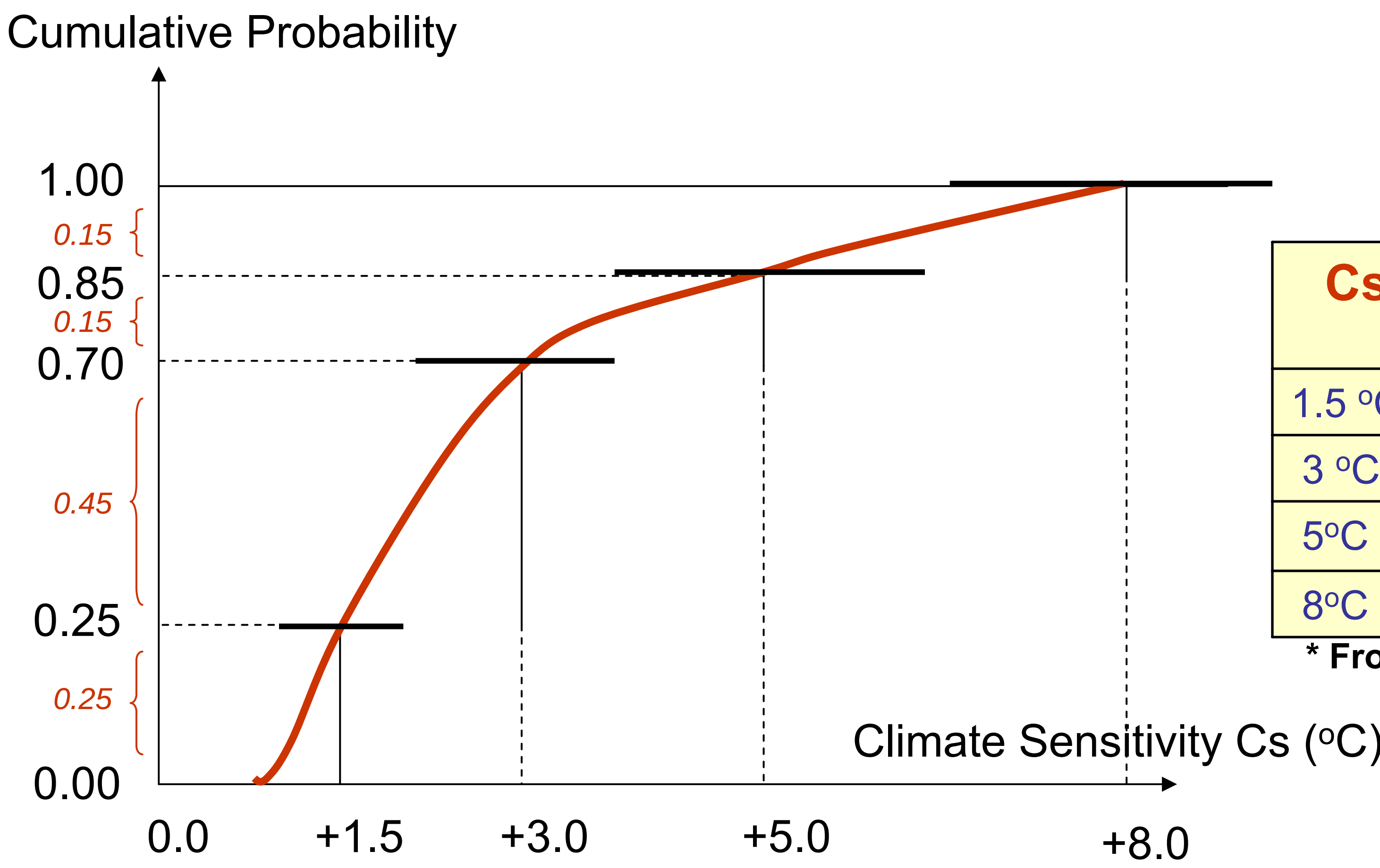
- Economic growth (and thus GHG emissions)
  treated via Stochastic Programming
- Technologies: Nuclear, Carbon sequestration
  treated via sensitivity analyses

Description of Uncertainties
(as per EMF-22)

	Economic Growth	Climate Sensitivity C_s
Unknown until and including	2040	2040
First certainty period in TIAM	2050	2050
Values	2 possible values High and Low (High growth = 2 x Low Growth) *Equal likelihood 0.5*	4 possible values (1.5, 3, 5, 8 ºC) with Lag parameter adjusted accordingly *Discrete Probability Distribution*

PDF of C_s

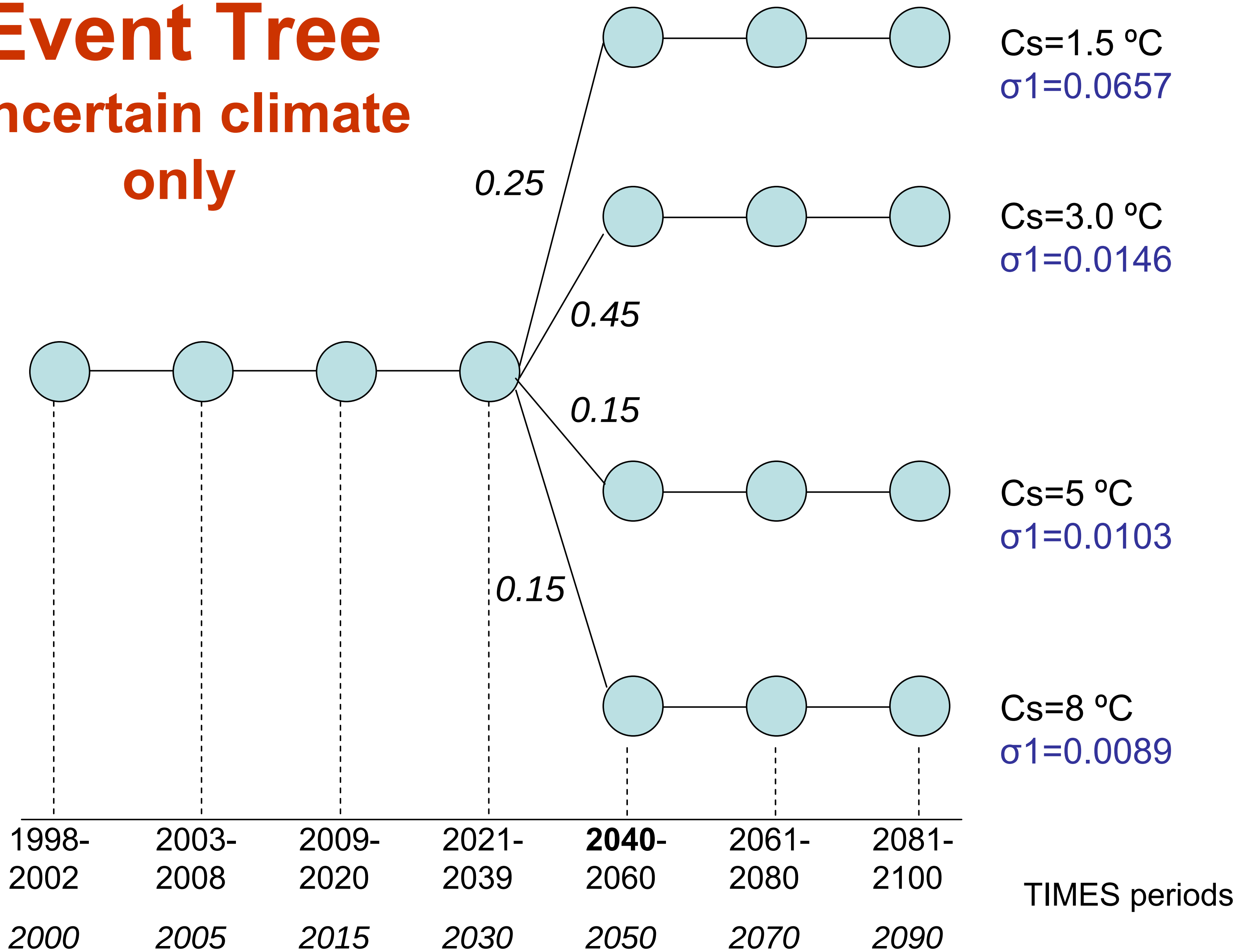
(adapted from Schlesinger and Andropova, 2001)



Cs	Prob	Lag σ_1*
1.5 °C	0.25	0.0657
3 °C	0.45	0.0146
5°C	0.15	0.0103
8°C	0.15	0.0089

*** From Yohe et al. (2004)**

Event Tree
Uncertain climate only



What is Stochastic Optimization?

- Define an event tree
- Maximize Expected Surplus

  Subject to:

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

- The optimal solution is a **Hedging Strategy**

Declaration of climate parameters

Documentation: http://www.etsap.org/Docs/TIMESDoc-Details.pdf

~FI_T: CM_HISTORY

CommName	1850	1875	1900	2000
CO2-ATM	780	780	780	780
CO2-UP	779	779	779	779
CO2-LO	19217	19217	19217	19217
DELTA-ATM	0.43	0.43	0.43	0.43
DELTA-LO	0.06	0.06	0.06	0.06

