Adaptation to climate change with a case study on a transport infrastructure (rail)

(+ optimal carbon tax on transportation)

Institute for Sustainable Aviation (ISA)
Workshop Air transport vulnerability to weather and climate change

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Roadmap

1. How to account for long-term or radical uncertainty? Illustrated examples
2. How to account for long-term or radical uncertainty? Methodology
3. How to account for long-term or radical uncertainty? Application to the resilience of the railway infrastructure against extreme heat
4. Optimal carbon taxation on transportation

Context

Motivation:

- Many investment decisions today operate on long horizons with high uncertainties
- The choice of the discount rate is essential to avoid systematically underweighting medium-to-long-term benefits
- Investing in certain infrastructures or technologies often carries *an insurance value and/or an option value*

Examples:

- Storing nuclear waste has impacts over hundreds of years;
- Investing in a next-generation nuclear reactor prototype (EPR) in the early 2000s is an option for the future (to pursue the industry if it proves useful)
- When is it optimal to invest in adaptation to climate change?

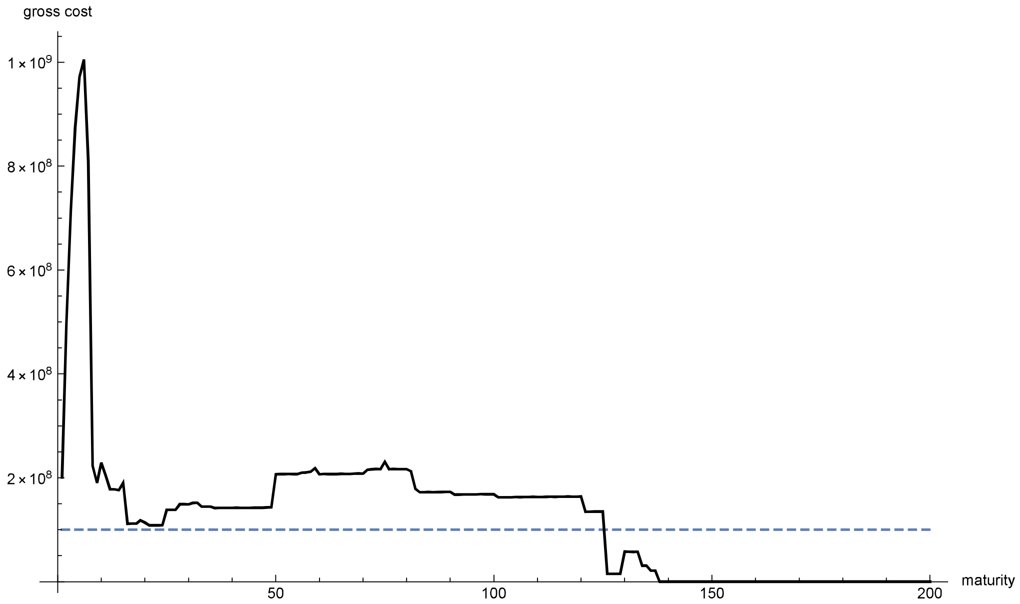
  → Case study for a transport infrastructure (railway)

Example 1: Nuclear Waste and Insurance Value

Approach and Result:

- Two options: Near-surface storage and deep geological storage (Cigéo)
- Method consisting in comparing the two options under a baseline scenario and a catastrophic scenario

  See Cherbonnier et al. (2025). Stress discounting. Journal of Risk and Uncertainty
- Cigéo dominates because it constitutes a form of insurance against catastrophic risk

