

**Exploration of uncertain
technology outlooks
and policy scenarios for
climate stabilization:
a TIAM-WORLD analysis**



Maryse Labriet*, Amit Kanudia, Richard Loulou
Eneris, Spain / KanORs, India / Kanlo, France

International Energy Workshop, Stanford, USA
July 6-9, 2011

How to decide about energy/climate policies in an uncertain context?

Uncertainties (amongst others):
Future technology outlook, Climate target

**Deterministic
scenario approach**

To understand the impacts of uncertain parameters on the possible solutions

Difficulty for the decision-maker: What to do *now*?

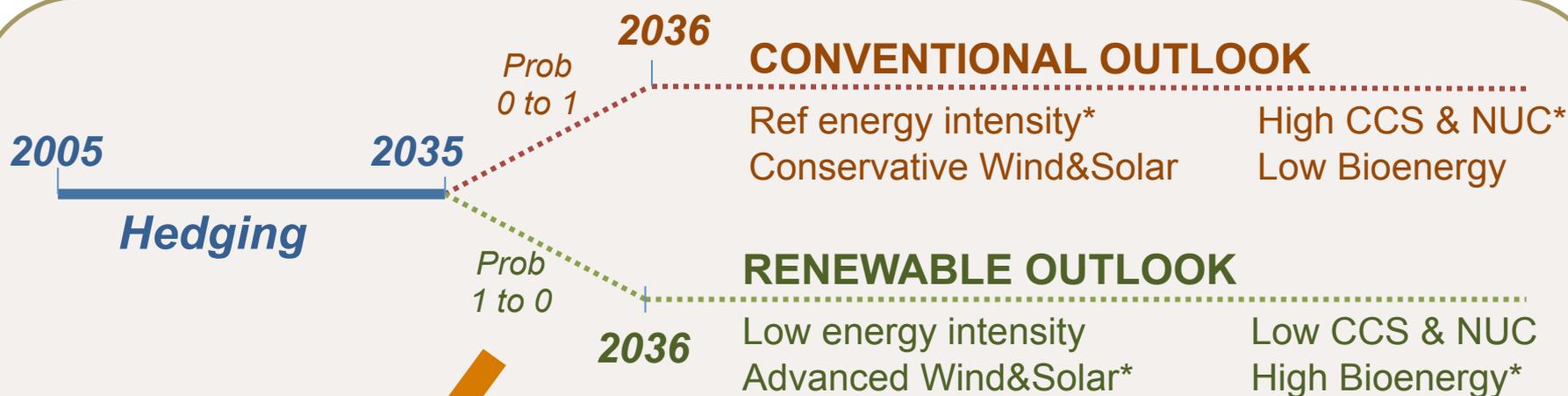
**Stochastic
approach**

To produce a *single* hedging policy taking into account all possible outcomes

Optimal compromise between the negative effects of “guessing wrong”

Scenarios: Technology uncertainties

① *Stochastic tree*: Conventional or Renewable Future Technology Outlook (inspired from EMF24, 2nd round)



Additional robustness dimension: To cover the **full range of probabilities**
⇒ To assess how the 20 resulting hedging strategies evolve with probabilities

Energy Intensity	About 40% lower by 2100 in the REN branch
Wind & Solar	Additional 3.5 ¢/kWh in CONV branch (conservative)
CCS & Nuc	Reduced investments beyond 2030 in REN branch
Bioenergy	Global cap = 50 EJ in the CONV branch (low)

Scenarios: Climate uncertainties

② *Scenario approach*: Three climate targets in 2100, no overshooting during the entire horizon

Severe	2.6 W/m ² (450 ppm CO ₂ -eq total forcing)
Easier	3.7 W/m ² (550 ppm CO ₂ -eq total forcing)
Intermediate	3.0 W/m ² (almost 500 ppm CO ₂ -eq tot forcing)



Stochastic analysis on technology outlooks + Climate targets

- What are the mid-term decisions respectively **least and most sensitive** to the technology outlooks (part of the Hedging for any or only a few sets of probabilities), for each of the climate targets?
- Do the Hedging strategies **vary uniformly or form clusters**?
- Do they even go **outside the range** of the Perfect Foresight strategies?

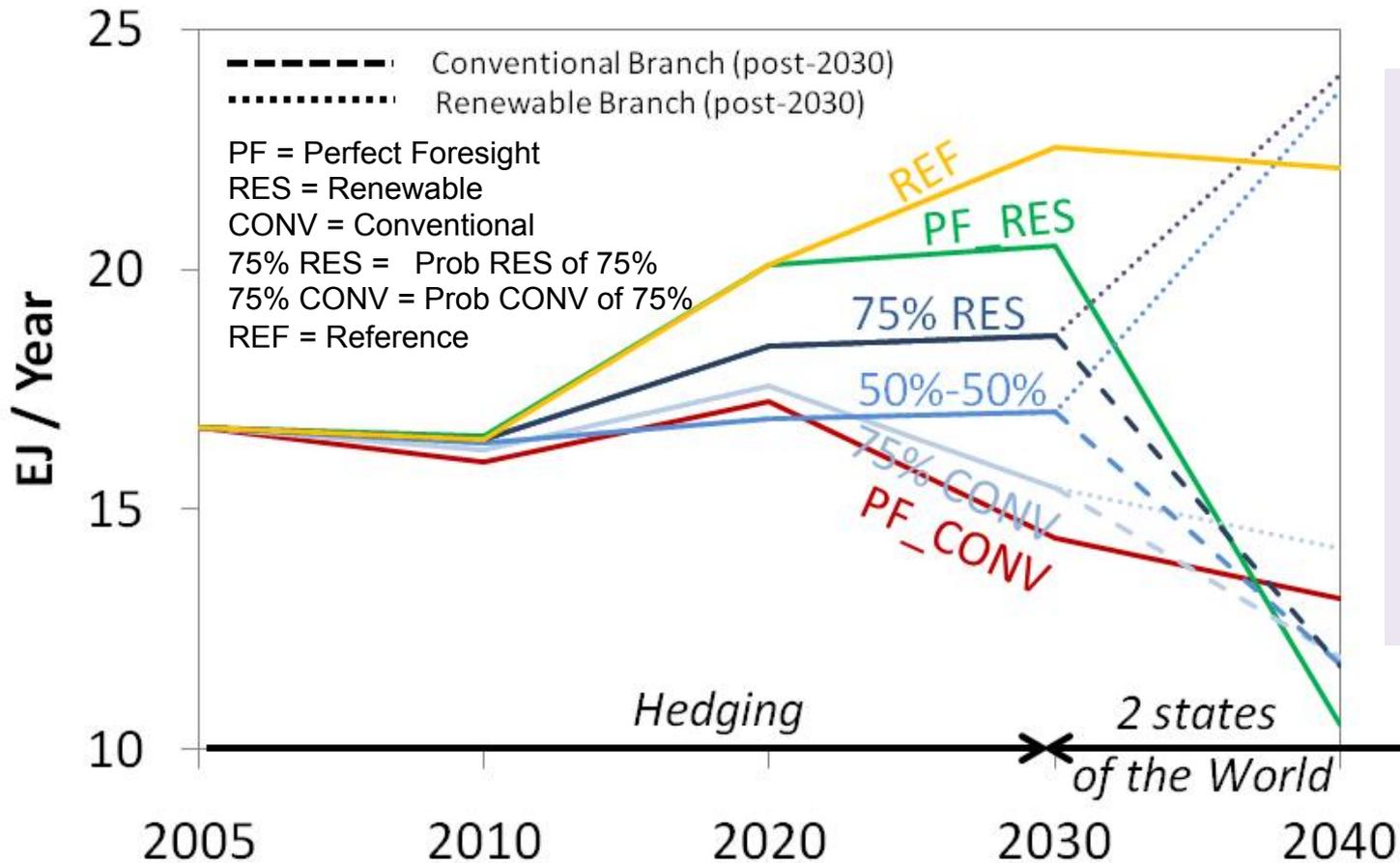
TIMES Integrated Assessment Model (TIAM-World)

