Evaluating Uncertain CO_2 Abatement over the Very Long Term

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jointly with

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Role of CCS in Climate Change Mitigation

- We need drastic GHG emission reductions to constrain climate change
- CCS will probably play a major role

But

- Part of stored CO2 may leak back into atmosphere
  - Optimist: Oil&Gas have been stored for very long time
  - Pessimist: We don't find Oil&Gas everywhere we expect it!
  - When CCS global & on large scale, mixed results probable (is 'CCS as safe as nuclear'?)
- CCS requires part of fossil fuel energy $\Rightarrow$ need more fossil fuels and more CO2 is stored than otherwise emitted

Thus

- In the long-term, CCS may be a delay, rather than a solution
- Should CCS receive full or partial exemption from carbon pricing (EU regulation proposes full exemption)

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Research Questions

1. How to evaluate the 'Net Present Value' of future leakage of CCS when these happen after, say, 500 years?
   - Discounting renders damages after 500 years irrelevant
   - For CCS leakage (500 yr delay), discounting is even more important than for Climate Change emission reduction (100 yr delay)
2. How to deal with uncertainty regarding future leakage?
   - And how to deal with context uncertainty: climate sensitivity, damage uncertainty, etc.
3. What is optimal hedging strategy when we understand CCS leakage better by 2050?
   - Wait / go ahead?

Literature on discounting

- Discounting
  - Nordhaus / Tol / Yohe: use market discount rate as other choice is inefficient
  - Broom / Stern (2007): use low discount rate as other choice is unfair
  - Chichilnisky / Heal: use non-dictator welfare function
- In this paper, we will consider both high&low, but prefer 'low discounting'
  - Capital markets are not designed to reveal social preferences for long-term!
  - Representative of the people (democratic government) can influence abatement but cannot influence aggregate capital savings, e.g. due to commitment problem
  - Impossibility to adjust capital savings cannot be a reason not to choose a just abatement level
  - Question for climate policy is what time-structure of preferences are good and which policy is practical. Not whether there exists an unattainable Pareto improvement

Literature on Hedging

- Uncertainty & Hedging when ceiling is uncertain
  - Ha-Duong et al., (1997), Yohe et al (2004): take above average action
  - Argument in a nutshell: convex abatement costs prefers smoothing. Possibility of very high action level in second period can be very costly
- Uncertainty & Hedging when damages are uncertain
  - Ulph and Ulph (1997) and Karp and Zhang (2006): (analytical result) delay abatement until uncertainty resolves
  - Nordhaus and Popp (1997), Webster (2000), Manne and Richels (2005), Ingham et al. (2007), Bosetti et al (2009) (IAM result) delay abatement until uncertainty resolves
  - Argument in a nutshell: you can't get back abatement costs when you've taken too much action (sunk costs)
- Difference uncertain damage vs uncertain ceiling
  - If taken too low action, you can accept higher damages as a bound on costs

Analysis: Climate Damage Module

- Consider a stock pollutant with depreciation (CO2: ε = 0.01/yr)

(1) $\dot{S}_t = E_t - \varepsilon S_t$

- Damages are delayed relative to stock (e.g. because related to temperature increase); ‘damage pressure’ is measured in same unit as stock (temp: δ = 0.02/yr)

(2) $\dot{d}_t = \delta(S_t - d_t)$

- Damages are proportional to population P_t and have elasticity μ with respect to per capita income y_t. Asterisks used for reference level.

(3) $D_t = \theta d_t \frac{P_t}{P^*}\left(\frac{y_t}{y^*}\right)^{\mu}$

- Ramsey rule for interest rate with ρ pure time preference, γ economic growth

(4) $r_t = \rho + \eta\,\gamma$

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Analysis: Shadow price for Emissions

- With some straightforward arithmetic, one finds the shadow price for the pollutant stock (for convenience assume $\mu = \eta$)

(5) $$\lambda_t = \theta \frac{P_t}{P^*} \left(\frac{y_t}{y^*} \right)^{\eta} \frac{\delta}{\rho - g + \delta}$$

- Where g is population growth
- And for the pollutant emissions, we find the shadow price

(6) $$q_t = \theta \frac{P_t}{P^*} \left(\frac{y_t}{y^*} \right)^{\eta} \frac{\delta}{(\rho - g + \varepsilon)(\rho - g + \delta)}$$

- Shadow price increases with population and income, increases with pure time preference $\rho - g$, increases with speed of temperature adjustment δ, decreases with CO2 depreciation ε.