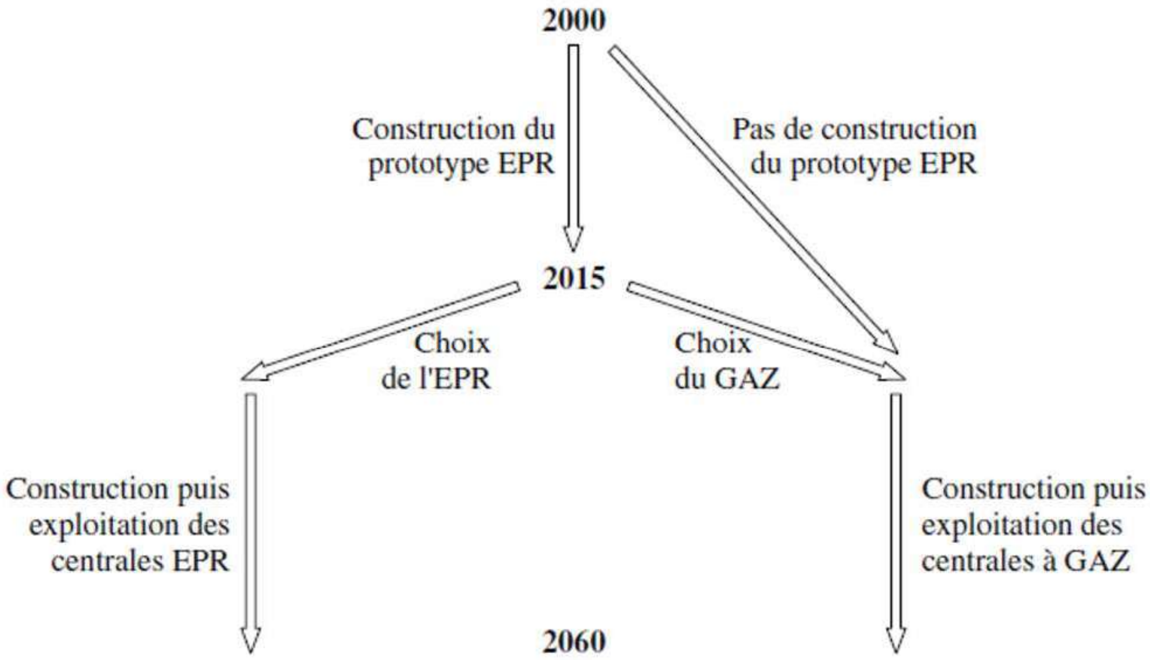


Example 2: Nuclear Reactor and Option Value

Approach and Result:

- Trend at the time: Phase out nuclear power because gas was available in large quantities at low prices
- Building the prototype confers an option value: The possibility to decide later whether to abandon nuclear energy

  See The valuation of the EPR nuclear project using the real options method. Eco and Prev (2001)
- Conclusion of the study: Accounting for option value multiplies the NPV of the EPR project by 4 ⇒ launch decision!



