Stress discounting *

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Abstract

Standard evaluations of public policies involve discounting the flow of expected net benefits at a unique discount rate. Consequently, they systematically ignore the insurance benefits of policies that hedge the aggregate risk, and the social cost of projects that raise the aggregate risk. Normative asset pricing theory recommends adjusting the discount rate to the project's risk, but few countries have attempted to implement this complex solution. We explore the equivalent "stochastic discount factor" approach based on the expected value of its state-contingent NPV, using the relevant state-contingent Ramsey discount rate. Under our "stress discounting" approach, projects are evaluated under two polar risk-free economic scenarios, one business-as-usual scenario, and one low-probability catastrophic scenario. Inspired by the recent asset pricing literature on macro catastrophes, we show that this approach adequately values assets' risk premia under a minimal, intuitive, and operationally simple departure from the standard risk-free approach with a unique discount rate. We carry out benchmarks to check the accuracy of this approach, then apply it to value a nuclear waste disposal.

Keywords: Project valuation, stochastic discount factor, rare disasters, cost-benefit analysis, social discounting.

JEL codes: G12, H43, Q54.

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1 Introduction

Under the standard practice, a project is deemed socially desirable if the discounted value of its flow of expected net social benefits is positive, using a unique public discount rate. But this procedure ignores the social cost of projects that increase the macroeconomic risk, and the social benefit of projects that reduce it. In other words, it ignores risk and risk aversion. Let us compare, for example, an investment in rail infrastructure, arguably most useful in a growing economy, with another investment in mass vaccination infrastructure, arguably most useful during an recession-prone pandemic. The standard public valuation practice values both projects equally if their expected net benefits are the same. However, risk aversion necessarily implies that a marginal reallocation of capital from railways to mass vaccination infrastructures would reduce the aggregate risk at no cost, thereby increasing welfare. Against this background, this paper proposes a simple and intuitive strategy to account for aggregate risk which significantly improves investment decisions and the allocation of public resources.

Modern asset pricing theory such as the Consumption-based CAPM (CCAPM) routinely recommends solving this problem by adjusting the discount rate to the risk profile of each project, and potentially of each of its specific costs and benefits (Bodie and Merton, 2000; Brealey et al., 2017). Although the CCAPM has a limited predictive power for asset pricing by financial markets, this model and its extensions provide a strong normative basis for policy evaluation. Under these models, the sufficient statistic of the risk profile is the CCAPM beta, which is the income-elasticity of the benefit under consideration. As shown by Gollier et al. (2023), three quarters of professional economists in an international survey of almost 1000 respondents believe that governments should stop using a single discount rate for public evaluations. However, this perfect solution has failed, in that no public administration applies it, generally using instead a single discount rate not adjusted for risk. For instance, in the U.K., there is a single official discount rate starting at 3.5% and declining with maturity thereafter, which includes a risk premium estimated at 1% supposed to cover "unpredictable risks not normally included in appraisal" (Treasury, 2020).[1] In the US, the circular-94 (and its Appendix D) specifies that risk should be accounted for by computing certainty equivalents that should then be discounted at a 2% risk-free rate that is the average real rate of return on long-term U.S. government debt over the last 30 years, adjusted for inflation. Even if there is a theoretical equivalent between discounted (at the Treasury bonds) certainty equivalents and risk-adjusted discount rates, Circular-A4 does not suggest that systematic risk should be incorporated in certainty equivalents, nor does it offer any guidance to do so.[2] Risk-adjusted discount rates are only a "back-up plan" in the absence of calculating certainty equivalents. However, in this case, the circular-A4 (appendix D) specifies that the market risk premium should be set at 2.5% and beta at 0.45 regardless the risk-profile of the project.[3] Therefore some economists strongly recommend this second option though with a beta capturing the correlation of each project's net benefits with the economy.[4]

We are aware of only three countries that have attempted to adapt their evaluation practices by adjusting their discount rate in order to take into account systematic risk. The Norwegian government in 1997 and the the Dutch government in 2020 (Rijksoverheid (2020)) have implemented discounting systems with three discount rates allocated to three risk classes defined by the projects' contribution to the aggregate uncertainty. However, such a system has been has been abandoned by Norway in 2012 as choosing the suitable risk class for a project was deemed too arbitrary.[5] Since then, Norway uses a single discount rate of 4%.