~FI_T

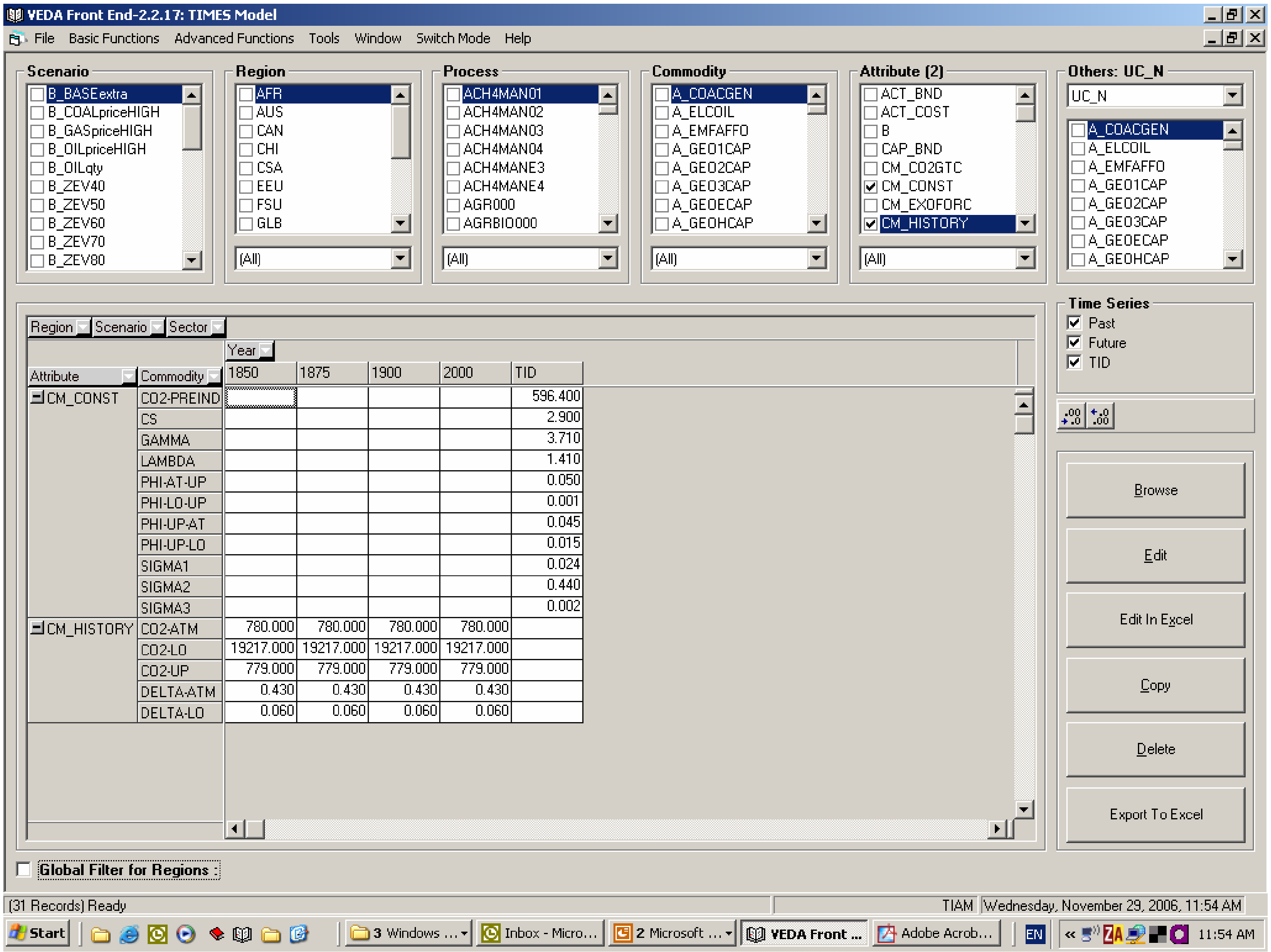
CommName	CM_CONST
GAMMA	3.71
PHI-UP-AT	0.0453
PHI-AT-UP	0.0495
PHI-LO-UP	0.00053
PHI-UP-LO	0.0146
LAMBDA	1.41
CS	2.9
SIGMA1	0.024
SIGMA2	0.44
SIGMA3	0.002
CO2-PREIND	596.4

In AFR_UPS template, sheet 'Climate'