Numerics for Back of Envelope (BoE)

- These six equations are reasonably accurate. They explain most of variation in IAMs from Stern to Nordhaus
- Damage estimates and pure time preference equally important
- Shadow price (€/tCO2eq) ($\mu=\eta=1$)

Pure time preference	Damage estimate for 2200 $GtCO_2eq$	
($\rho - g$)	2 %GDP	10 % GDP
0 %/yr	39	195
1 %/yr	13	65
2 %/yr	7	33

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Analysis: Shadow price for CCS Leakage

- When applying CCS, one needs $\alpha \approx 1.4$ units of fossil fuels for the same net energy output. If the stored CO2 leaks back at a rate φ, the leakage flow will by $\varphi\, e^{-\varphi t}$, and the net present value will be

(7) $$p_t = \theta \frac{P_t}{P^*} \left(\frac{y_t}{y^*} \right)^{\eta} \frac{\alpha \delta \varphi}{(\rho - g + \varepsilon)(\rho - g + \delta)(\rho - g + \varphi)}$$

- $\zeta = 1 - p_t / q_t$, is the called the economic effectiveness of CCS (Herzog *et al*. 2003).

(8) $$\xi = 1 - \frac{\alpha \varphi}{\rho - g + \varphi}$$

Effectiveness decreases with energy penalty α, increases with time preference ρ, decreases with population growth g, and decreases with leakage φ.

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Numerics for Back of Envelope (BoE)

- CCS effectiveness (%) (α=1.4)

Pure time preference (ρ–g)	CCS leakage rate (φ) 0.1 %/yr	CCS leakage rate (φ) 1 %/yr
0.1 %/yr	25%	-36%
1 %/yr	86%	25%
2 %/yr	93%	50%

- With ‘zero discounting’ only 100% secure CCS is acceptable
- With ‘market discounting’, even leaky CCS storage is acceptable
- CCS becomes ineffective (ζ<0.5) when leakage exceeds half of pure time preference.

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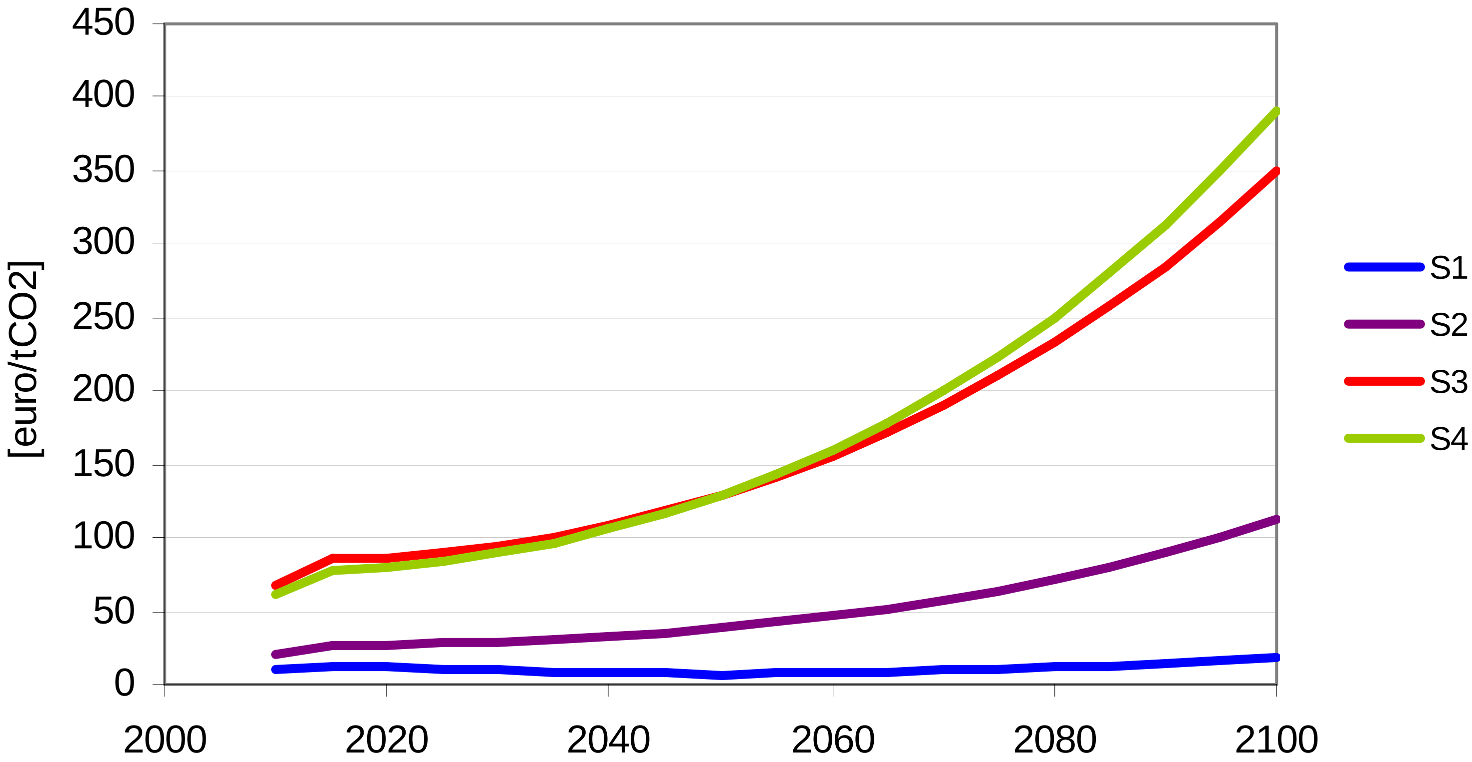
Illustration through Simulations