2000

Construction du prototype EPR

Pas de construction du prototype EPR

2015

Choix de l'EPR

Choix du GAZ

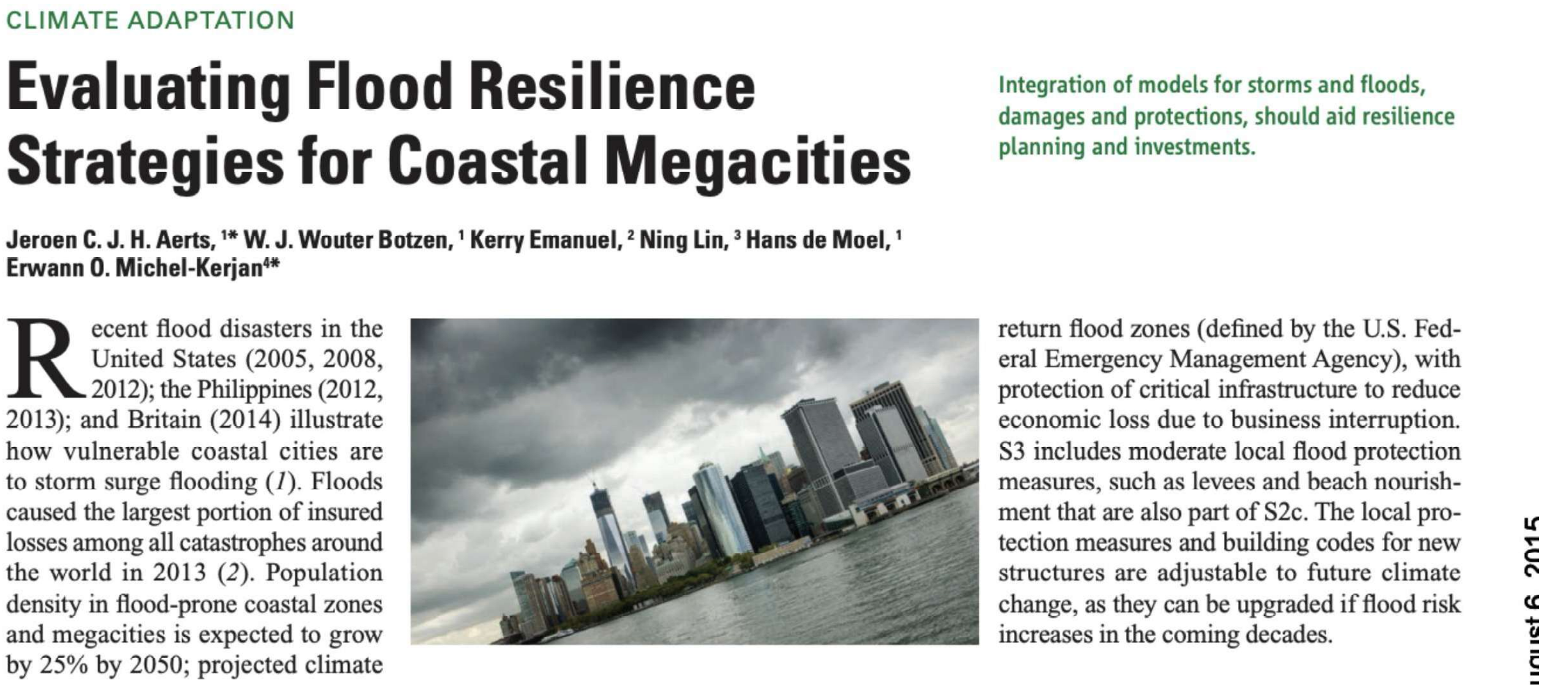
Construction puis exploitation des centrales EPR

Construction puis exploitation des centrales à GAZ

2060

Example 3: Adaptation to Global Warming

- Requires properly identifying key parameters: The risk to be prevented, the value of what is being protected, and the risk-adjusted discount rate
- And accounting for insurance values and option values inherent to the project (not at all the case today, see e.g., Science 2014 below)
- Ongoing work on adapting rail infrastructure to global warming, which involves arbitrating between acting quickly (to limit damage) and waiting (to learn more, to benefit from technical progress...)



CLIMATE ADAPTATION

Evaluating Flood Resilience Strategies for Coastal Megacities

Integration of models for storms and floods, damages and protections, should aid resilience planning and investments.

Jeroen C. J. H. Aerts,[1]* W. J. Wouter Botzen,[1] Kerry Emanuel,[2] Ning Lin,[3] Hans de Moel,[1] Erwann O. Michel-Kerjan[4]*

Recent flood disasters in the United States (2005, 2008, 2012); the Philippines (2012, 2013); and Britain (2014) illustrate how vulnerable coastal cities are to storm surge flooding (*1*). Floods caused the largest portion of insured losses among all catastrophes around the world in 2013 (*2*). Population density in flood-prone coastal zones and megacities is expected to grow by 25% by 2050; projected climate

return flood zones (defined by the U.S. Federal Emergency Management Agency), with protection of critical infrastructure to reduce economic loss due to business interruption. S3 includes moderate local flood protection measures, such as levees and beach nourishment that are also part of S2c. The local protection measures and building codes for new structures are adjustable to future climate change, as they can be upgraded if flood risk increases in the coming decades.