Used in climate equations

All these data can be changed by the user

Climate parameters in VFE after importing template



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

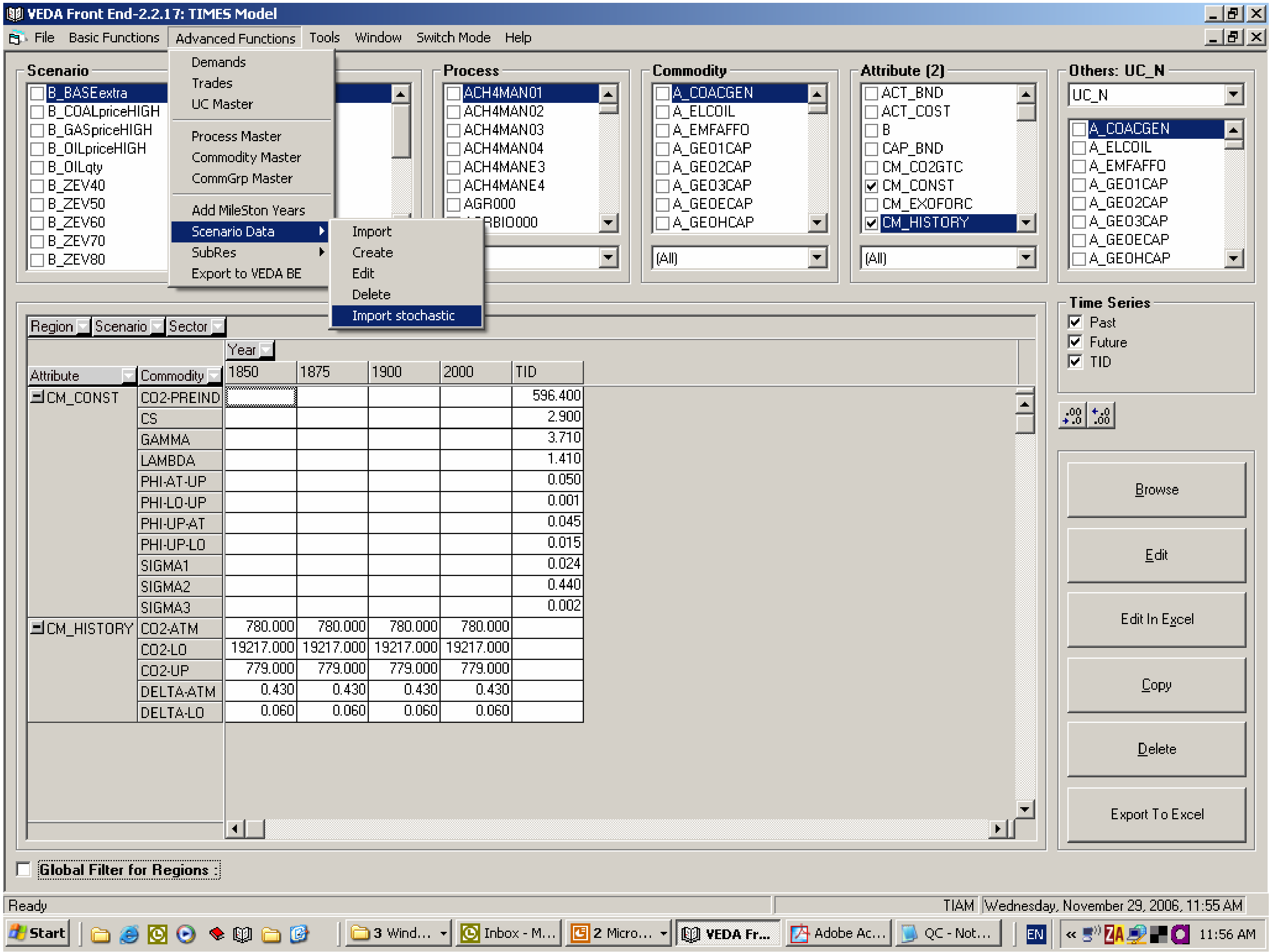
~include_comm

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

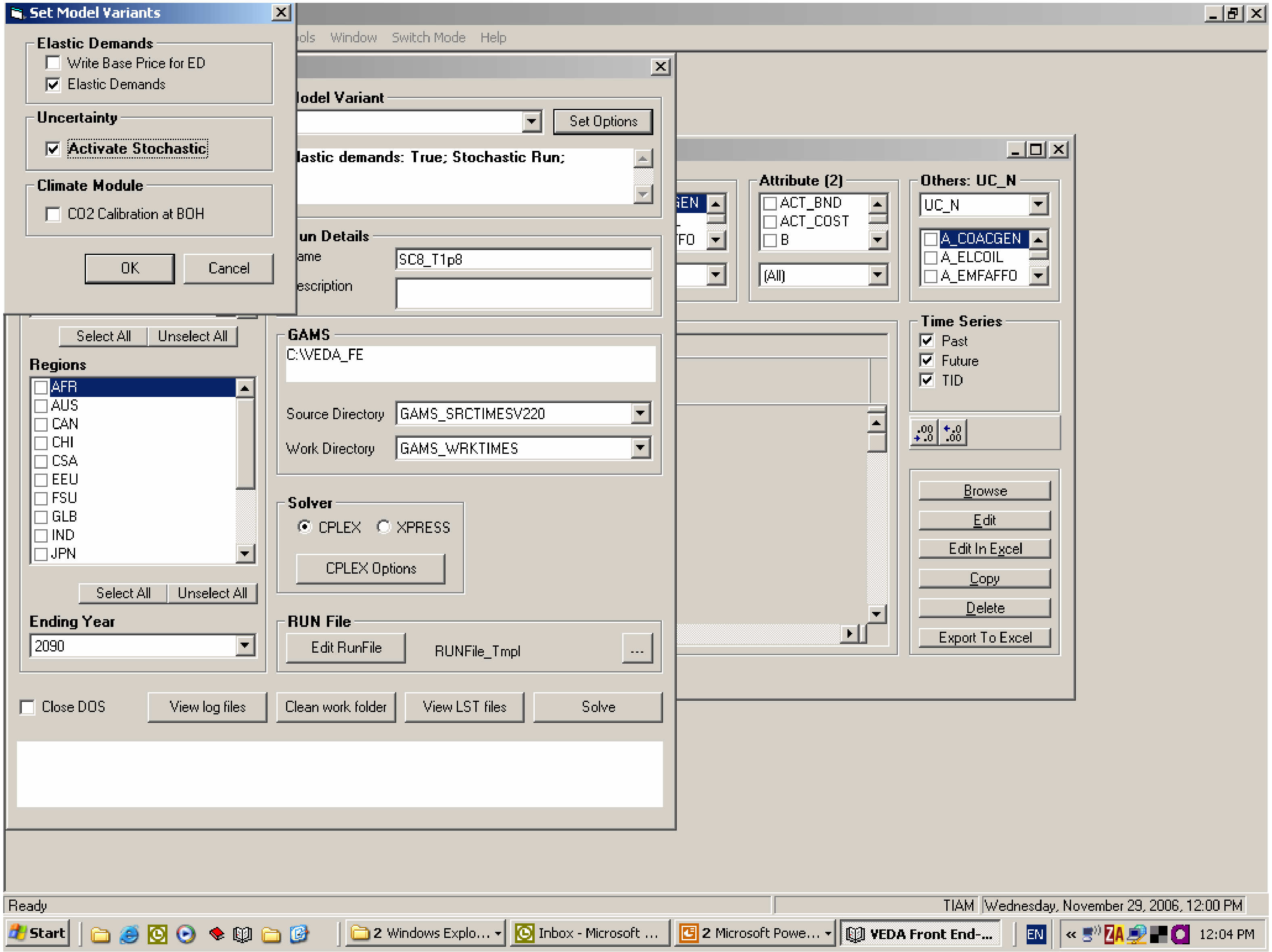
Probabilities for each branch

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

In VFE


VEDA Front End-2.2.17: TIMES Model
File
Basic Functions
Advanced Functions
Tools
Window
Switch Mode
Help
Scenario
B_BASEextra
B_COALpriceHIGH
B_GASpriceHIGH
B_OILpriceHIGH
B_OILqty
B_ZEV40
B_ZEV50
B_ZEV60
B_ZEV70
B_ZEV80
Demands
Trades
UC Master
Process Master
Commodity Master
CommGrp Master
Add MileSton Years
Scenario Data
SubRes
Export to VEDA BE
Import
Create
Edit
Delete
Import stochastic
Process
ACH4MAN01
ACH4MAN02
ACH4MAN03
ACH4MAN04
ACH4MANE3
ACH4MANE4
AGR000
Commodity
A_COACGEN
A_ELCOIL
A_EMFAFFO
A_GEO1CAP
A_GEO2CAP
A_GEO3CAP
A_GEOECAP
A_GEOHCAP
(All)
Attribute (2)
ACT_BND
ACT_COST
B
CAP_BND
CM_CO2GTC
CM_CONST
CM_EXOFORC
CM_HISTORY
(All)
Others: UC_N
UC_N
A_COACGEN
A_ELCOIL
A_EMFAFFO
A_GEO1CAP
A_GEO2CAP
A_GEO3CAP
A_GEOECAP
A_GEOHCAP
Region
Scenario
Sector
Year
Attribute
Commodity
1850
1875
1900
2000
TID
CM_CONST
CO2-PREIND
596.400
CS
2.900
GAMMA
3.710
LAMBDA
1.410
PHI-AT-UP
0.050
PHI-LO-UP
0.001
PHI-UP-AT
0.045
PHI-UP-LO
0.015
SIGMA1
0.024
SIGMA2
0.440
SIGMA3
0.002
CM_HISTORY
CO2-ATM
780.000
CO2-LO
19217.000
CO2-UP
779.000
DELTA-ATM
0.430
DELTA-LO
0.060
Time Series
Past
Future
TID
Browse
Edit
Edit In Excel
Copy
Delete
Export To Excel
Global Filter for Regions :
Ready
TIAM
Wednesday, November 29, 2006, 11:55 AM
Start
11:56 AM

In VFE


Set Model Variants
Elastic Demands
Write Base Price for ED
Elastic Demands
Uncertainty
Activate Stochastic
Climate Module
CO2 Calibration at BOH
OK
Cancel
Window
Switch Mode
Help
lodel Variant
Set Options
lastic demands: True; Stochastic Run;
un Details
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SC8_T1p8
escription
Select All
Unselect All
Regions
AFR
AUS
CAN
CHI
CSA
EEU
FSU
GLB
IND
JPN
Ending Year
2090
GAMS
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GAMS_SRCTIMESV220
Work Directory
GAMS_WRKTIMES
Solver
CPLEX
XPRESS
CPLEX Options
RUN File
Edit RunFile
RUNFile_Tmpl
Close DOS
View log files
Clean work folder
View LST files
Solve
Attribute (2)
ACT_BND
ACT_COST
B
(All)
Others: UC_N
UC_N
A_COACGEN
A_ELCOIL
A_EMFAFFO
Time Series
Past
Future
TID
Browse
Edit
Edit In Excel
Copy
Delete
Export To Excel
Ready
TIAM
Wednesday, November 29, 2006, 12:00 PM
Start
2 Windows Explo...
Inbox - Microsoft ...
2 Microsoft Powe...
VEDA Front End-...
EN
12:04 PM

Declaration of stochastic parameters

Set of possible uncertain parameters:

COM_PROJ Demand projection
CAP_BND Bound on total installed capacity
COM_CUMPRD Cumulative bound on commodity production
COM_CUMNET Cumulative bound on commodity net production

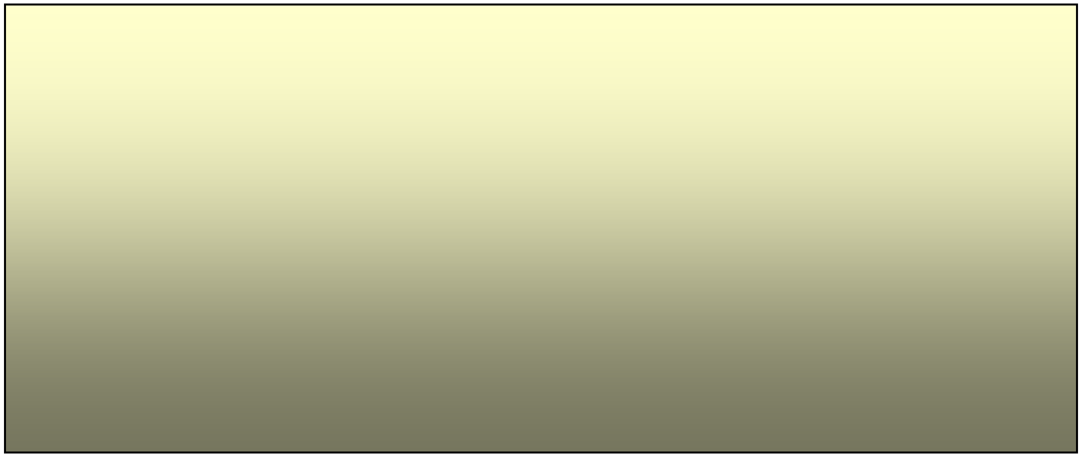
CM_MAXC(item) Maximum level of Climate variable (upper bound).
Item can be :

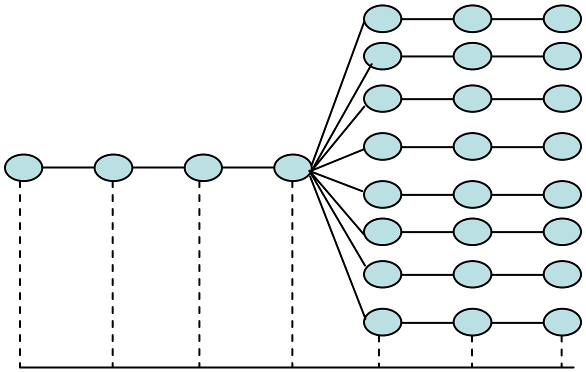
CO2-ATM	Max. Concentration ratio M/M0 (M0=pre-industrial conc.)
CO2-PPM	Max. CO2 Concentration in PPM
FORCING	Max. Radiative forcing in W/m2
DELTA-ATM	Max. Temperature change in C
CO2-GTC	Max. Total global CO2 emissions in GtC

III. Scenarios

Uncertainty on Climate and Economic Growth (previous work)

After 2040, both C_s and demands are uncertain





**Note: Most TIAM demands are strongly correlated to GDP*

► **Result: Hedging decisions are almost unaffected by GDP uncertainty. Hence, GDP uncertainty does not require *additional* hedging**

Base Case

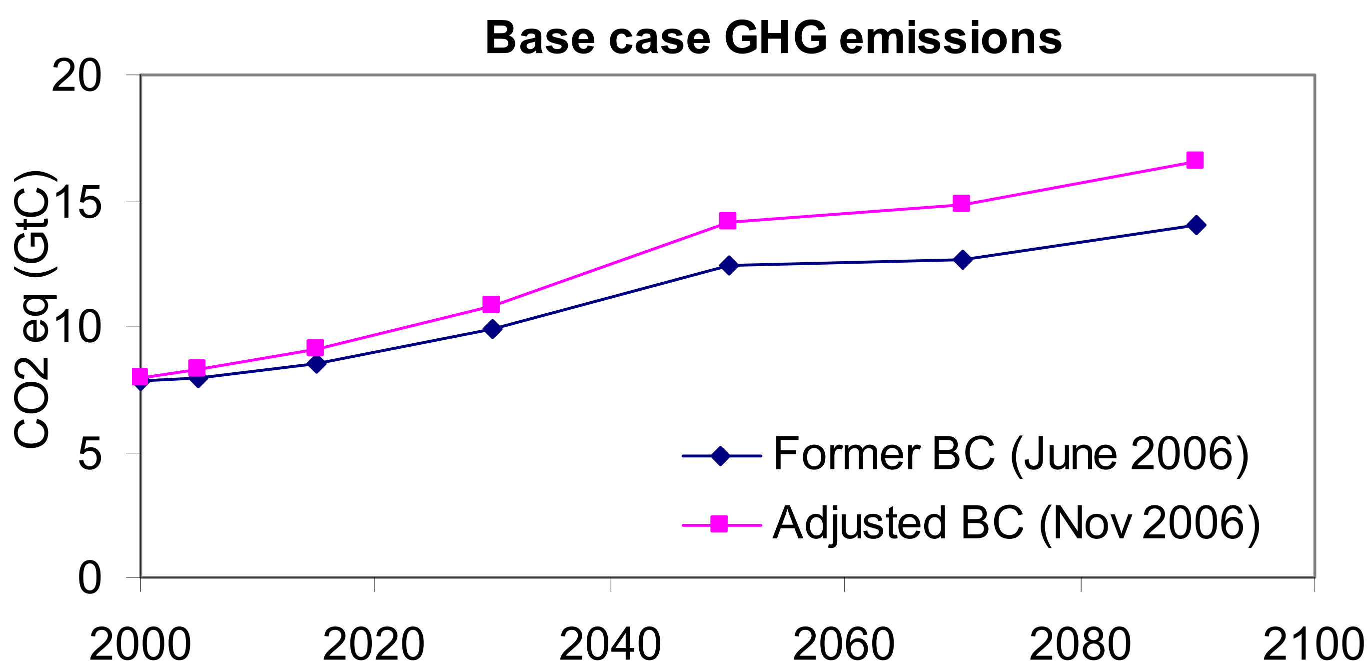
- Moderate economic growth
  - World GDP 2100 = 8*GDP in 2000
  - High technical progress
  - Large oil resources (by region)
  - Large Biomass resources (by region)
  - Moderately large Nuclear allowed (Region dependent)