- Update DEMETER model with non-constant leakage, climate module up to year 3000, economic module up to 2400, constant savings rate of 25% gross,
- Define BAU scenario with sudden increase in oil price 2005-2010, flat emissions, high growth thereafter
- Define 4 policy scenarios to test dependency of CCS on discounting, damage estimate & leakage

Scenarios	Discounting	Damages	Leak-back time
S1	3 %/yr	2 % GDP	100 yrs
S2	3 %/yr	10 % GDP	100 yrs
S3	1 %/yr	10 % GDP	100 yrs
S4	1 %/yr	10 % GDP	500 yrs

Optimal carbon price confirms BoE



- High discount rate + low damages (S1) ⇒ low carbon tax
- Higher damages (S2 vs S1) ⇒ higher carbon tax
- Lower discount rate (S3 vs S2) ⇒ very high carbon tax
- Available CCS with low leakage (S4 vs S3) ⇒ not much effect

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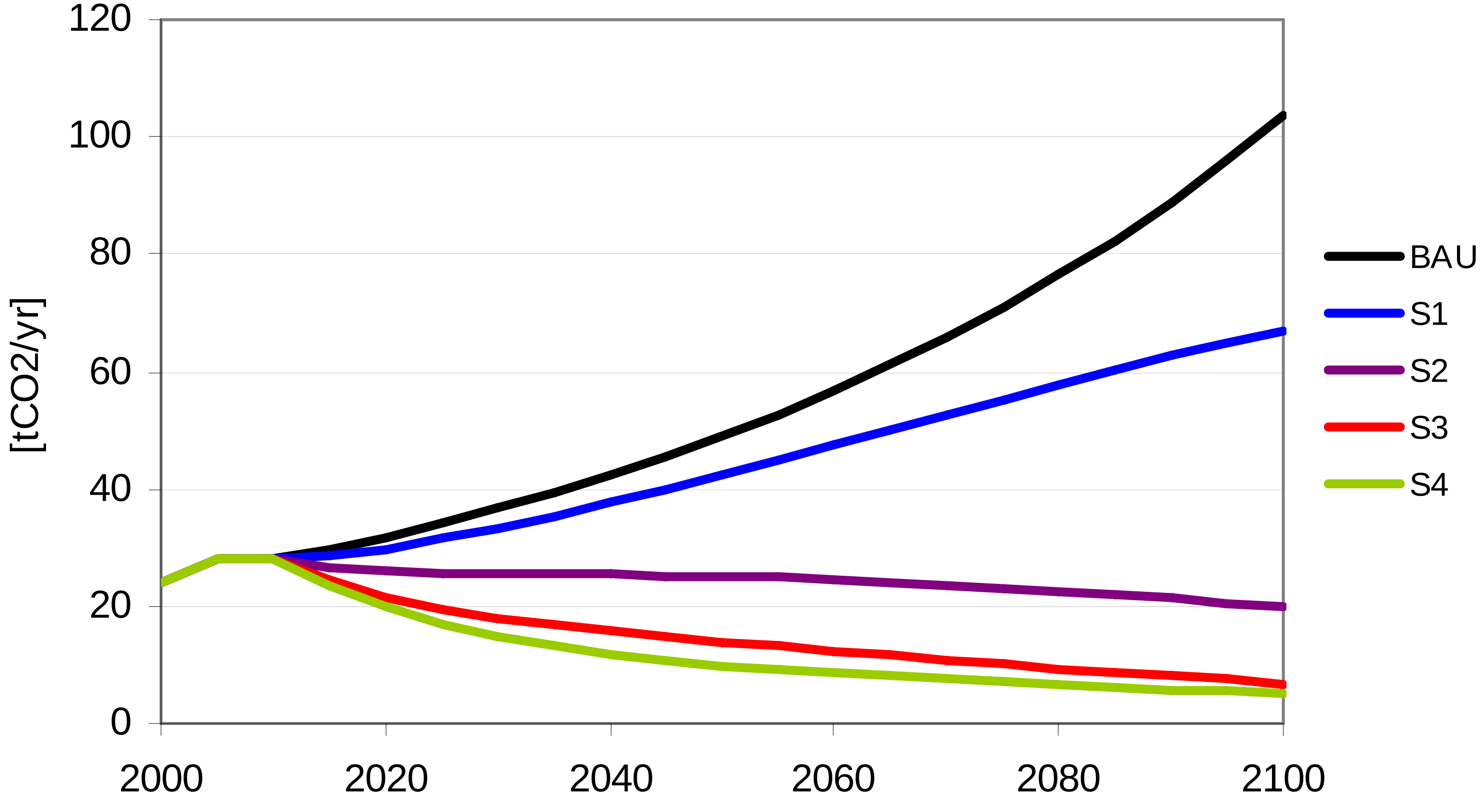
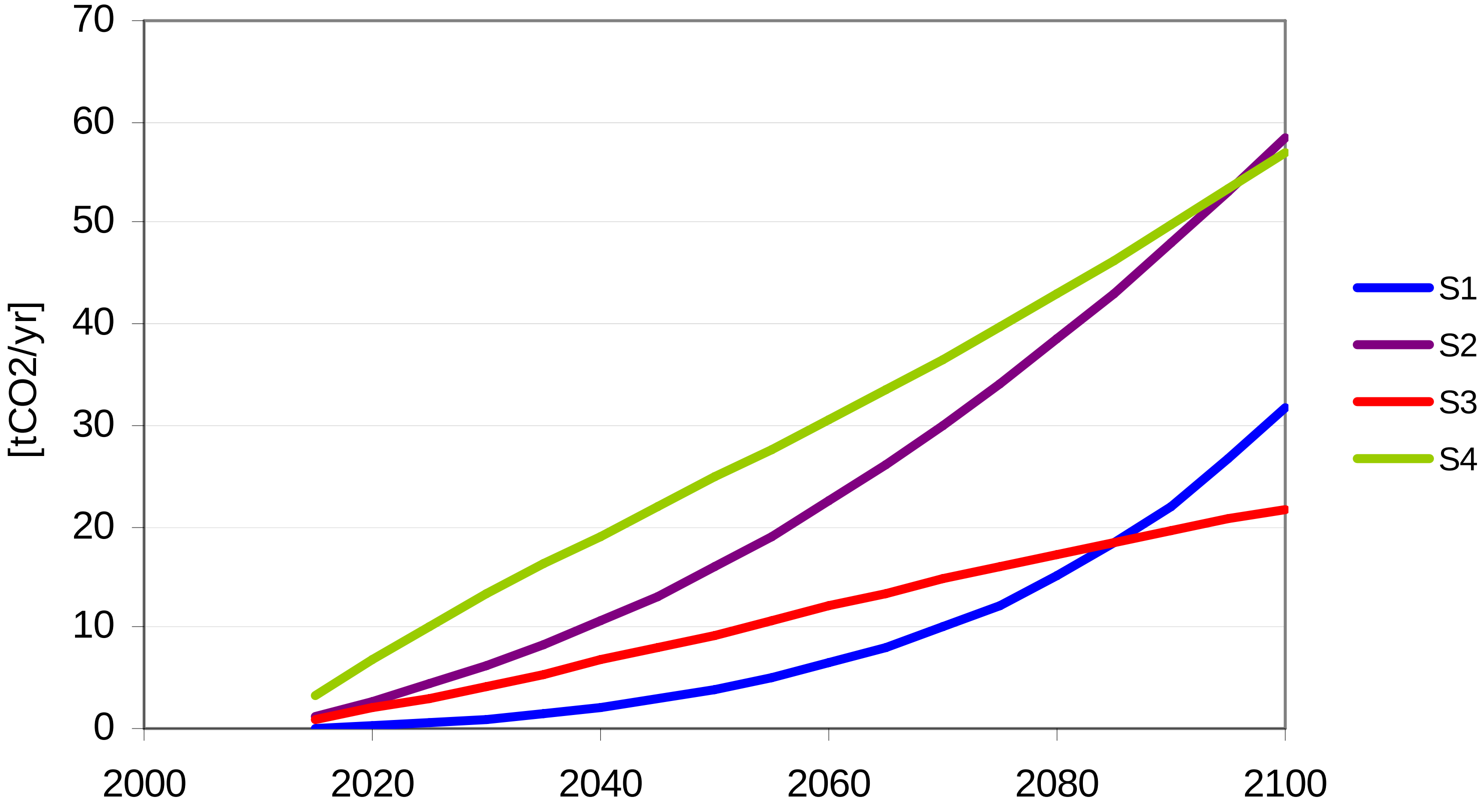
Emissions & abatement similar