- **Multi-region (16 regions) technology rich model** representing the World energy system (extraction, conversion, end-uses, trade of energy and emission permits if needed)
- **Driven by demands** for energy services (T-alu, km-by-car, etc.) with own price elasticities
- **Partial equilibrium** based on **maximization of the total surplus**
- **CO₂, CH₄, N₂O** explicitly modeled + other radiative forcing agents
- **Climate module**
- **Reference year 2005** (IEA Energy Statistics), **horizon** 2005-2100
- **TIMES** family of models, developed by the authors with support of the Energy Technology System Analysis Program

Websites: www.kanors.com
www.etsap.org/documentation (TIMES equations)

How does the Hedging compare to Reference and to the Perfect Foresight strategies?

Electricity generation; World; 3.7 W/m²



Bifurcation after 2030

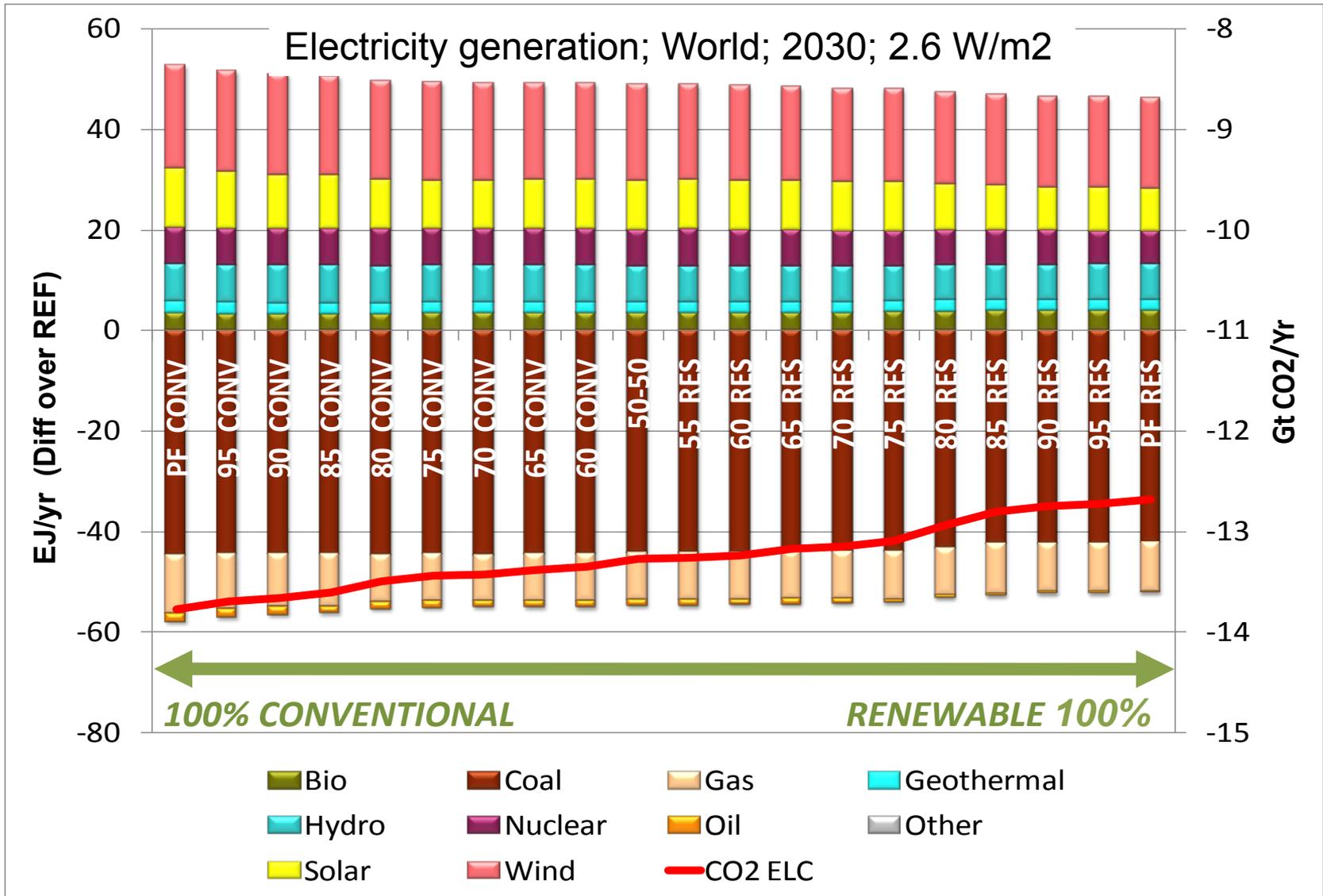
Delay in mitigation when renewable outlook is expected