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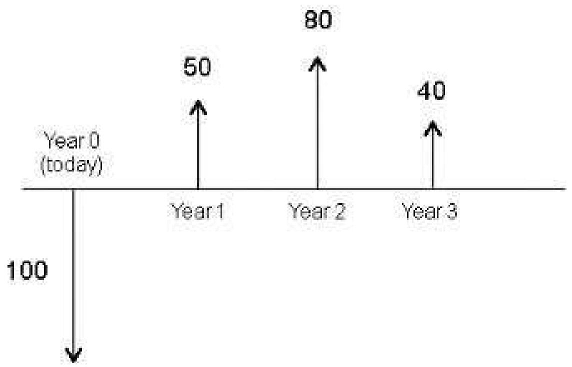
Investment's decision and discounting

For private investment, the "net present value" or "discounted free cash flow" criterion

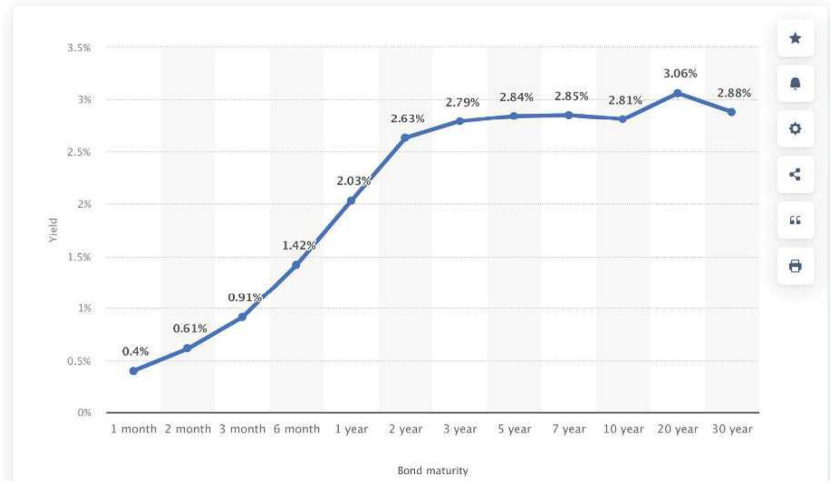
$$\text{Net Present Value } = \Sigma \frac{FutureValue_t}{(1+r)^t}$$

where r is a rate of return reflecting the weighted average cost of capital (WACC) taking into account debt and shareholders' equity



This rate depends on the time horizon and, in some cases, can be given directly by financial markets. Here the risk-free rate obtained US treasury:

Treasury yield curve in the United States as of April 25, 2022



Investment's decision and discounting: risk adjustment

For **private investment**, the discount rate r takes into account firm's or project's specific risk according to the Capital Asset Pricing Model or CAPM (Sharpe 1964, Lintner 1965, Mossin 1966)

$$r = r_f + \underbrace{(r_M - r_f) \times \underbrace{\frac{cov(\tilde{r}, \tilde{r}_M)}{Var(\tilde{r}_M)}}_{\beta}}_{\text{premium for \underline{non-diversifiable risk}}}$$

What about public investment ?

→ Consumption-based asset pricing model by Rubinstein (1976), Lucas (1978) and Breeden (1979):

$$r = r_f + \beta \times \phi$$

- ϕ: systematic risk premium
- β: consumption beta, defined as the elasticity of the net social benefit of the project to a change in aggregate consumption

Investment's decision and discounting: insurance value

- $\beta >> 0$ means that the project gains value in times of growth, and helps to reinforce macroeconomic risk (transportation).
- $\beta < 0$ means that the project has an insurance value (hospitals, nuclear wastes deep repository) → high value when everything goes wrong.