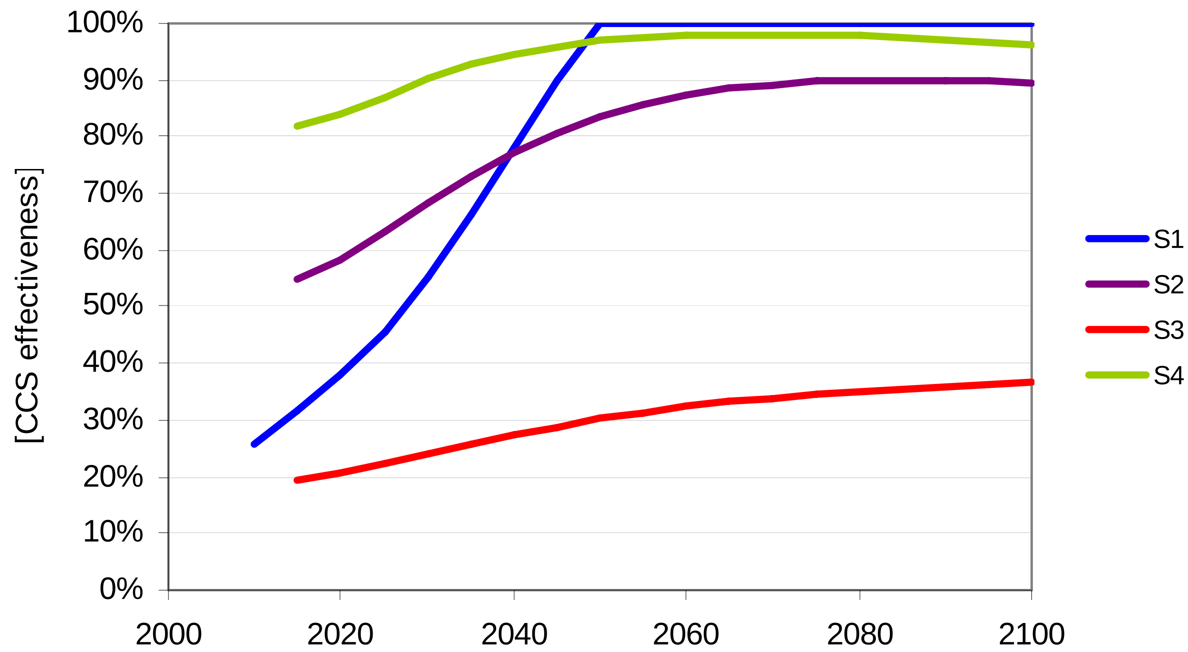
- High discount rate + low damages (S1) ⇒ low abatement
- Higher damages (S2 vs S1) ⇒ more abatement
- Lower discount rate (S3 vs S2) ⇒ more abatement
- Available CCS with low leakage (S4 vs S3) ⇒ more abatement

CCS inflow



- CCS plays a substantial role in cutting emissions

CCS economic effectiveness confirms BoE



- With high discounting (S1+S2), CCS efficiency is ok from 2050 onwards, even with substantial leakage
  - CCS is most effective when CO2 stock peaks! That is, to lower the peak of atmospheric CO2 and spread the concentration more evenly.
- With low discounting (S3 vs S2), CCS efficiency drops sharply
- With low leakage (S4 vs S3), CCS is fine even with low discounting

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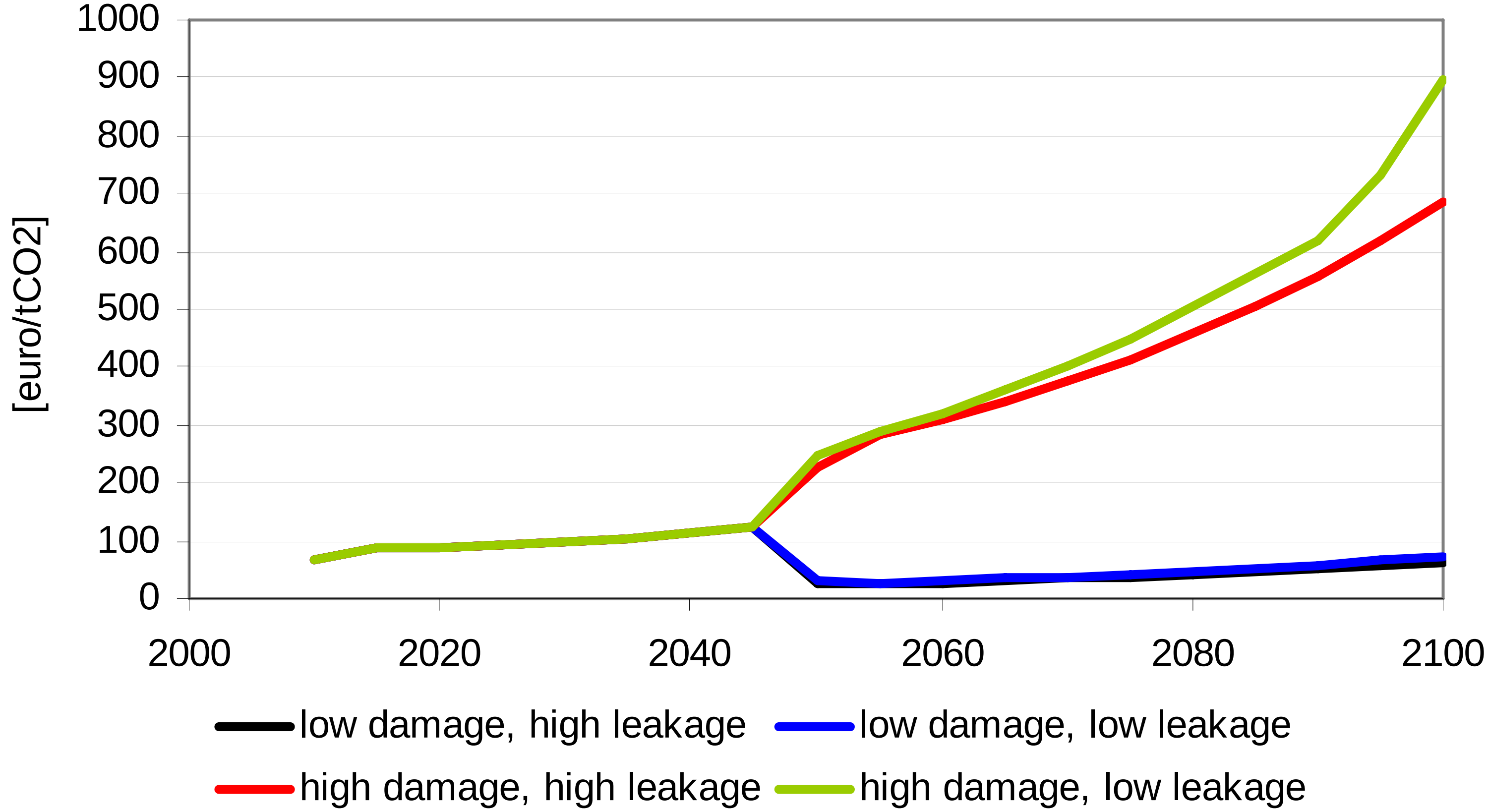
Uncertainty and Hedging