- Somewhat close to IPCC SRES B2 scenario

Base Case Emissions

Demand projections were adjusted since last work *(Labriet et al., 2006)* ⟶ Base Case emissions are increased

⇒ *Climate policies will cost more!*



Six climate change scenarios

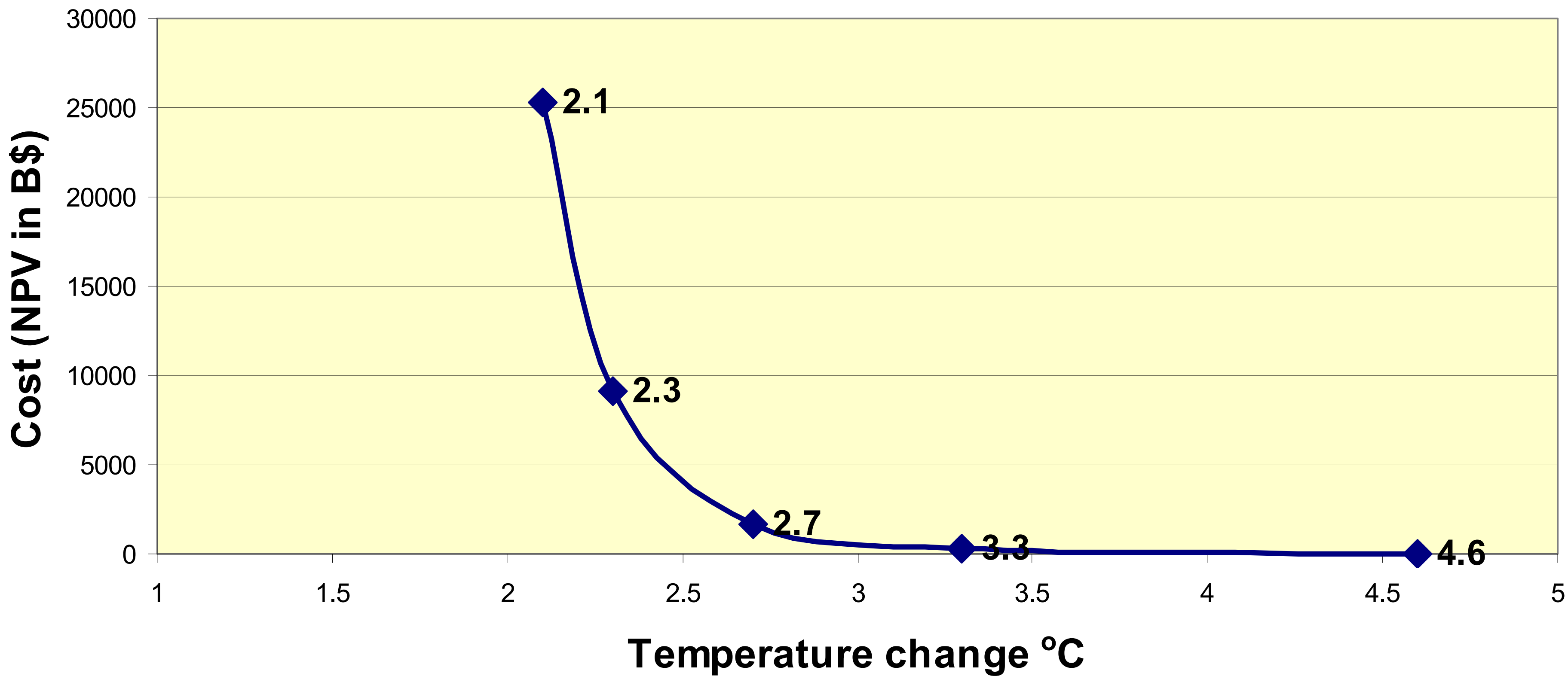
ΔT_{2090}	ΔT_{max} (long term)	Cost ($G\$_{2000}$)	Annuity ($G\$_{2000}$)
1.4°C		*Infeasible*	
1.5°C	2.1°C	25283	$1,274
1.6°C	2.3°C	9075	$457
1.8°C	2.7°C	1692	$85
2.0°C	3.3°C	249	$13
2.3°C	4.6°C	Base Case	

Lowest ΔT achievable (1.5°C row)

Detailed analysis (1.8°C row)

- The calculation of $\Delta T_{LongTerm}$ (outside TIAM) assumes a progressive elimination of all GHG emissions from 2100 to 2200.
- Labriet *et al.* (2006) show that emission policies beyond 2100 have a minor impact on temperature increase, as long as a GHG emissions are eventually eliminated, irrespective of the speed of that eradication.

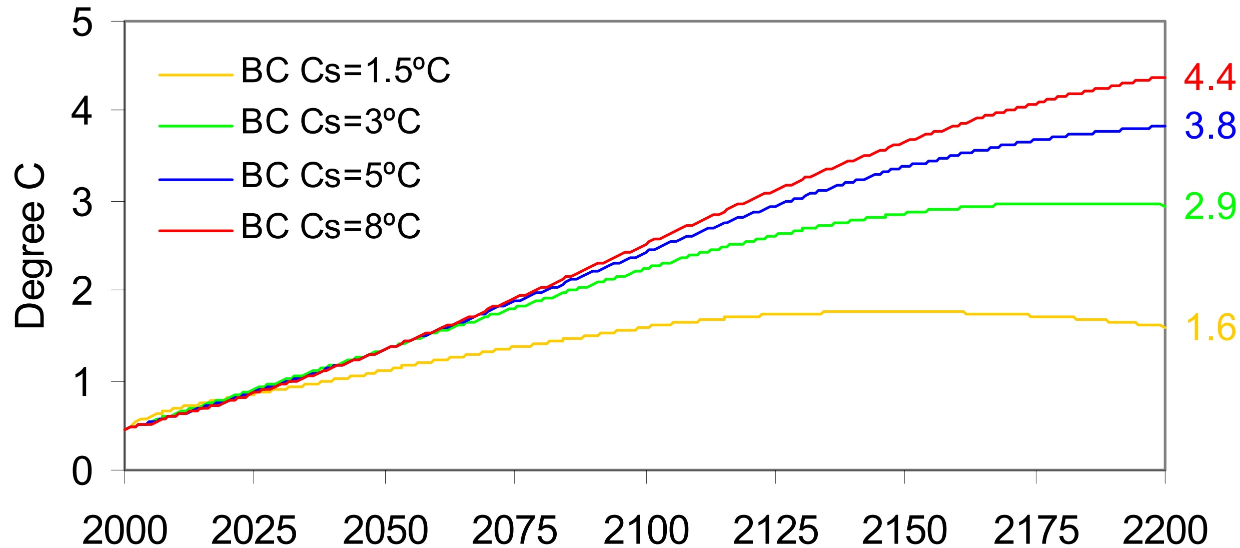
Cost vs. Delta T



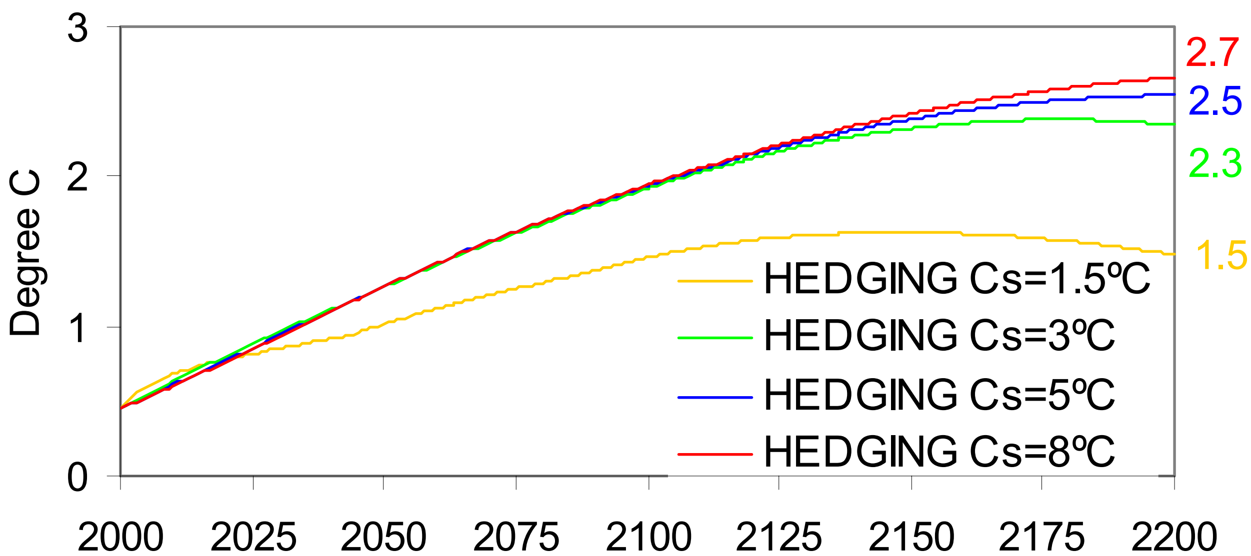
IV: RESULTS
focus on the 2.7°C long term target (=1.8°C in 2100)

Long term atmospheric temperature change

Temperature increase in the Basecase



Temperature increase in the Hedging



Hedging differs Very little from BASE When Cs=1.5

2.7°C target: Global Cost and Expected Value of Information (EVI)

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

- in 2005 (perfect foresight)? *EVPI*
- in 2020 (earlier knowledge)? *EVII*

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

Resolution date	Loss of surplus (vs Basecase)	EVI
2040	1692 B$ (85 B$/yr)	-
2005 (perfect info)	1135 B$ (57 B$/yr)	EVPI = 557 B$ (28 B$/yr)
2020 (earlier info)	1230 B$ (62 B$/yr)	EVII = 462 B$ (4/5 of EVPI)

Is Hedging relevant ?

Hedging is relevant if decisions prior to 2040 are different under hedging than under Base.