Evolution of the Hedging not necessarily uniform

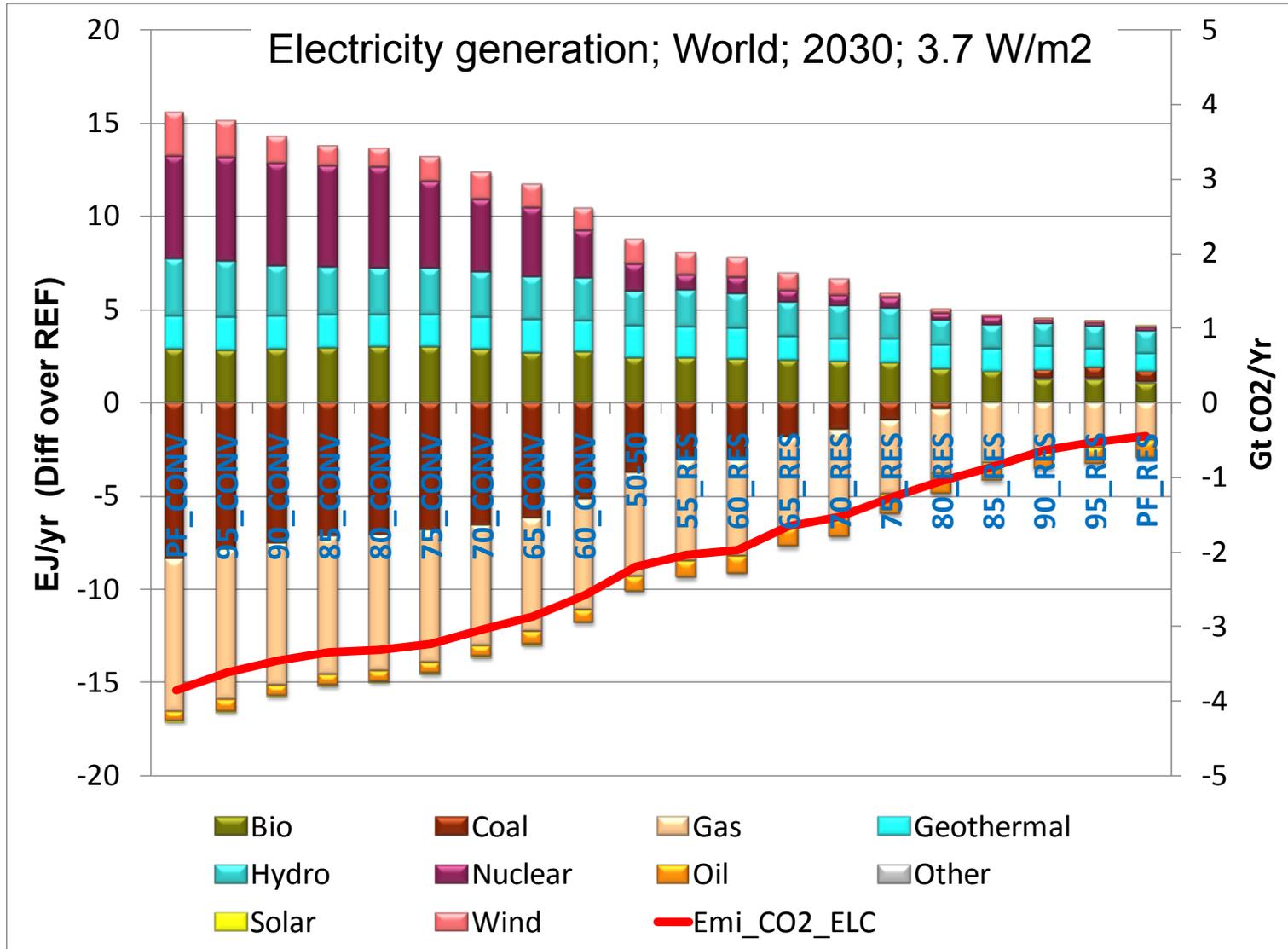
Hedging

2 states of the World

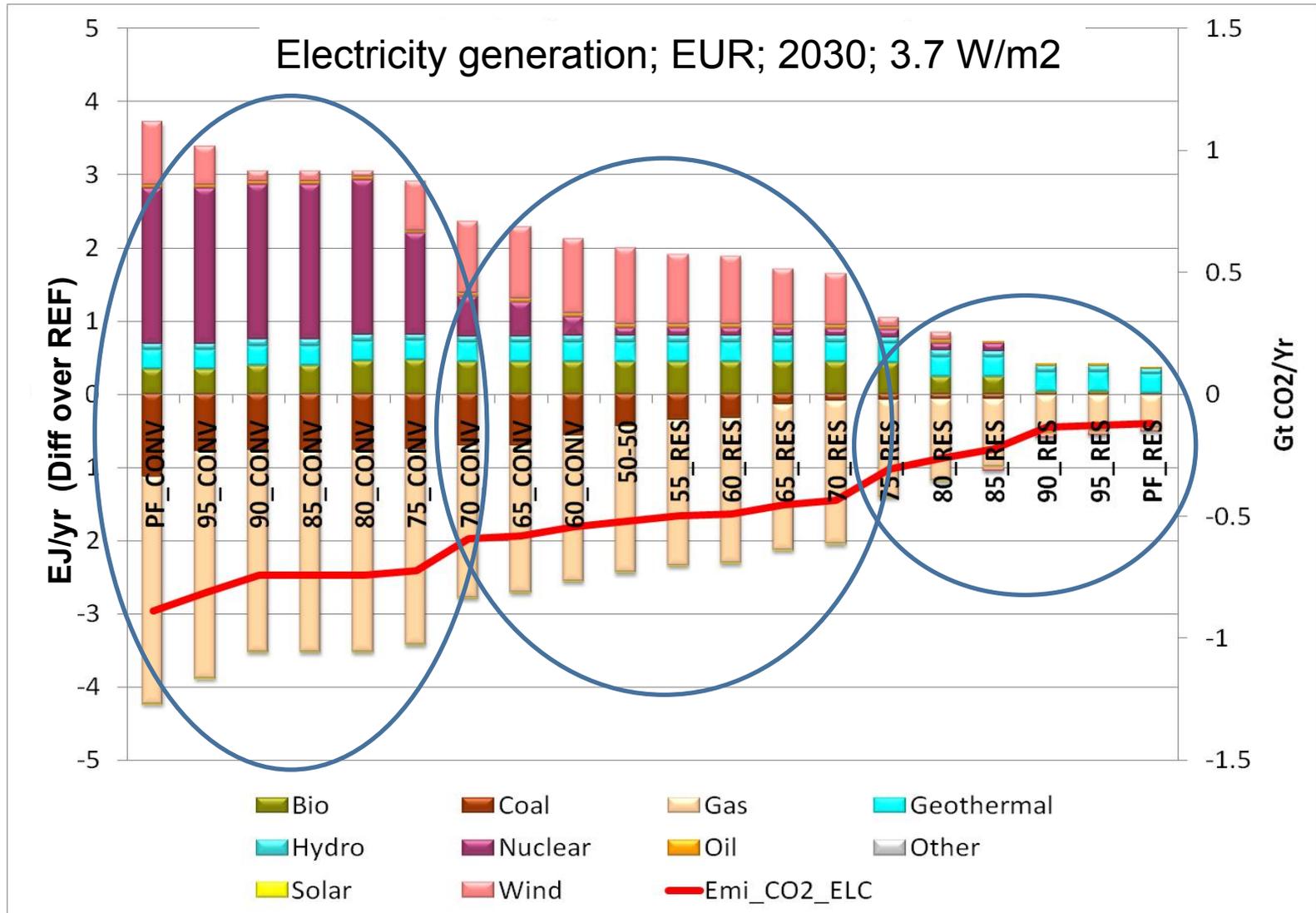
Example of low sensitivity of the Hedging to technology uncertainty