- What is optimal CCS strategy if we don't know future CC damage or CCSleakage?
- Define 4 new policy scenarios plus one hedging scenario (all 1%/yr pure time preference)

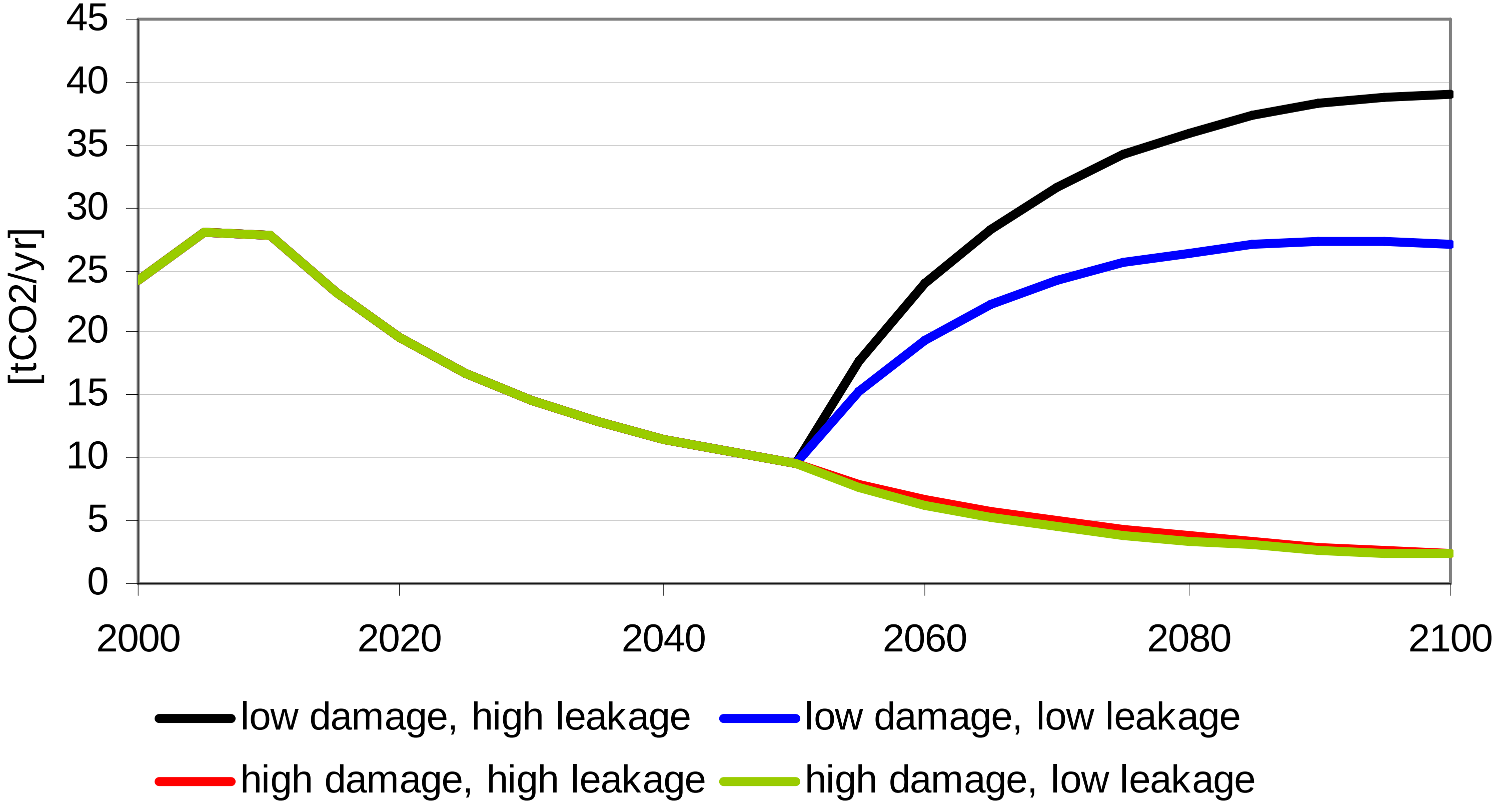
Scenarios	Probability	Damages	Leak-back time
S5	10 %	2 % GDP	100 yrs
S6	40 %	2 % GDP	500 yrs
S7	10 %	10 % GDP	100 yrs
S8	40 %	10 % GDP	500 yrs
S9	Uncertainty resolved in 2050		