Otherwise, '*wait and see*' is a good policy

Main interest of a hedging strategy = what to do prior to the resolution date

Hedging actions are actions that are chosen in the Hedging strategy but not in Basecase

Super Hedging actions are those actions that are higher in Hedging than in ANY PF strategy

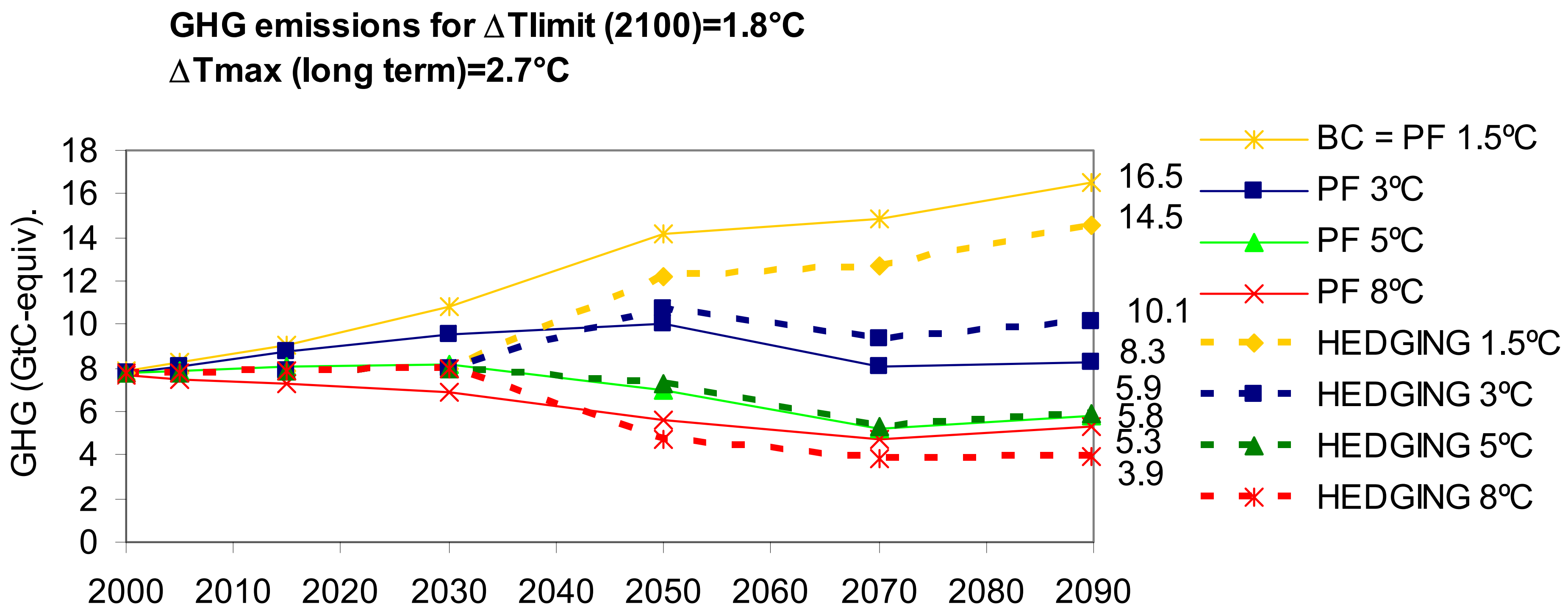
Hedging vs. classical scenario analysis

- Hedging strategy has the crucial advantage of providing a SINGLE strategy in the short term. That strategy is robust against uncertainty

- (Whereas each PF scenario provides a *different* strategy starting 2005)

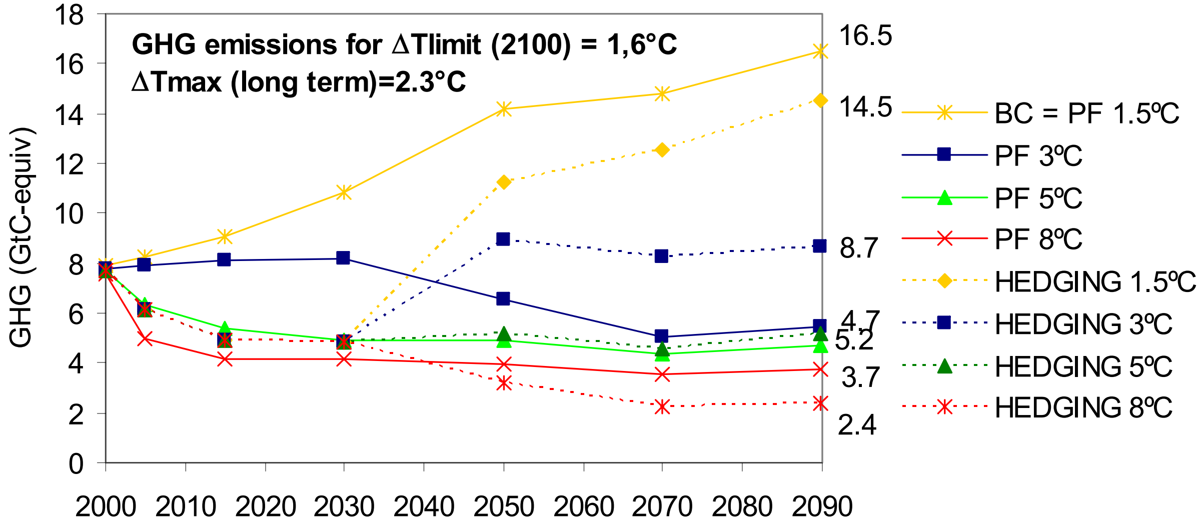
- In what follows we show Hedging and the four PF strategies, before 2040.

GHG Emissions



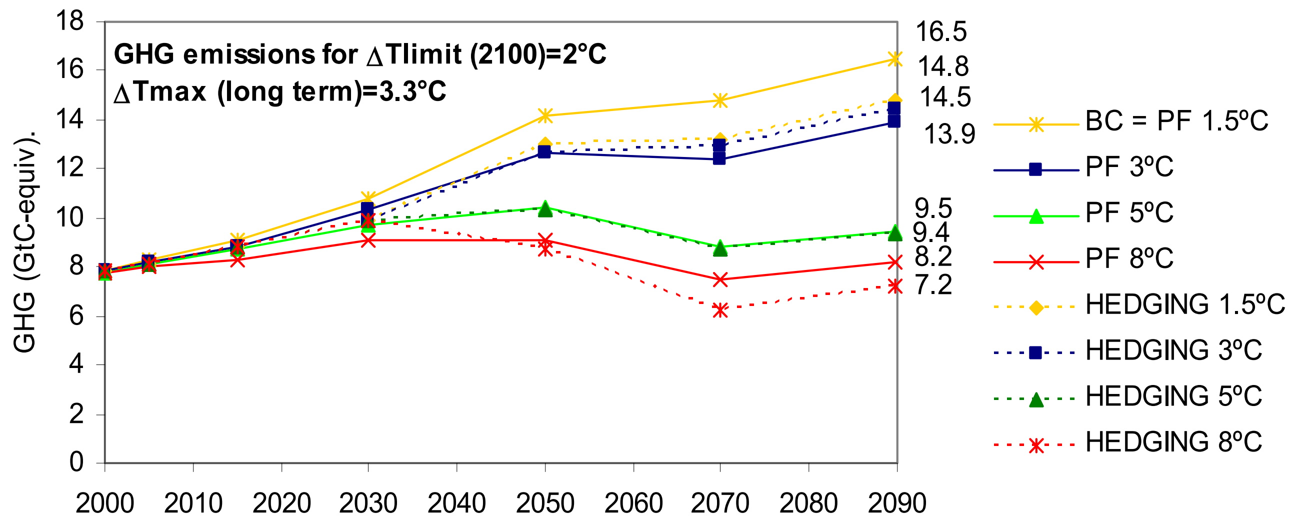
- **Perfect forecast strategies show *diverse* emission paths even before 2040**
- **When Cs=1.5, no emission reduction is needed**
- **Hedging (before 2040) is close to PF/5ºC**