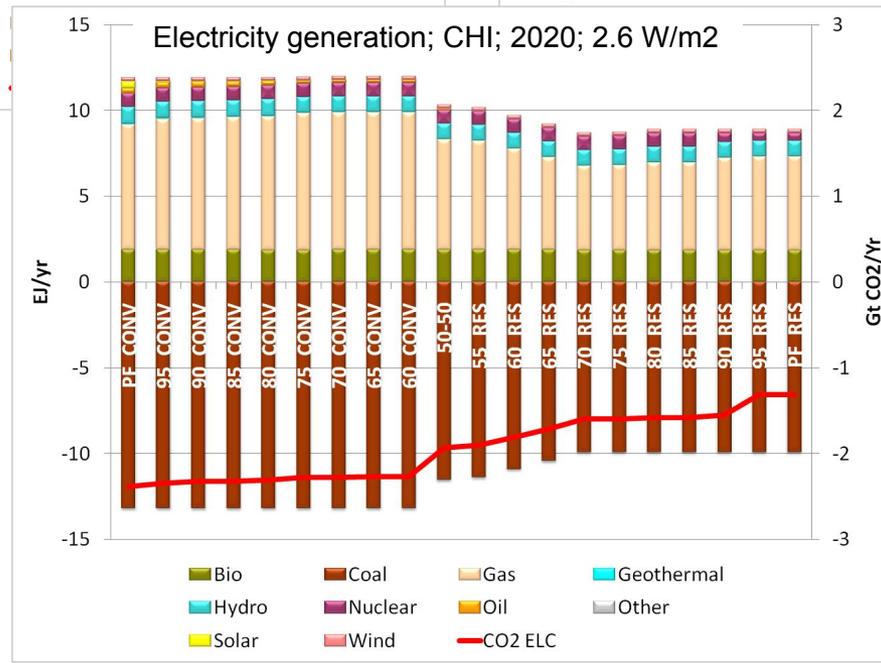
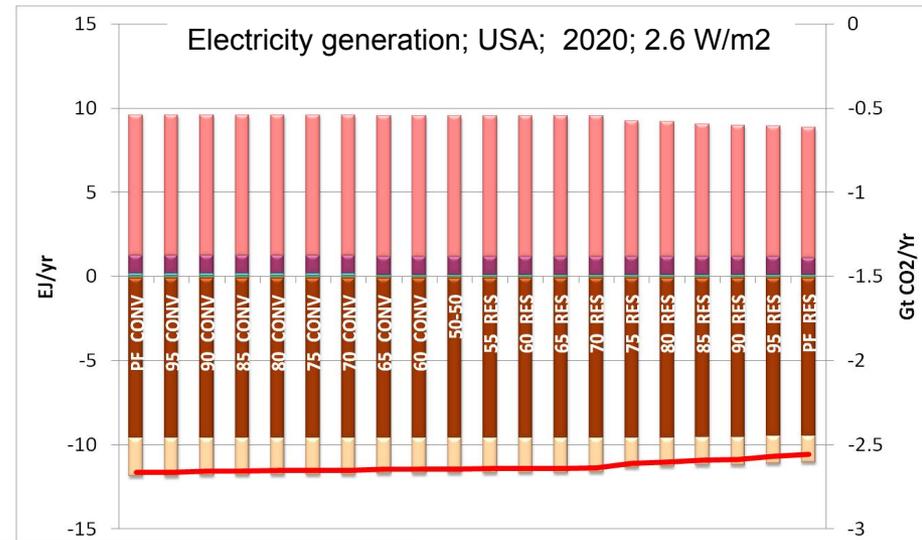
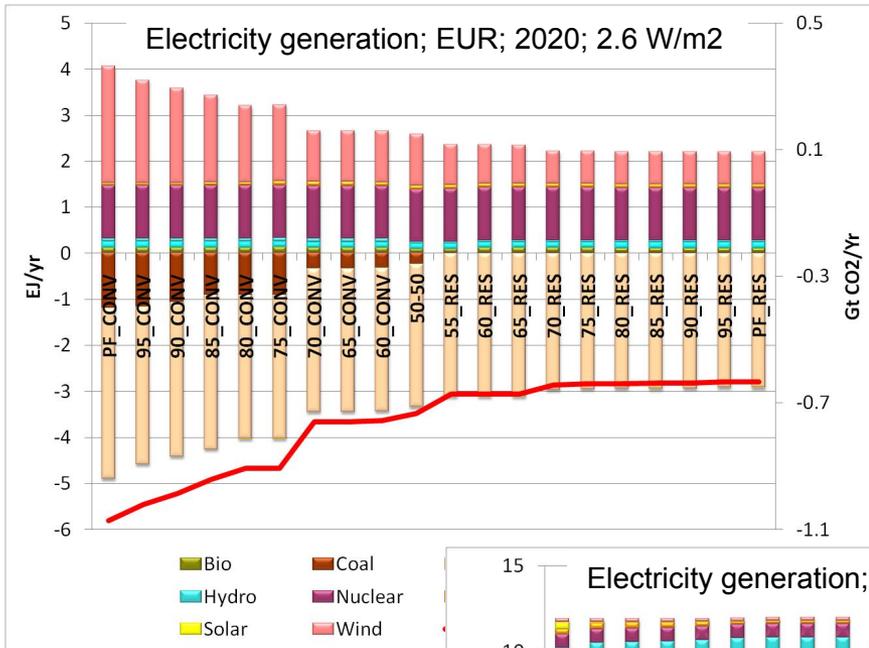
Example of high sensitivity of the Hedging to technology uncertainty