[1] This rate can be reduced to 1.5% for health projects. This does not result from an adjustment of the risk premium, but from the removal of the wealth effect contained in the Ramsey rule for the risk-free rate - in order to take into account the specific nature of health-related benefits (such as VSL or QALY).

[2] It states that "idiosyncratic risks are the primary focus".

[3] Such a beta captures the correlation in equity markets for economic sectors closest to government investment adjusted for the difference in non-payment risk between equity market investment and government investments.

[4] It should be noted that Executive Order 14192 of January 31, 2025 directed the Director of OMB to revoke Circular A-4 of 2023 and reinstate the earlier version (2003). This circular recommends that for a regulatory analysis, a discount rate of 3% and 7% be used, with a variant based on a lower rate when it concerns effects affecting future generations. The question of how to factor in project-specific risk, by adjusting the discount rate or using a certainty equivalent, is not addressed.

[5] See Hagen et al. (2012) page 77: "*Experience from previous practice with several risk classes suggests that many project analysts have been uncertain about the technical criteria for choosing the risk class, and that such choices may therefore at times seem somewhat arbitrary. These circumstances suggest that it may be preferable to recommend simple and transparent rules that capture the most important aspects of the matter,*

France has introduced a CCAPM rule since 2013. In 2023, the tutelar values that must be used by evaluators in France yield a risk-free discount rate of 1.2% and a market risk premium of 2% (Quinet (2013), Guesnerie (2021)). This risk premium even accounts for catastrophic risk.[6] The experience shows that very few evaluators have tried to estimate the beta of their projects. They rather used a default beta of one, yielding an implicit single discount rate of 3.2%. To sum up, most existing public evaluation systems do not control for systematic risk.

There are several reasons why economists failed to improve the public discounting systems in the western world. The obvious argument is that using a single discount rate makes life much easier for the evaluators who are well accustomed with this practice. Estimating the income-elasticity of the net benefit of a project, which is the right way to measure its impact on the aggregate risk, may be technically difficult. The literature on this question is very scarce, apart from theoretical works on the risk adjustment of the discount rate[7] and more recent work on the risk-adjusted discount rate to be applied on the social cost of carbon (Dietz et al., 2018; Cai and Lontzek, 2019; Van den Bremer and Van der Ploeg, 2021). One can cite a few rare notable exceptions, and in particular Breeden who, following his seminal work on the CCAPM, derived asset-specific betas from a system of demand (Breeden, 1980). Also, Pierru and Matar (2014) quantify the CCAPM betas of energy-related public investment project in Saudi Arabia. More recently, Cherbonnier and Gollier (2022) address the general question of the determinants of the risk-adjustment coefficient beta and show how it can be derived from the price and income elasticities of supply and demand. They also consider the large class of public investments in core infrastructures, showing that their betas exhibit a decreasing term structure and can take negative values when they provide a transport service between two countries (such as a cross-border electricity connection). The

without being too complex to understand or to apply."

[6] In fact, accounting for catastrophic risk, the French administration obtained a non-linear relationship between the specific risk premium and the beta of that project. The expression $1.2\% + 2\%\beta$ is therefore a linear approximation in order to make the social discount rate easier to use.