Sensitivity: GHG Emissions with different temperature targets



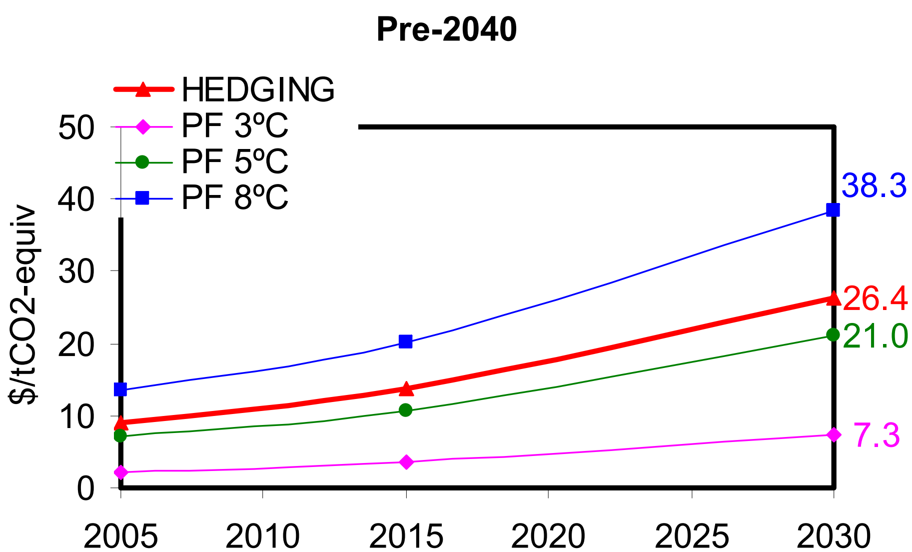
2.3ºC

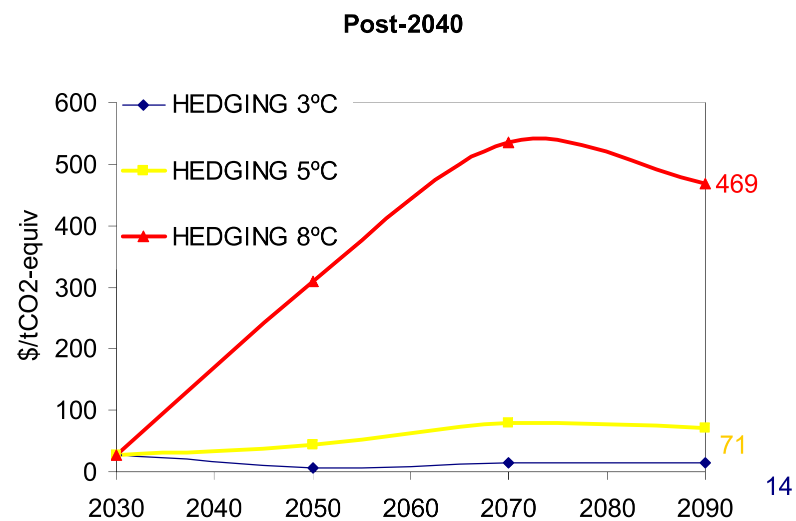
3.3ºC



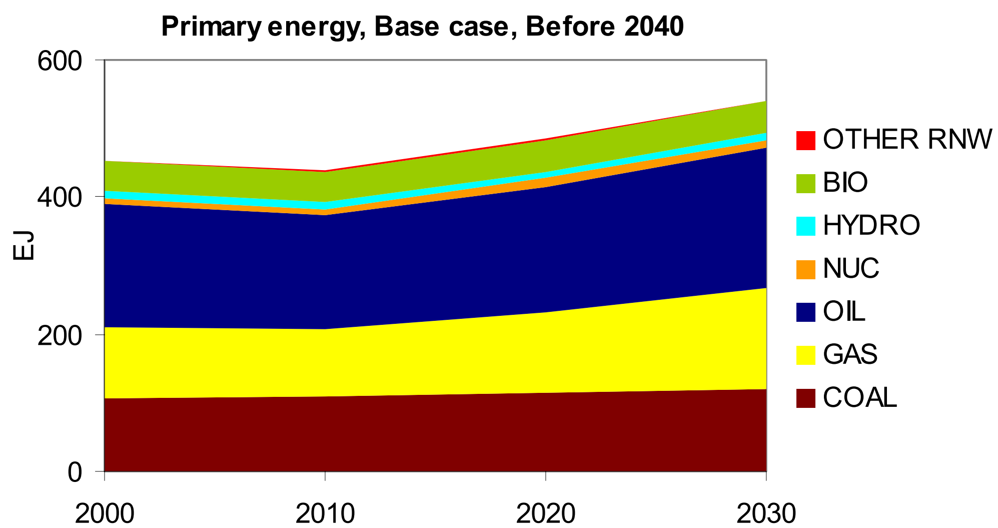
GHG Price

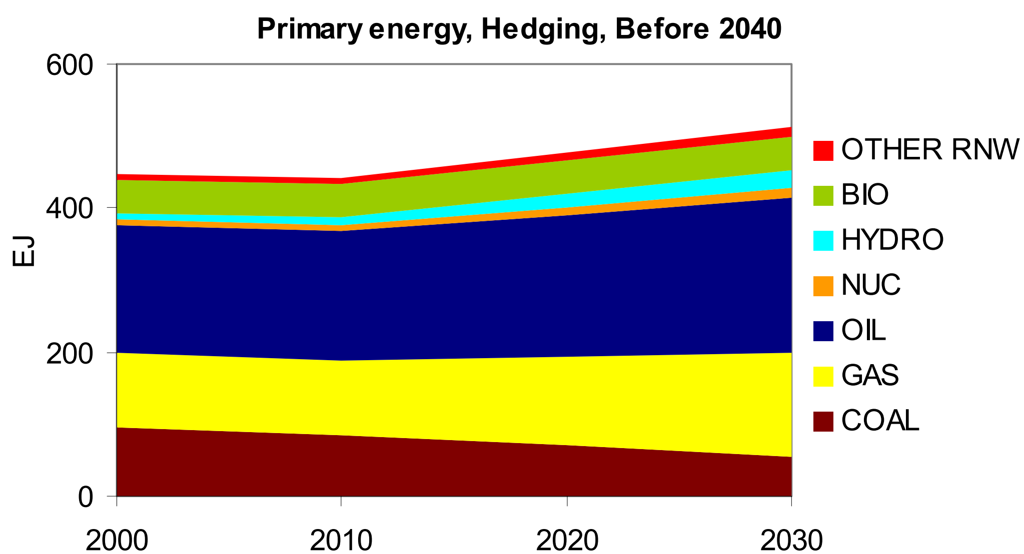
- Again, Hedging differs from all perfect forecast strategies
- Low price before 2040: CH_4 and forestry measures help !
- Long term high price: due to the absence of CH_4 abatement options in agriculture





Primary Energy before 2040





Hedging actions

- Decrease of coal (mainly power plants, very slightly in industry)
- Sequestration by forests
- Hydro, wind
- N_2O and CH_4 abatement
- Moderate Demand reductions
- More nuclear (2030)

Non-hedging actions

- Power plants with CO_2 capture
- Energy substitution in end-use sectors
- H2 for transport (weak, late)

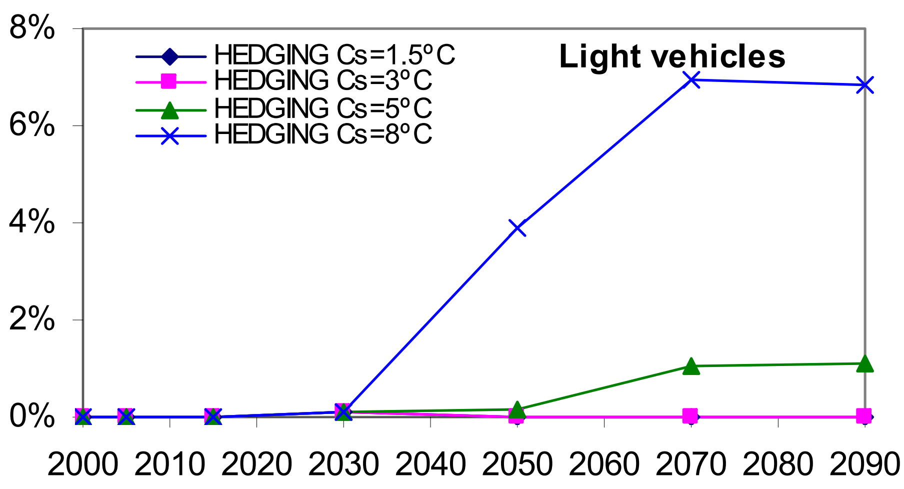
Post-2040 abatement actions (for large values of Cs)

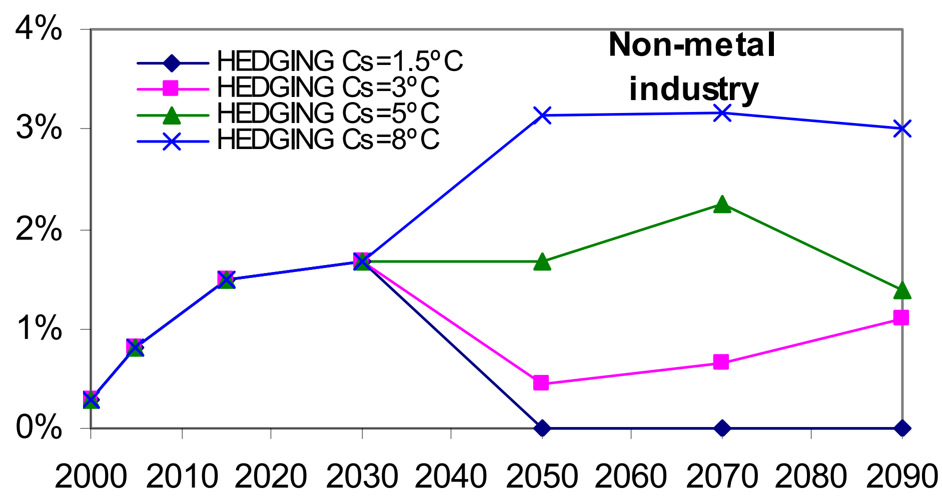
- **Power plants:** Hydroelectricity, Nuclear, Wind, Solar (very late), CCS
- **Transportation:** Large Substitution of RPPs by alcohols and gas (not by H2 and Elec)
- **Buildings:** Substitution of gas and RPPs by electricity, mainly for space heating
- **Industry:** Substitution of coal by gas (and electricity) in some industries
- **Demand** reductions (economic feedback)

Demand reductions

Reduction of demands appear in most demand sectors, typically from 2 to 10%

Examples of demand reductions:

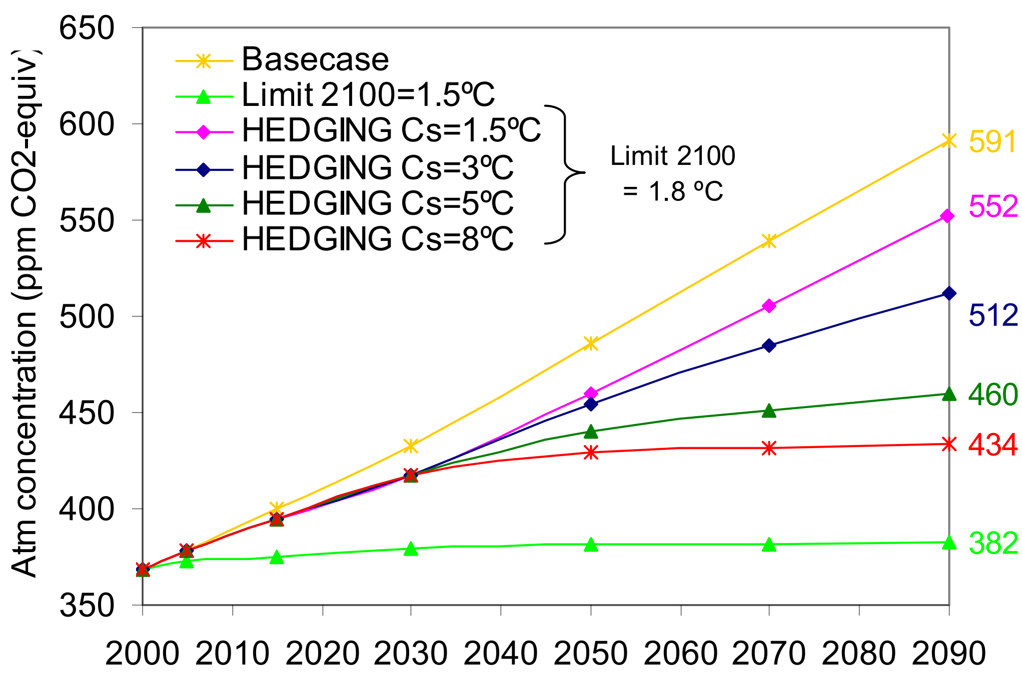




Sensitivity analyses

Temperature change (2100) = 1.5°C

- *Smallest achievable target*
- *Corresponds to Max (long term) = 2.1°C*
- *Extreme situation, feasible at very large cost*
- *GHG concentration must stay almost constant*