Hedging carbon price



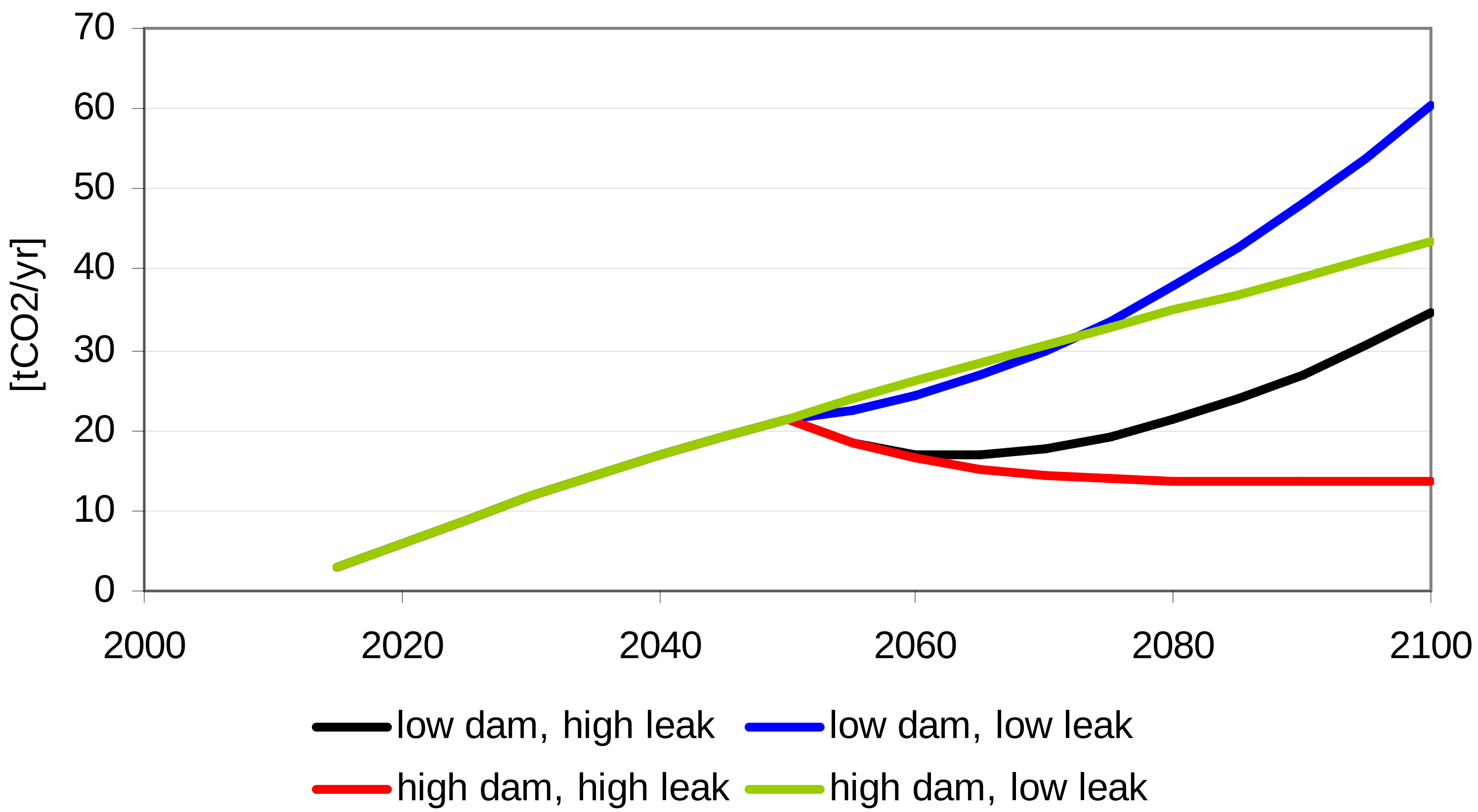
- Use of expected damages gives reasonable fit for optimal hedging strategy