[7] For instance Weitzman (2012) studies the risk-adjusted discount rate for a project that hedges against catastrophic states of nature, while Traeger (2014) derives consumption discount rates in a model in which risk aversion, ambiguity aversion and intertemporal substitution are disentangled.

second argument is that there is much at stake for many lobbies, in particular in those sectors with larger income-elasticities. On the one hand, they are the losers of risk-adjusting the standard discounting system, hence contributing to the resistance towards risk-adjusted discount rates. On the other hand, there is a clear agency problem associated to the existence of various asymmetric information problems in this context. More flexibility in choosing project-specific discount rates may favor strong lobbies equipped with a good understanding of how to estimate CCAPM betas. To sum up, complexity in implementing the CCAPM is the central argument for why most countries have preferred using a single discount rate for policy evaluation. This is a serious issue because it leads to a misallocation of capital, resulting in significant welfare losses.[8]

It is important to note that these issues are also very relevant for the private sector. As has been shown by Krueger et al. (2015), if a company simply uses a single company-wide discount rate, based on market data, it will overinvest (underinvest) in projects with a market beta higher (lower) than the firm's core industry beta. Dessaint et al. (2020) also show that using the CAPM methodology in an M&A context leads to valuation errors either due to market imperfections or failure of the simple CAPM methodology. Our approach that considers the systematic socio-economic risk attached to the induced welfare can also be applied to the non-diversifiable market risk of long term private projects. Hence, our method allows a private company to better estimate the value of its projects. This is obviously true in the regulated sector: since the State increases (or covers) the risk of private companies, the private beta must take into account the possibility of a State failure, in a catastrophic situation à la Barro. But more generally, the approach developed here can help the private sector overcome the inability of the CCAPM to predict the risk premium associated with a specific project when these cannot be directly estimated from financial markets.

[8]In Gollier (2024), the welfare cost of ignoring the risk-adjustment in the discount rate has been estimated to be large, equivalent to at least 15% of permanent consumption at least – cf. also Cherbonnier and Gollier (2023).

In this article, we propose an alternative strategy to account for systematic risk with a minimal increment in operational complexity. Our strategy is based on the Stochastic Discounting Factor approach (SDF) of the fundamental asset pricing principle (Lucas, 1978):[9] Any state-dependent benefit $B_t = B_{ts} \mid_{s \in S}$ materializing at date t has a Present Value at date 0 equaling

$$PV = E[e^{-r_t t} B_t], \tag{1}$$

where $r_t = r_{ts} \mid_{s \in S}$ is the stochastic discount rate associated to maturity t and E is the expectation operator with respect to the states of nature $s \in S$. The state-dependent discount rate r_{ts} is the rate at which benefits in t should be discounted conditional to state s, i.e., under certainty. The Ramsey rule can be used to determine it. Project analysts just need to perform a sequence of NPV estimations under certainty, based on their estimation of the state-dependent benefit of the project. The complexity of this alternative approach depends upon the number of states of nature (or macroeconomic contingencies) that evaluators will have to consider. A priori, one would have to simulate a large number of states by running Montecarlo simulations. This is what is done for instance by the EPA in order to evaluate the social cost of carbon (EPA, 2023). In the spirit of Barro (2006), our work shows that using a small number of scenarios is enough to get a good approximation once catastrophic scenarios are included. Thereafter, we refer to this strategy as the "stress-discounting method".

This approach is much simpler than the CCAPM because it only requires to use the Ramsey discount rate contingent to each state considered, thereby eliminating the complexity of risk-adjusting the discount rate by estimating the project's beta. This alternative approach is also more intuitive because the Ramsey rule is by now well understood. Moreover, measuring the value creation of an asset through the expectation of its contingent NPV should also be easily understood by practitioners. Finally, this approach does not give up anything to the basic principles of asset pricing. The fact that the contingent discount rate is smaller in bad

[9]This principle is a direct consequence of the double additivity of the Discounted Expected Utility model, with respect to the states and to time. It does not hold under recursive preferences.

states of nature, i.e., in low-consumption states, provides the right instrument to deliver a positive premium to assets that yield more benefits in those states. Finally, our approach provides information about the circumstances in which the project is most valuable, as it measures the conditional PV of the project in each state of nature. This may be useful for the transparency of the decision-making and the public debate.