Example of clusters of actions

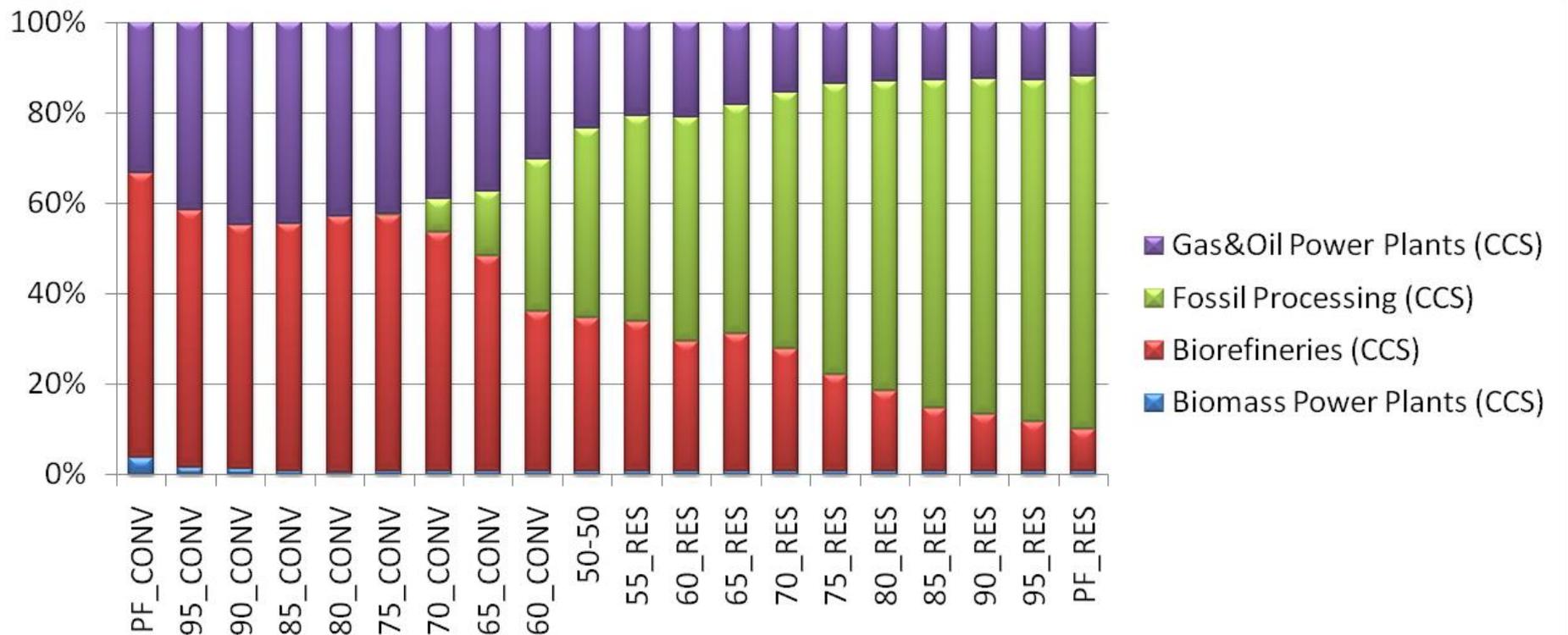


Different regional sensitivities



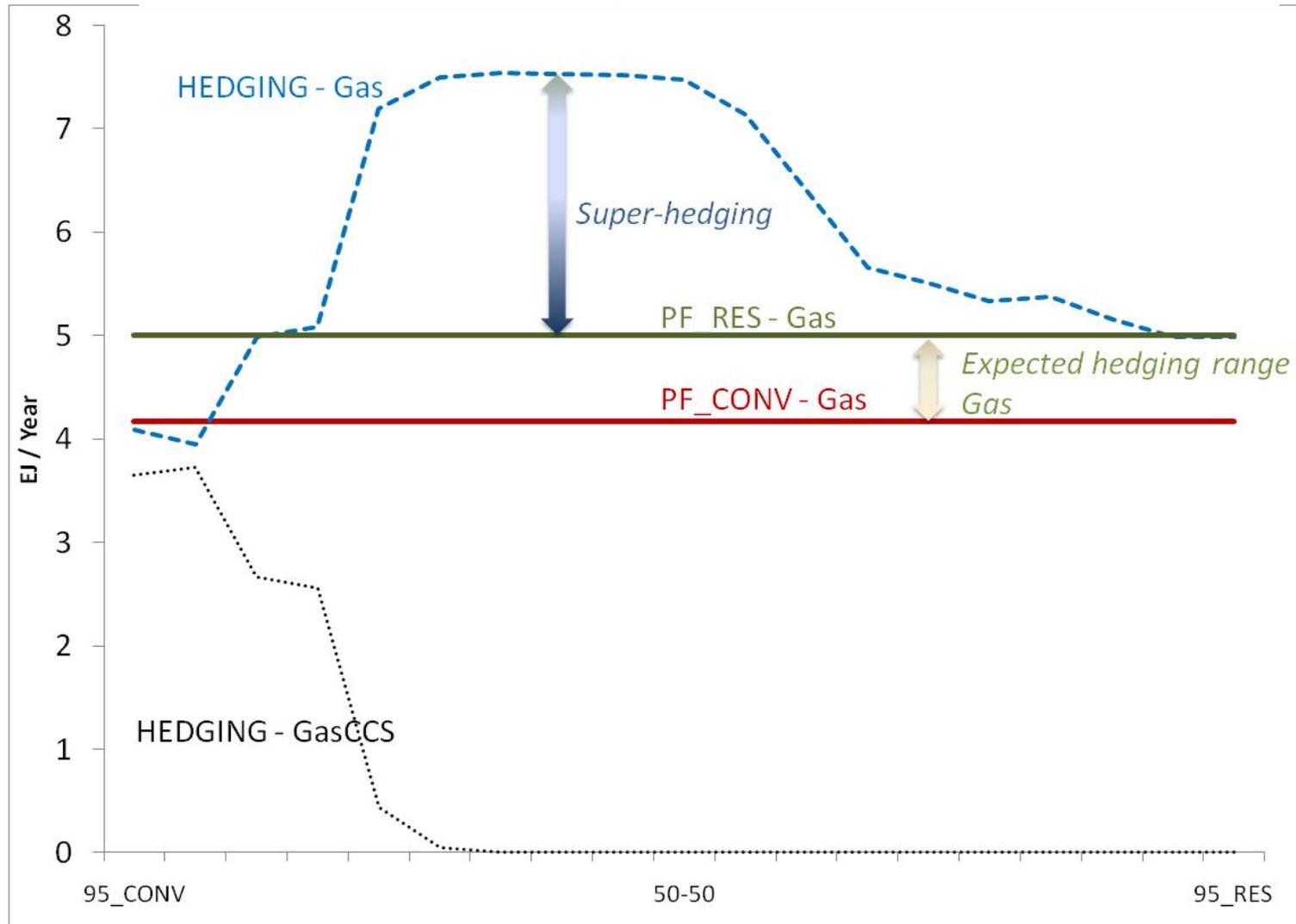
Example of sensitivity at the technology level: CO2 capture

CO2 Capture; World; 2030; 2.6 W/m2



Super-hedging strategies: role of gas in the Chinese power sector

Role of gas in electricity generation; China; 2030; 3.7 W/m²



Conclusion: Main results

- Higher sensitivity in the **short-term** and under **mild climate** targets when the pressure for decarbonization is not (yet) too strong: a flexible energy system is more sensitive to the technology outlooks
- **Delay in mitigation** when the expected future is renewable/ efficiency oriented
- High sensitivity of **nuclear, CCS**. Crucial role of **gas** in the power sector and industry in the uncertain context
- **USA, CHI** (to a certain extent) less sensitive than other regions, like EUR, given the characteristics of their energy system and the pressure for mitigation
- **Final energy sector** much less sensitive than power sector
- *Paper submitted to **Energy Economics** (Asian Modelling Exercise)*

Conclusion: Systematic representation of the variability over scenarios

How to represent in one figure all the results?

Numbers : changes over Ref, averaged over the 20 hedging strategies.

Color : variability of individual hedging strategies around this average number (CoV)