Hedging emission abatement



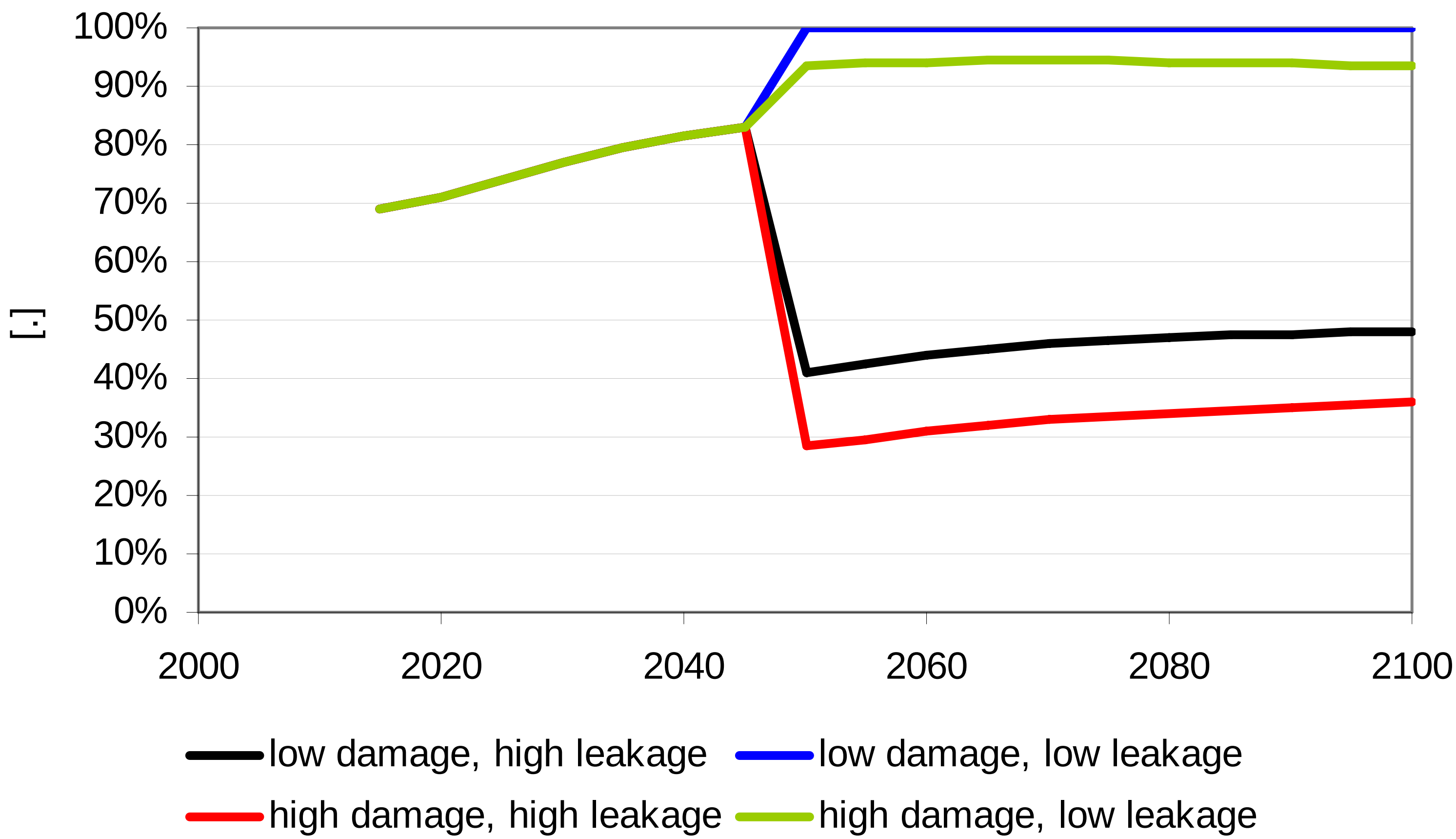
- Quite substantial emission cuts: precautionary principle
- Explanation: abatement is concave in carbon price, thus abatement is above average

Hedging CCS



- Low probability of high leakage does NOT reduce optimal CCS inflow (no extreme caution)

CCS economic effectiveness



With uncertain leakage, one should give CCS partial exemption only for carbon price!

Conclusions

- With high discounting substantial CCS leakage is acceptable
- With very low discounting, only very low leakage is acceptable
- Only in a model with very long time horizon can this be studied
- As for hedging, in practice, taking average is a good guess
- CCS should not receive full exemption, but only partial exemption from carbon pricing