To choose the number of scenarios and their characteristics, let us start by recalling that the CCAPM fails to predict interest rates and risk premia in financial markets (Mehra and Prescott, 1985; Weil, 1989). In short, this means that the gaussian volatility of the growth rate of consumption is too small to explain why the interest rate has been so low over the last century, and why the aggregate risk premium has been so large. Rietz (1988), Barro (2006, 2009) and Weitzman (2007) showed that this failure of the CCAPM can be solved by recognizing that the lower tail of the distribution of economic growth is fatter than assumed in the standard CCAPM. Of course, the plausibility of rare disasters is not the only explanations put forward for the equity premium puzzle, and are certainly not the whole story – cf. in particular Constantinides and Duffie (1996); Campbell and Cochrane (1999); Bansal and Yaron (2004a) to only cite a few. However, this approach provides a very simple and operational way to obtain estimates that are consistent with market prices. Notice finally that in Barro's work, the equilibrium risk-free rates and risk premia are mainly determined by the probability of a macroeconomic catastrophe, and the gaussian volatility plays only a marginal role on these matters. The price of an asset is only marginally affected by how it behaves around the business-as-usual scenario. On the contrary, this asset's price is deeply affected by how it behaves in catastrophic states.

In this paper, we push this idea to this logical end by proposing to perform the expected NPV valuation with only two states, a Business-As-Usual (BAU) scenario and a catastrophic scenario. Calculating the two contingent discount rates is then trivial using the Ramsey rule. The calibration of the few parameters of this dynamic growth process is disciplined to duplicate existing asset prices, the risk-free rate and the aggregate risk premium along their term structures. Comparing the results obtained with this stress-discounted method under this calibration with some cutting-edge analytical methods (that depart from the classical Gaussian CCAPM in order to explain the asset pricing puzzles) allows to appraise the performance of the stress discounting method. We first compare the asset prices obtained from our approach to those generated by a Barro type model in which catastrophes can occur every year. Second, we extend Barro's model by allowing the catastrophe to be normally distributed (Martin, 2013). We show that the stress discounting method provides prices similar to these complex methods. On the other hand, we show that enriching the stress discounting method by adding a Gaussian uncertainty does not significantly improve its performance. In addition, we compare the results with those obtained using the standard public valuation practice. We show that the stress discounting method generates a much better allocation of capital than when using a single discount rate. We also conduct additional analyses, by adding one more scenario and discussing the possible values of the parameters we need to calibrate. Finally, we illustrate this new method by applying it to the case of a nuclear waste repository project planned for France.

The paper is organized as follows. We recall in section 2 the principles of the SDF approach for public investment valuation. The basic stress discounting method with two scenarios is explained, calibrated and illustrated in section 3. Section 4 presents the application on a French nuclear waste project.

2 Public investment valuation and risk

In this section, we first summarize the Stochastic Discount Factor (SDF) approach to asset pricing. We then recall the methodology of the standard approach to value public investment and policies, stressing its operational complexities.

2.1 Expected and contingent present values

There is a representative agent in the economy whose discrete flow of consumption is given by the stochastic process $(C_0, C_1, ..., C_t, ...)$. This agent extracts utility $u(C_t)$ from consuming C_t at date t. Social welfare at date 0 is measured by the discounted sum of temporal expected utility, using a rate of pure preference for the present δ. Let's consider an investment project that generates a flow of net benefits $(B_0, B_1, ...)$ that are potentially correlated to consumption.[10]

The Present Value (PV) of the project is defined as the sure monetary benefit received today that has the same impact on social welfare as a marginal investment εB_t in that project. In other words, PV equals

$$PV = \frac{1}{u'(C_0)} \left.\frac{\partial}{\partial \varepsilon}\right|_{\varepsilon=0} \sum_{t=0}^{+\infty} e^{-\delta t} Eu(C_t + \varepsilon B_t). \tag{2}$$