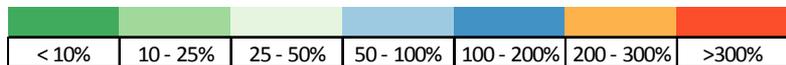
Color-coded on CoV

	CHI		EUR		IND		JPN		USA		World	
	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030
ELEC												
Bio	1.85	1.87	0.14	0.09	1.66	2.40	0.02	0.03	-0.15	-0.12	4.17	3.72
Coal	-11.05	-19.64	-0.27	-3.46	-3.07	-5.51	-0.43	-0.88	-9.47	-10.19	-27.47	-43.37
Gas	6.01	5.38	-3.16	-4.59	0.25	-0.08	-0.19	-0.04	-2.07	-2.91	-6.12	-10.53
Geothermal	0.01	0.05	0.12	0.26			0.05	0.05	0.00	0.00	1.78	2.29
Hydro	0.94	0.88	0.06	0.16	0.23	0.55	0.01	0.04	0.10	0.27	4.12	7.13
Nuclear	0.76	0.42	1.14	2.12	0.27	0.65	0.18	0.21	1.09	1.83	4.37	7.08
Oil	0.07	0.04	0.08	0.06	0.00	0.12	0.17	0.30			-0.15	-0.62
Solar	0.00	9.25	0.00	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.00	9.82
Wind	0.22	0.22	1.13	4.52	0.03	0.03	0.03	0.12	8.28	8.60	13.00	18.94
FINAL												
Bio	-2.97	-3.05	-0.07	-0.04	-2.81	-2.72	0.02	0.04	0.00	0.03	-5.36	-9.62
Coal	-27.98	-43.66	-1.58	-2.75	-3.27	-6.58	-1.07	-1.21	-1.89	-2.50	-44.20	-67.84
Electricity	-0.90	-1.11	-0.62	-0.51	-0.14	-0.35	-0.19	-0.17	-2.11	-2.40	-4.76	-3.65
Gas	15.69	29.34	0.75	0.61	1.67	2.91	0.35	0.34	3.03	2.44	25.32	39.64
Heat	-0.11	-0.20	-0.03	-0.14	-0.01	-0.03	-0.02	-0.03	-0.03	-0.09	-0.26	-0.54
Hydrogen		-0.20				-0.06						-0.25
Liq	5.14	4.12	-1.94	-1.93	0.64	0.82	-0.25	-0.77	-2.57	-2.78	-5.63	-16.97
ELEC												
Bio	1.62	2.23	0.33	0.47	0.94	2.31		0.02	-0.13	-0.12	3.56	4.99
Coal	-3.92	-12.43	0.00	-2.47	-1.56	-5.11	-0.41	-0.54	-4.57	-9.38	-11.45	-32.52
Gas	0.25	7.42	-2.72	-3.47	-0.07	0.69	0.05	-0.05	-1.69	-2.92	-8.25	-6.23
Geothermal	0.00	0.01	0.11	0.25			0.00	0.00	0.00	0.00	1.57	1.96
Hydro	0.80	0.84	0.00	0.20	0.10	0.46	0.01	0.03	0.07	0.15	2.43	6.08
Nuclear	0.62	0.40	1.07	1.97	0.26	0.62	0.18	0.20	0.81	1.49	3.43	6.21
Oil			0.06	0.05	0.01	0.01	0.05	0.06		0.00	-0.61	-0.60
Solar	0.00	0.79	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	1.12
Wind	0.00	0.04	0.64	1.98	0.00	0.00		0.11	3.53	8.16	4.69	13.49
FINAL												
Bio	-2.79	-2.89	-0.04	-0.02	-2.22	-2.69	0.02	0.03	0.00	0.03	-4.26	-5.12
Coal	-16.29	-40.31	-1.15	-2.37	-2.16	-5.36	-0.62	-1.02	-0.85	-2.32	-27.31	-61.29
Electricity	-0.42	-0.32	-0.41	-0.67	-0.04	0.07	-0.12	-0.15	-1.80	-2.31	-3.35	-3.58
Gas	9.64	28.19	0.69	1.53	1.38	3.33	0.15	0.46	2.23	3.20	17.59	42.63
Heat	-0.06	-0.15	-0.01	-0.12	-0.01	-0.02	-0.01	-0.02	-0.02	-0.07	-0.14	-0.43
Hydrogen		-0.06				-0.03						-0.09
Liq	2.80	4.44	-1.21	-1.21	0.32	0.88	0.00	-0.25	-1.00	-1.05	-3.40	-6.82
ELEC												
Bio	-0.05	0.58		0.39	-0.02	0.69		0.00	-0.02	-0.08	0.04	2.34
Coal	0.03	0.23	1.01	-0.50	0.17	-0.23	-0.04	-0.03	-0.89	-2.22	0.14	-3.23
Gas			-1.17	-1.81	-0.14	-0.93	-0.01	-0.10	-0.14	-0.61	-2.69	-6.09