Main conclusions

- Stochastic programming produces a **hedging strategy** against climate uncertainty, that is not well approximated by any PF strategy
- **Hedging is important for Cs uncertainty, but not for economic uncertainty**
- Method reveals **hedging actions** that are not predicted by any deterministic strategy
- **Hedging strategy robust w.r.t. several technological assumptions**
- **2.1ºC temperature increase** very costly to achieve
- **Min temperature increase** achievable = 2.3ºC
- **2.7ºC achievable** at reasonable cost

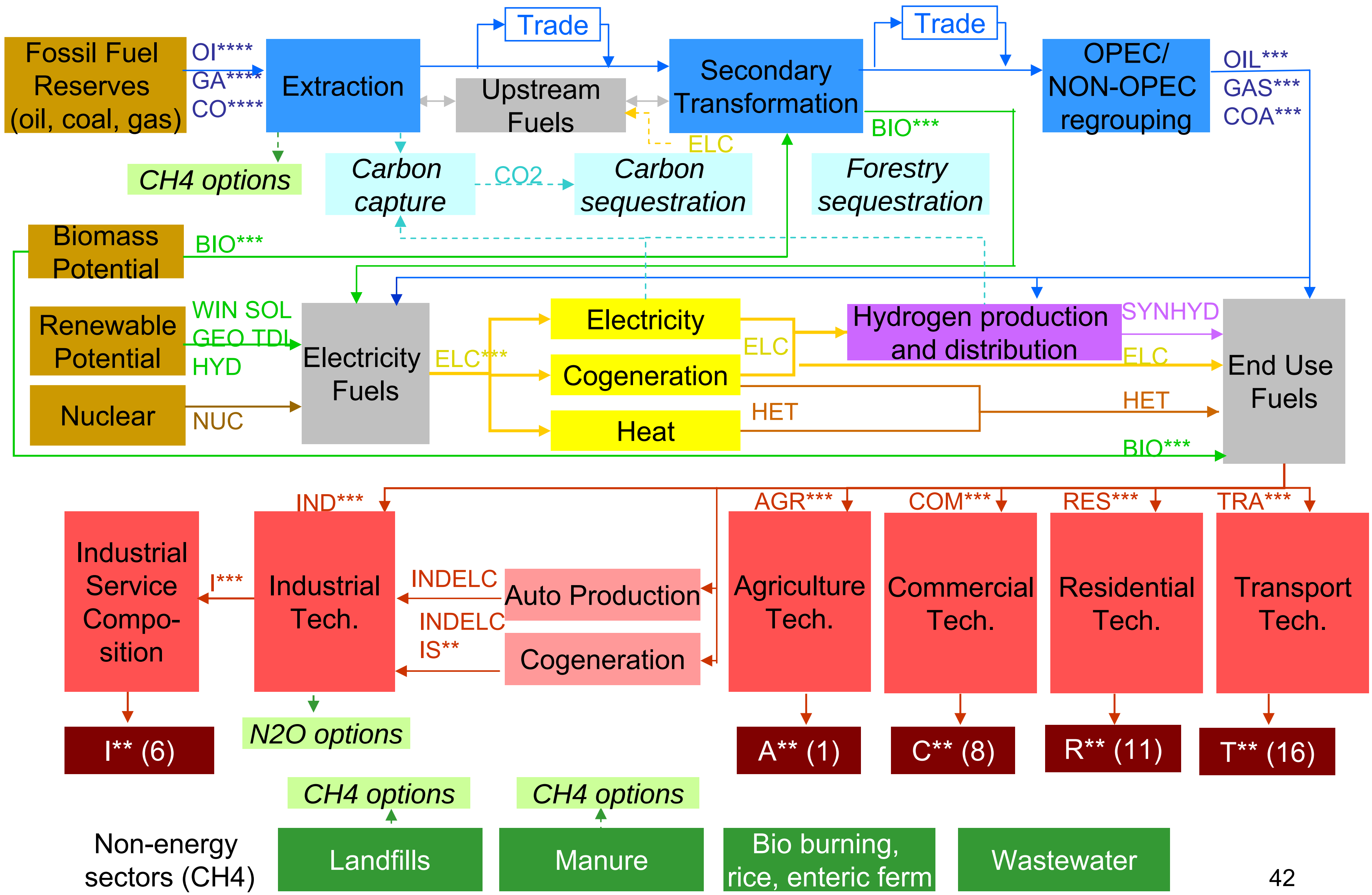
To Do

- **Further analyses**
  - Detailed technological and regional analysis
  - Evaluate expected cost of *wait-and-see* strategy (i.e. follow Base until 2040, then optimize)
  - Try alternate Base scenario with higher GDP

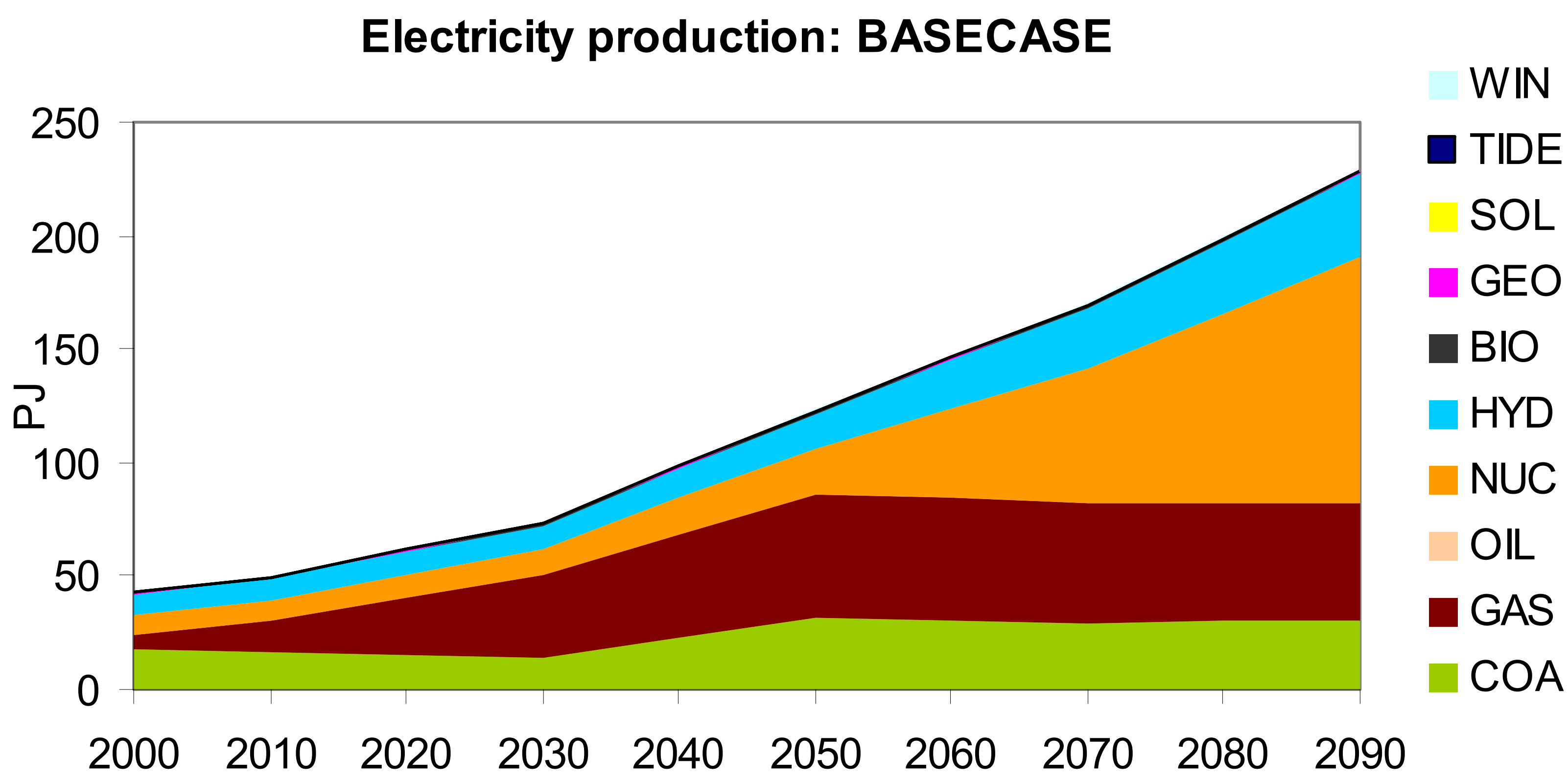
- **Model improvements**
  - Refine some technological information (H_2, CCS)
  - Refine relationship Lag ↔ Cs
  - Enhance the model with feedbacks from Climate to Economy ?
    - Eg. modified demands for space heating and cooling, hydro potentials, release of methane from permafrost …