By definition, it is socially desirable to invest in the project if and only if PV is positive. This condition can be rewritten as follows:

$$PV = E\left[\sum_{t=0}^{+\infty} B_t e^{-r_t t}\right], \tag{3}$$

where the state-contingent discount rate r_t is defined as

$$r_t = \delta - \frac{1}{t}\log\left(\frac{u'(C_t)}{u'(C_0)}\right). \tag{4}$$

This means that the value creation of an investment project is the expectation of the contingent present values $\sum B_t \exp(-r_t t)$, using a stochastic discount factor $\exp(-r_t t)$. We hereafter assume that the utility function u exhibits constant relative risk aversion γ. Let g_t denote the annualized growth rate of consumption:

$$g_t = \frac{1}{t}\log\left(\frac{C_t}{C_0}\right) \tag{5}$$

[10] As is well-known, risks that are not correlated to aggregate consumption should not be priced. Therefore, B_t should be interpreted as the expected net benefit at date t conditional to C_t.

Combining this definition with equation (4) yields the Ramsey rule:

$$r_t = \delta + \gamma g_t. \tag{6}$$

The pair of equations (3) and (6) fully describes an "Stochastic Discount Factor" (SDF) valuation procedure in which the project analyst must perform three different tasks:

1. Characterize the flow of net benefits $(B_0, B_1, ...)$ in each growth scenario;

2. Compute the contingent PV of this flow in each scenario, using the associated SDF;

3. Compute the expectation of the contingent PVs to obtain the PV of the project.

Each of these tasks is intuitive and simple. The complexity of the procedure may emerge however if the number of scenarios to consider is large. This is what is done for instance by the US administration in order to estimate the social cost of carbon. More precisely, they run 10 000 Monte Carlo simulation in which the uncertain parameters are represented by random draws from their defined probability distributions (EPA, 2023). It should be noted that they write this approach in a slightly different but equivalent way. They first compute the certainty equivalent at time τ of the damages εB_t induced at times $t \geq \tau$ by emitting one ton of CO2 at time τ, that is $scghg_\tau$, the social cost of green house gaz emissions at time τ:

$$scghg_\tau = \frac{1}{\mathbb{E}[u'(C_\tau)]} \left.\frac{\partial}{\partial \varepsilon}\right|_{\varepsilon=0} \sum_{t=\tau}^{+\infty} e^{-\delta(t-\tau)} \mathbb{E}u(C_t + \varepsilon B_t).$$

This certainty equivalent is then discounted using the risk-free social discount rate (called in the EPA report the “certainty equivalent” discount rate, cf. annex A.3 of this report)

$$R_t = \delta - t^{-1} \log\left(\frac{\mathbb{E}[u'(C_t)]}{u'(C_0)}\right)$$

It is straightforward that the present value obtained $scghg_\tau e^{-R_\tau \tau}$ is the same as the one given by the equation (2).

A special case is worthy examining in more details at this stage. Consider a risk-free project, or a project whose net benefits are independent of economic growth. In that case, equation (3) simplifies to

$$PV = \sum_{t=0}^{+\infty} E[B_t] e^{-r_{ft} t}, \tag{7}$$

where the risk-free discount rate r_{ft} is defined as follows:

$$r_{ft} = -\frac{1}{t} \log \left(E e^{-r_t t} \right). \tag{8}$$

From this benchmark, one can observe that when projects are risky, their PV will be larger or smaller than the risk-neutral PV depending upon whether their net benefits are negatively or positively statistically linked to economic growth. More precisely, equation (3) directly implies that

$$\begin{aligned} PV &= \sum_{t=0}^{+\infty} E\left[B_t e^{-r_t t} \right] = \sum_{t=0}^{+\infty} \left(E\left[B_t \right] E\left[e^{-r_t t} \right] + cov(B_t, e^{-r_t t}) \right) \\ &\geq \sum_{t=0}^{+\infty} E\left[B_t \right] e^{-r_{ft} t} \end{aligned} \tag{9}$$

whenever the net benefit of the project and the stochastic discount factor covary positively. From the Ramsey rule (6), this is the case when the net benefit and consumption growth vary in opposite direction, i.e., are anti-comonotone. Inequality (9) states that the project has a negative risk premium in that case, i.e., its value creation is larger than if one would assume independence between its net benefit and aggregate consumption. The opposite result holds when they are comonotone.