⇒ First concrete example of a negative beta : electricity transfrontier link connecting France and Spain (Cherbonnier Gollier 2022)

⇒ Using a single discount rate generates a misallocation of capital for both public investment (Gollier 2021) and private investment (Krueger et al. 2015)

Long debate on the "climate beta" = risk-premium to be added when discounting the damage induced by a marginal emission of 1ton of CO2

- Is it positive (Nordhaus 2011) since more growth ⇒ more CO2 emission ⇒ more climate damage per ton of CO2 ?
- Is it negative (Weitzman 2013) since more climate sensitivity ⇒ more climate damage ⇒ less growth ?

→ β slightly negative and decreasing (Dietz, Gollier & Kessler 2018)

Investment's decision and discounting: climate adaptation

Similar issue for an investment in adaptation whose benefit is

$$B_t = V_t \times P_t$$

where V_t protected asset and P_t probability of a climatic event that the investment protects against.

Two benchmark specifications for P:

- **Extreme temperature damages.** Following Bilal & Känzig (2024), a $1°C$ global temperature shock is associated with a five-fold increase in the frequency of extreme heat events. $\Rightarrow \quad P = A^T$
- **Flood damages.** Following Van Dantzig (1956), the flood probability depends exponentially on the height of the dike H net of sea-level rise (assumed proportional to temperature with factor τ): $\Rightarrow \quad P = 1 - e^{-\lambda(H-\tau T)}$

Modified version of DICE enriched with the two main sources of uncertainty identified by Dietz et al. (2018): productivity shocks and climate sensitivity (truncated log-logistic distribution with mean 2.9°C)

→ **Hump-shaped & positive adaptation beta** (Cherbonnier Pommeret 2026)

Timing of investment decision: Real Option Theory

Key idea: Investment is *irreversible* and can be *delayed* ⇒ waiting has value

Decision problem: At each date t, choose between:

- **Invest now:** obtain net value $V(B_t) - I$
- **Wait:** keep the option to invest later

Bellman equation:

$$F(B_t) = \max\left(V(B_t) - I, \mathbb{E}\left[e^{-\delta dt} F(B_{t+dt}) \mid B_t\right]\right)$$

Interpretation:

- $F(B_t)$: value of the option to invest (“option value”)
- $V(B_t)$: value of the project if undertaken immediately
- I: irreversible investment cost
- Second term: value of waiting (expected continuation value)

Main trade-off:

- Investing early ⇒ capture benefits sooner
- Waiting ⇒ learn more (reduce uncertainty) and keep flexibility

Optimal investment occurs when B_t exceeds a *threshold* above the NPV rule.

Timing of investment decision: application to adaptation

Real option framework with specific assumptions:

- **Consumption dynamics.** The value of the protected asset depends on economic growth which follows a jump-diffusion process (catastrophic risk à la Barro):

$$\frac{dC_t}{C_t} = \mu_C dt + \sigma_C dW_{C,t} + (J-1)dq_t$$

- **Climate hazard dynamics.** Random shocks $\Lambda_t dt$ during a period t : Homogeneous Poisson process whose intensity Λ_t varies according to a Geometric Brownian Motion

$$\frac{d\Lambda_t}{\Lambda_t} = \mu_\Lambda dt + \sigma_\Lambda dW_{\Lambda,t}$$

Calibration of the model:

- Regarding the climatic events, we follow Truong (2018) who estimate the process governing the frequency of extreme fire weather events in Southeastern Australia, that is, $\mu = 1.59\%$ and $\sigma = 15.03\%$ for Λ_t .
- Regarding the economic growth, we follow Barro (2006) and choose $\mu_C = 2\%$, $\sigma_C = 1.5\%$, $\lambda = 1.7\%$ and $J = 70\%$. We assume also a zero pure rate of preference for the present and a risk aversion equal to 4.