Geothermal	0.00	0.00	0.12	0.26			0.00	0.00	0.00	0.00	1.22	1.48
Hydro	0.30	0.39	-0.01	0.09	0.03	0.22	0.00	0.01	0.05	0.05	0.42	2.00
Nuclear	0.16	-0.04	0.62	0.62		0.56		0.06		0.98	0.20	2.37
Oil			0.03	0.03	0.03		0.00	0.01			-0.17	-0.38
Solar	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wind	0.00	0.00	-0.05	0.52	0.00	0.00			0.00	0.08	0.06	0.75
FINAL												
Bio	0.21	-1.35	0.01	0.02	0.22	-0.60	0.01	0.01	0.00	0.00	1.41	-0.26
Coal	0.27	0.57	-0.28	-1.09	0.09	-0.83	-0.33	-0.33	-0.02	0.07	-0.84	-2.68
Electricity	0.40	1.20	-0.09	-0.19	0.10	0.40	-0.05	-0.05	-0.94	-1.63	-0.53	0.01
Gas	0.82	3.84	0.33	1.18	-0.22	-0.81	0.08	0.16	1.08	1.64	2.73	9.15
Heat	-0.01	-0.03	0.00	-0.06	0.00	-0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.10
Liq	0.50	-0.41	0.15	-0.39	0.45	-0.11	0.19	-0.02	0.36	0.33	1.56	-1.06

450 ppm

500 ppm

550 ppm



Appendix

Some references related to the topic

Applications related to stochastic / robustness analysis

- Labriet M., Kanudia A. and R. Loulou R. 2011. *Climate mitigation under an uncertain technology future: a TIAM-WORLD analysis*. Submitted to Energy Economics.
- Babonneau F., Kanudia A., Labriet M., Loulou R. and J-P. Vial. 2011. *Energy Security: a robust optimization approach to design a robust European energy supply via TIAM-WORLD*. Environmental Modeling and Assessment, to appear.
- Loulou, R., Labriet M. and A. Kanudia. 2009. *Deterministic and Stochastic Analysis of alternative climate targets under differentiated cooperation regimes*. Energy Economics, Volume 31, Supplement 2, International, US and EU Climate Change Control Scenarios: Results from EMF22, p.S131-143.
- Labriet M., Loulou R. and A. Kanudia, 2009. *Modeling Uncertainty in a Large scale integrated Energy-Climate Model*. In: Environmental Decision Making under Uncertainty, J.A. Filar and A.B. Haurie (eds), pp.51-77.

Principles of TIMES and TIAM

- Loulou, R., Remme U., Kanudia A., Lehtilä A. and G. Goldstein. 2005. *Documentation for the TIMES Model*. Energy Technology Systems Analysis Programme (ETSAP), April 2005.
<http://www.etsap.org/documentation.asp>
- Loulou, R. and M. Labriet. 2008. *ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure*. Computational Management Science, Special issue "Managing Energy and the Environment", Vol. 5 (1-2), pp.7-40.
- Loulou, R. 2008. *ETSAP-TIAM: the TIMES integrated assessment model Part II: Mathematical formulation*. Computational Management Science, Special issue "Managing Energy and the Environment", Vol. 5 (1-2), 41-66.

Typical questions

Differences from Reference?

Differences between the perfect foresight strategies?

How do the hedging strategies vary between the two PFs : uniformly or clusters?