2.2 Lessons from the standard approach

The tradition in the asset pricing literature is to value an asset as the discounted sum of its flow of expected benefits using a risk-adjusted discount rate:

$$PV = \sum_{t=0}^{+\infty} E\left[B_t \right] e^{-\rho_t t} \tag{10}$$

This approach is compatible with the SDF approach described in the previous section if and only the risk-adjusted discount rate ρ_t is defined as

$$\rho_t = -\frac{1}{t}\log\left(E\left[\frac{B_t}{E[B_t]}e^{-r_t t}\right]\right) \tag{11}$$

Further simplifications can be obtained by making two additional assumptions. First suppose that the net benefit of the project is linked to aggregate consumption through the following functional form:

$$\log\left(\frac{B_t}{B_0}\right) = a_t + \beta_t \log\left(\frac{C_t}{C_0}\right) + \epsilon_t, \tag{12}$$

where we assume exogeneity, so that $E\left[\epsilon_t \mid C_t\right] = 0$ for all C_t. Observe that we can interpret the project-specific β_t as the income-elasticity of its net benefit at date t. Second, suppose that aggregate consumption follows a discrete version of a geometric brownian motion so that $\log(C_t/C_0)$ is normally distributed with mean μt and variance $\sigma^2 t$. In that case, it is well-known that the risk-adjusted discount rate equals

$$\rho_t = r_f + \beta_t \Pi, \tag{13}$$

with risk-free discount rate $r_f = \delta + \gamma\mu - 0.5\gamma^2\sigma^2$ and aggregate risk premium $\Pi = \gamma\sigma^2$. This is the standard CCAPM approach to discounting. Under that approach, the project analyst has an a priori simple task to perform. The analysis requires estimating the income-elasticity β_t of the project to determine the risk-adjusted rate to discount the flow of expected benefits.

The most immediate one arises from the estimation of the beta. The income-elasticities need to be evaluated for each project. Moreover, the flow of benefits and costs of a project may include several distinct components (for example a financial one and some externalities). Each of these has a specific income elasticity that needs to be estimated, and gives rise to a separate risk-adjusted discount rate. In addition, some components may be the product of different factors. In this case, the corresponding beta is equal to the weighted sum of the income elasticities of these two components (for example, the benefit of an investment reducing transport times is proportional to both the value of time and the number of passengers).

And crucially, the standard asset pricing puzzles arising of the CCAPM must be addressed.[11] As mentioned in the introduction, over the last three decades, these puzzles have been resolved by considering different assumptions, generally linked to a better consideration of the risks involved, in particular by considering consumption growth processes that fatten the tails of the distribution of future consumption.[12] Bansal and Yaron (2004b) has pioneered a new literature on "long run risks" in which trend of growth reverses to the mean and in which growth volatility is itself stochastic.[13] Rietz (1988) and Barro (2006, 2009) showed that the inclusion of rare disasters in the growth process can also solve these puzzles. The effect of risk on the risk-free rate and the aggregate risk premium is at least one order of magnitude larger when taking account of these rare disasters than when limiting the analysis to the standard gaussian volatility.

It is often overlooked that these strategies to solve the puzzles of the standard CCAPM make it more complex to operationalize for project analysts. This is because the CCAPM formula (13) needs to be revised when exiting the Gaussian world. Indeed, as shown by Martin (2013), the efficient risk-adjusted discount rate becomes a polynomial function of the beta of the project, where the coefficient associated to the nth power of β is proportional to the $n+1$ cumulant of the annual change in log consumption. This clearly raises more complexity to the analysis. Another source of complexity comes from the observation that the coherence of the calculation requires the project analyst to estimate the flow of expected benefits EB_t by using the complex growth stochastic processes that have been used to estimate the risk-

[11] With a growth process calibrated on Western data over the last century, typically yielding a growth rate around $\mu = 2\%$ and a volatility around $\sigma = 3\%$ and using a CRRA of $\gamma = 2$, we obtain a risk-free discount rate net of the rate of impatience of 3.82% and an aggregate risk premium 0.18%. In particular this risk premium is so low that it makes sense in practice to discount all projects using a mean beta $\beta_t = 1$, yielding a universal discount rate of 3.82+0.18=4%, which is exactly what the Ramsey rule would tell us to do. Financial markets reveal much smaller risk-free rates on average (risk-free rate puzzle, Weil (1989)), and much larger risk premia (equity premium puzzle, Mehra and Prescott (1985)).