Complements

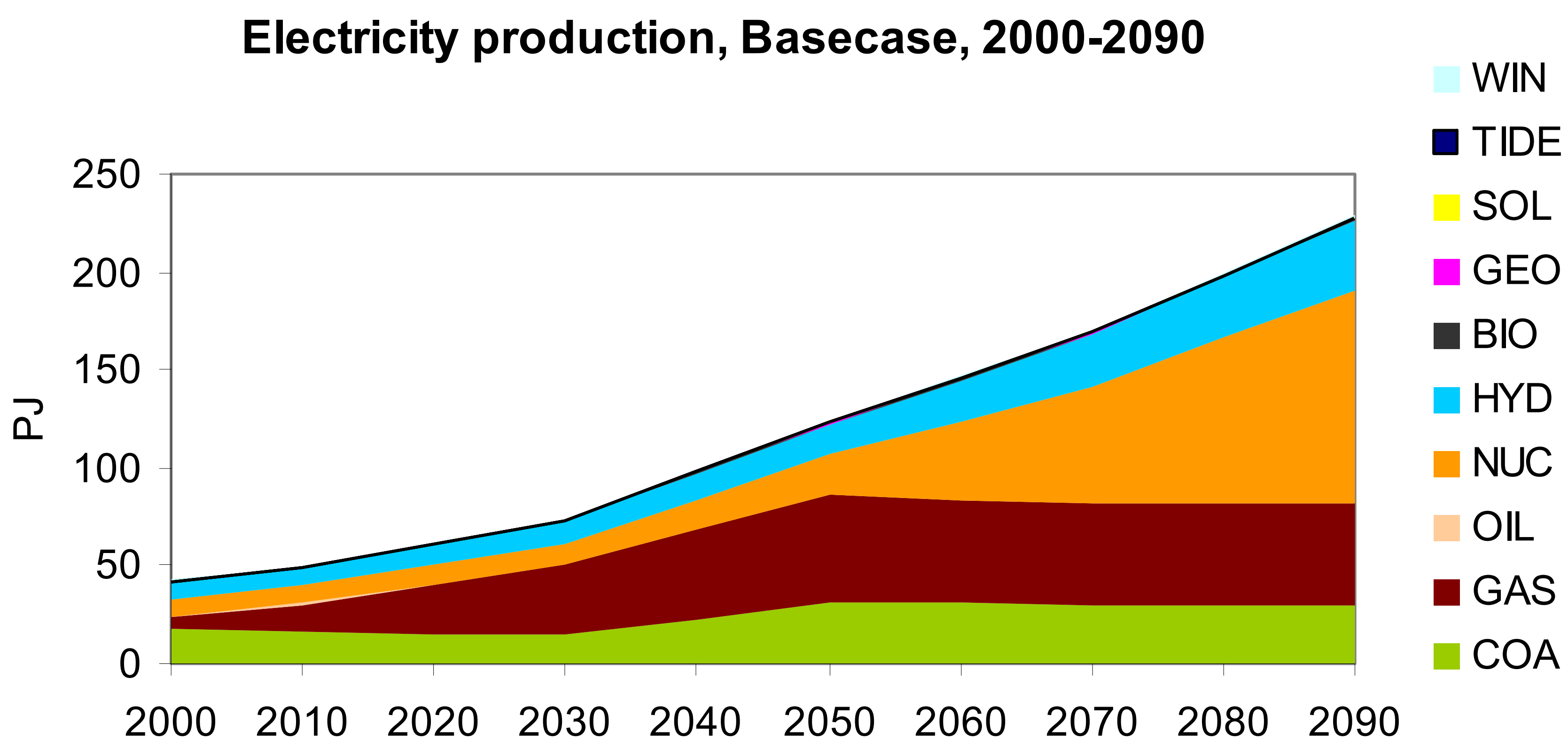
Reference Energy System of TIAM



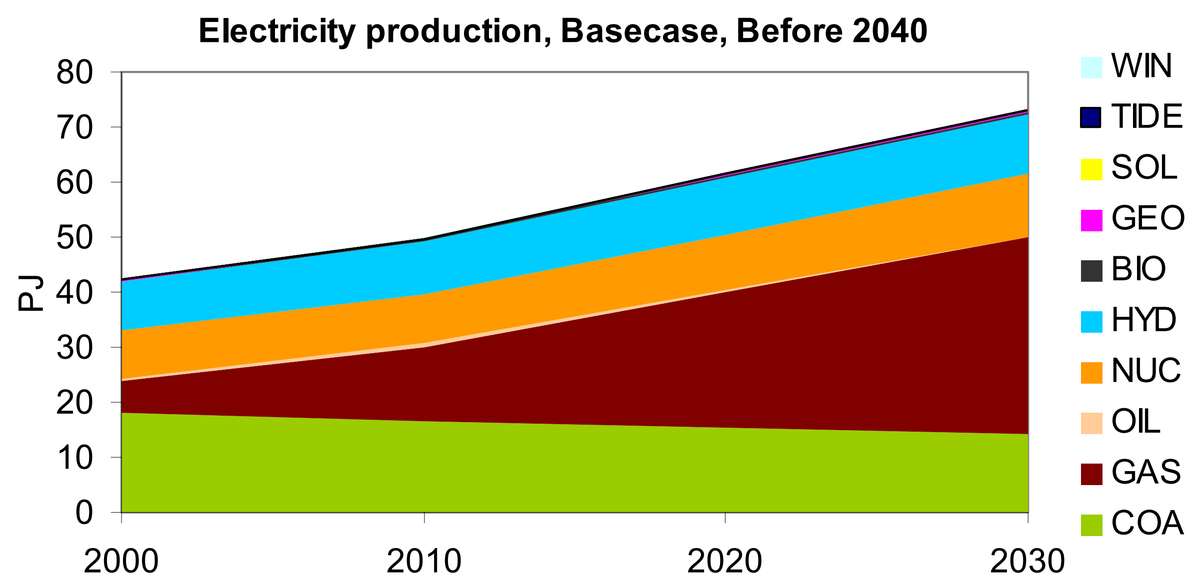
Electricity production by fuel

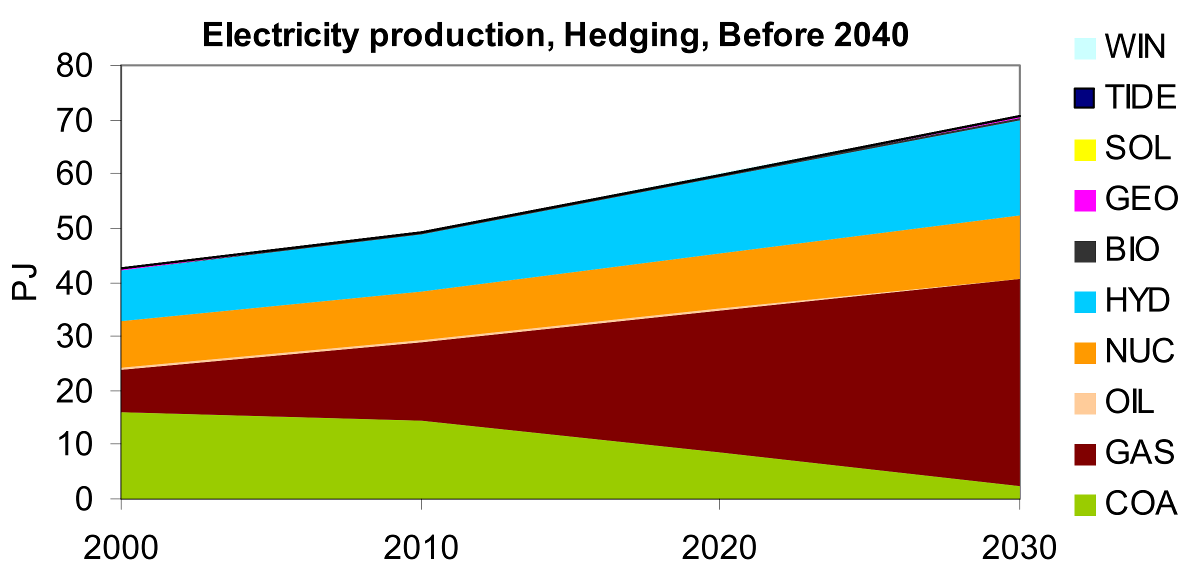


Electricity production by fuel (basecase)



Electricity production by fuel (hedging)





Power plants

PLANT TYPE	Scenario	Year 2000	2005	2015	2030	2050	2070	2090
	TIMES period	*1998-2002*	*2003-2008*	*2009-2020*	*2021-2039*	*2040-2060*	*2061-2080*	*2081-2100*
COAL FIRED	BASE, PF Cs=1.5ºC	18	17	16	14	32	30	30
	PF Cs=3ºC	16	16	16	8	5	5	6
	PF Cs=5ºC	16	16	11	0	13	9	7
	PF Cs=8ºC	16	16	11	1	14	11	7
	HEDGING Cs=1.5ºC					26	28	29
	HEDGING Cs=3ºC					13	7	8
	HEDGING Cs=5ºC	16	16	11	0	11	9	7
	HEDGING Cs=8ºC					16	13	13
OIL+GAS FIRED	BASE, PF Cs=1.5ºC	6	10	18	36	55	52	52
	PF Cs=3ºC	8	10	19	35	55	38	30
	PF Cs=5ºC	8	10	20	35	33	26	23
	PF Cs=8ºC	8	10	18	24	30	26	21
	HEDGING Cs=1.5ºC					47	49	51
	HEDGING Cs=3ºC					51	41	43
	HEDGING Cs=5ºC	8	10	19	32	35	26	23
	HEDGING Cs=8ºC					30	26	28
NUCLEAR	BASE, PF Cs=1.5ºC	9	8	10	11	20	59	109
	PF Cs=3ºC	9	8	10	11	23	72	130
	PF Cs=5ºC	9	8	10	11	27	74	134
	PF Cs=8ºC	9	8	10	13	28	74	134
	HEDGING Cs=1.5ºC					20	59	109
	HEDGING Cs=3ºC					20	71	120
	HEDGING Cs=5ºC	9	8	10	12	27	74	134
	HEDGING Cs=8ºC					28	74	137

Power plants (cont.)

HYDRO	BASE, PF Cs=1.5ºC	9	9	10	11	15	27	36
	PF Cs=3ºC	9	9	10	17	34	43	48
	PF Cs=5ºC	9	9	12	21	35	43	49
	PF Cs=8ºC	9	9	13	27	35	43	49
	HEDGING Cs=1.5ºC					26	32	38
	HEDGING Cs=3ºC					33	42	47
	HEDGING Cs=5ºC	9	9	13	24	35	43	49
	HEDGING Cs=8ºC					35	45	52
BIOMASS	BASE, PF Cs=1.5ºC	0	0	0	0	1	1	1
	PF Cs=3ºC	0	0	0	0	1	2	1
	PF Cs=5ºC	0	0	0	0	5	5	3
	PF Cs=8ºC	0	0	0	2	6	4	3
	HEDGING Cs=1.5ºC					1	1	1
	HEDGING Cs=3ºC					1	1	0
	HEDGING Cs=5ºC	0	0	0	0	5	5	3
	HEDGING Cs=8ºC					9	6	5
OTHER	BASE, PF Cs=1.5ºC	0	0	0	0	1	1	1
RENEWABLES	PF Cs=3ºC	0	0	0	0	1	1	1
	PF Cs=5ºC	0	0	0	0	2	3	3
	PF Cs=8ºC	0	0	0	0	3	4	4
	HEDGING Cs=1.5ºC					1	1	1
	HEDGING Cs=3ºC					1	1	1
	HEDGING Cs=5ºC	0	0	0	0	2	3	3
	HEDGING Cs=8ºC					5	8	9
TOTAL	BASE, PF Cs=1.5ºC	42	44	55	73	124	170	229
	PF Cs=3ºC	42	44	55	73	119	161	216
	PF Cs=5ºC	42	43	54	68	115	161	219
	PF Cs=8ºC	42	43	53	67	116	162	218
	HEDGING Cs=1.5ºC					122	170	229
	HEDGING Cs=3ºC					119	163	220
	HEDGING Cs=5ºC	42	43	54	69	115	161	219
	HEDGING Cs=8ºC					123	173	244

Reduction of demands (examples)