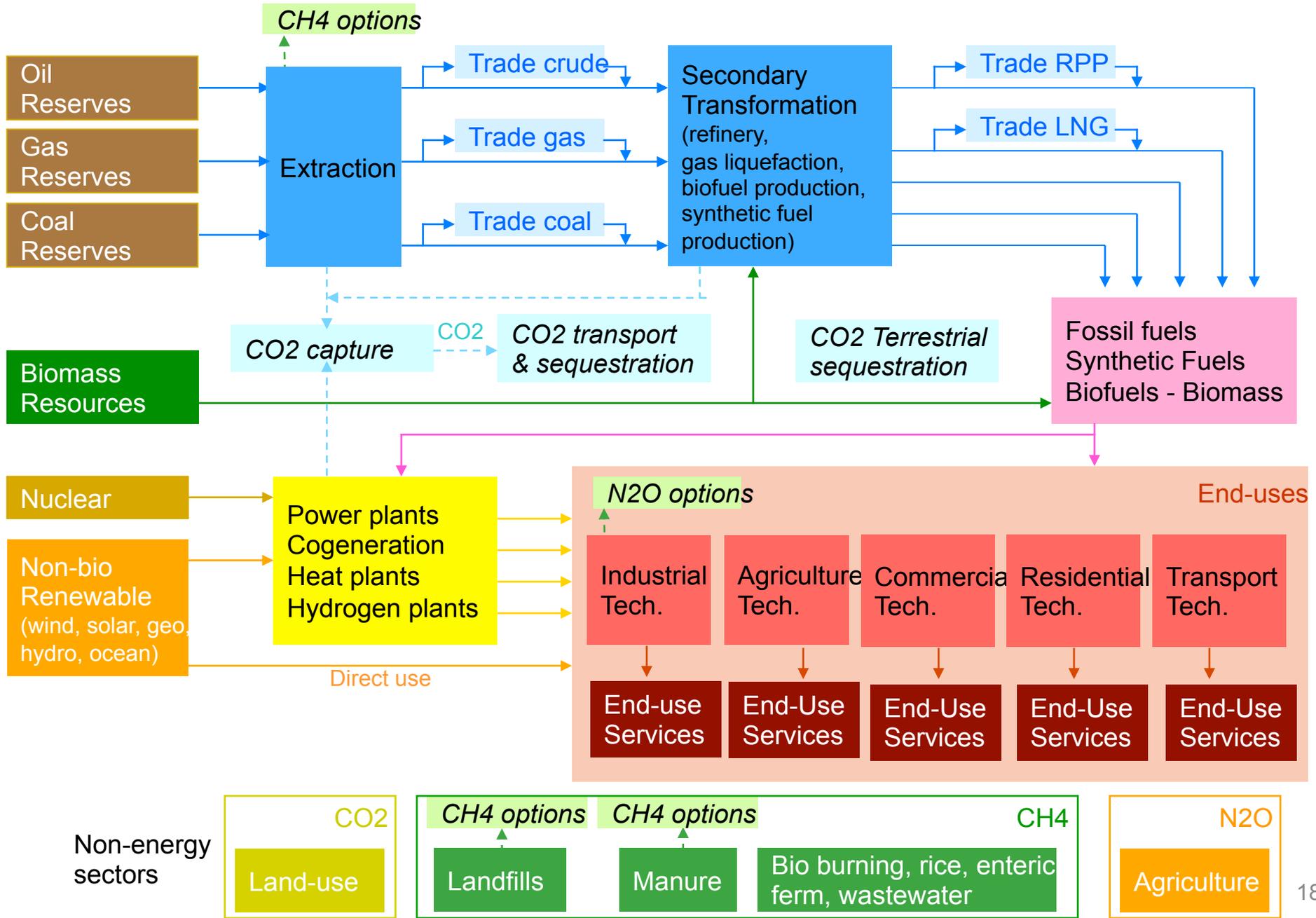
Do the hedging strategies go outside the PF range?

➔ *Actions*

➔ *Sensitive actions*
⇒ Interest for stochastic analysis

➔ *Stochastic analysis is required*

Reference Energy System of TIAM-WORLD



Regions of TIAM-WORLD

Code	Name	Countries
AFR	Africa	Algeria, Angola, Benin, Botswana (from 1981), Cameroon, Congo, Democratic Republic of Congo, Côte d'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Morocco, Mozambique, Namibia (from 1991), Nigeria, Senegal, South Africa, Sudan, United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe, and Other Africa*.
AUS	Australia, New-Zealand, Oceania	Australia, New-Zealand, Oceania
CAC	CentralAsia&Caucase	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Armenia, Azerbaidjian, Georgia
CAN	Canada	Canada
CHI	China	China
CSA	Central & South America	Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela and Other Latin America.
IND	India	India
JPN	Japan	Japan
MEA	Middle East	Bahrain, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen, and Turkey, Cyprus.
MEX	Mexico	Mexico
ODA	Other Developing Asia	Bangladesh, Brunei Darussalam, Cambodia (from 1995), Chinese Taipei, Indonesia, DPR of Korea, Malaysia, Mongolia (from 1985), Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam and Other Asia**
OEE	Other EastEurope	Belarus, Moldova, Ukraine Albania, Bosnia-Herzegovina, Croatia, Macedonia, Montenegro, Serbia (Kosovo)
RUS	Russia	Russia
SKO	South Korea	South Korea
USA	USA	USA
EUR	Europe 27+	Austria, Belgium, Bulgaria, Cyprus, Switzerland, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, Greece, Hungary, Ireland, Iceland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Norway, Poland, Portugal, Romania, Sweden, Slovenia, Slovakia, United Kingdom

End-Use Demands in TIAM-WORLD (1/2)

TIAM useful demands	Code(s)	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)	PJ/year	TWI
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	PJ/year	REA
Other energy uses	ROT	PJ/year

End-Use Demands in TIAM-WORLD (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	PJ/year	CRF
Electric equipments	COE	PJ/year
Other energy uses	COT	PJ/year
Agriculture segment (1)		
Agriculture	AGR	PJ/year
Industrial segments (6)		
Iron and steel	IIS	Millions tonnes/year
Non ferrous metals	INF	Millions tonnes/year
Chemicals	ICH	PJ/year
Pulp and paper	ILP	Millions tonnes/year
Non metal minerals	INM	PJ/year
Other industries	IOI	PJ/year
Other segment (1)		
Other non specified energy consumption	ONO	15,16