  → risk-free rate 2.4% and macroeconomic risk premium 1.7%

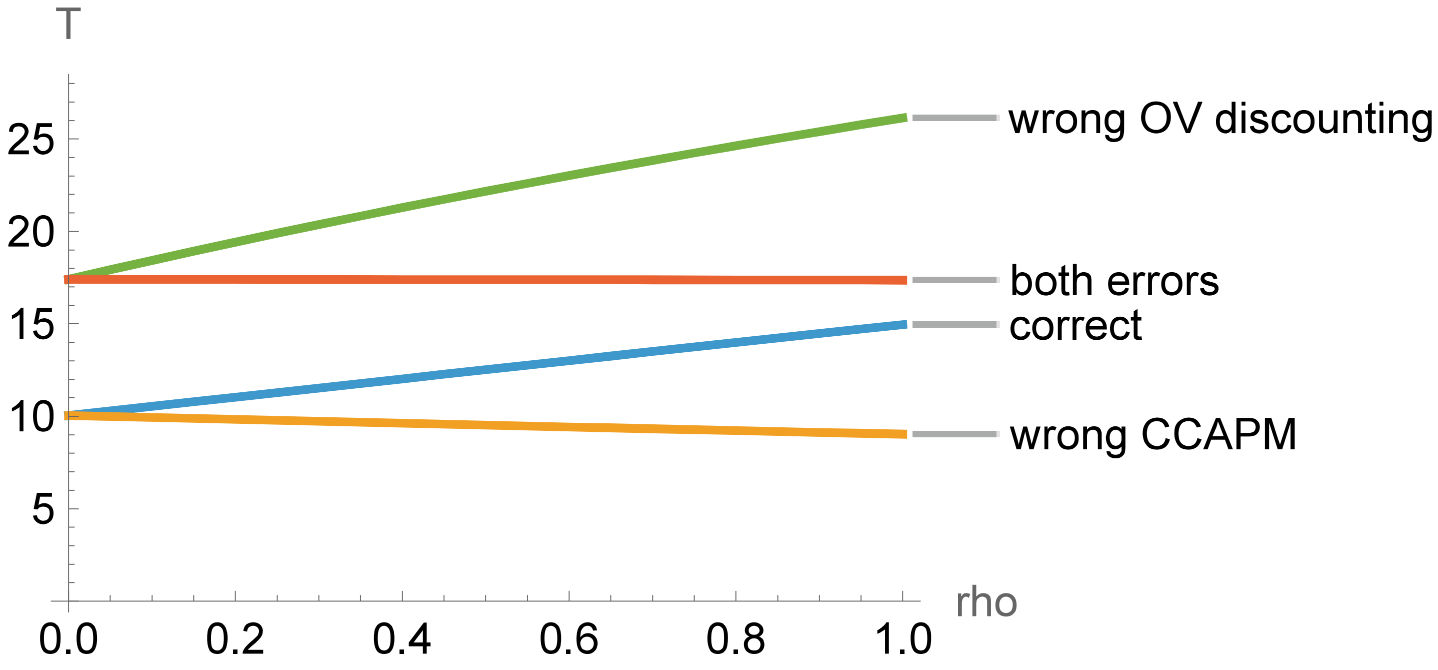
Timing of investment decision: discount rate & estimation

The Bellman equation must use a risk-adjusted discount rate:

$$F(B_t) = \max\left(V(B_t) - I, \mathbb{E}\left[e^{-\tilde{r}dt} F(B_{t+dt}) \mid B_t\right]\right)$$

Analytical results: Large impact of those bias on the timing of decision

- Wrongly discounting the option value may delay investment twice as much as what is optimal.



Timing of investment decision: discount rate & estimation

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... and analytical resolution are not feasible with realistic assumptions on uncertainty

- **Climate hazard dynamics:** the probability of climate-related events takes more complex forms depending on the type of adaptation considered : dike against flood, resilience against extreme temperatures...
- **Additional state variables:** Other factors may affect the value of adaptation over time: technological progress , deterioration of existing infrastructures...

Numerical simulations are therefore required, with uncertainty represented in discrete time (e.g., through multinomial trees).