[12] Another path to solve the financial puzzle is to generalize the discounted expected utility framework into its Epstein-Zin-Weil extension. This approach raises two issues. First, Epstein et al. (2014) have shown that the calibration of EZW preferences necessary to solve the asset pricing puzzles generates a new puzzle, which is related to the implausibly large value of an early resolution of uncertainty. Second, under the veil of ignorance, risk aversion and the aversion to consumption fluctuations should be equivalent from a normative viewpoint, i.e., for public policy evaluation.

[13] See Gollier (2018) for a discussion on the link between stochastic volatility and the fourth moment of the distribution of consumption.

free rate and the aggregate risk premium. In practice, this is infeasible without allowing some shortcuts that have not yet been provided in the literature. Lastly, the relationship between growth and project benefit is not a priori as simple and direct as that described by relationship (12). The income elasticity can itself depend on the level of growth, and thus be very different whether we assume that the economic growth is close to the business as usual scenario on the contrary affected by possible catastrophic events.[14]

We retain two key lessons from this discussion. First, Gaussian volatility does not contribute much to asset prices compared to using a universal discount rate based on the Ramsey rule. Second, the recognition of the existence of a low-probability high-intensity macro catastrophe surrounding our collective beliefs has the potential to generate asset prices that are aligned with those observed on financial markets.

3 Basic project evaluation: stress discounting with two states of the economy

In the face of the failure of the standard CCAPM to generate a credible valuation system, given the complexity of departing from this generic model, should we go back recommending a universal public discount rate, as is the case in most countries ? We believe not, because the welfare cost of ignoring the social cost of risk in the economy is potentially large (Gollier (2024)). In this section, we develop an evaluation procedure based on the SDF methodology presented in Section 2.1. This alternative procedure aims at two objectives. First, we want it to generate valuations that approximate well the true value of assets and investment projects. Second, we want it to be simple, intuitive and easy to operationalize.

3.1 Methodology

We propose a procedure based on the SDF approach using only two states or scenarios, a BAU scenario and a stressed scenario. Because gaussian volatility does not add much to

[14] See for instance the case of a core infrastructure investment characterized by capacity constraints, treated in section 3 of Cherbonnier and Gollier (2022).

the analysis as shown by the asset pricing puzzles, we ignore it in our procedure.[15] Rather, relying on recent works on rare disasters, we base our procedure on the plausibility of a macro-catastrophe involving an immediate large drop in consumption followed by a durable lower growth rate. In the BAU scenario, consumption grows at a steady rate of g^b forever. The associated contingent discount factor is $\exp(-r^b t)$, where $r^b = \delta + \gamma g^b$.

In the stressed scenario, which occurs with probability π, consumption is immediately reduced in a proportion $\theta \in [0, 1]$, and consumption will afterwards grow at a lower steady rate of g^s forever. The associated contingent discount factor is $(1-\theta)^{-\gamma} \exp(-r^s t)$ with $r^s = \delta + \gamma g^s$. This is equivalent to discounting at rate r^s the net benefits inflated by a constant "boost" factor $\Delta = (1-\theta)^{-\gamma}$, which is larger than unity. Δ is the proportional increase in the marginal utility of consumption along the stressed scenario generated by the initial fall in consumption.

The project's present value should then be computed as follows:

$$PV = (1-\pi) \sum_{t=0} e^{-r^b t} B_t^b + \pi \Delta \sum_{t=0} e^{-r^s t} B_t^s \tag{14}$$

where B_t^b and B_t^s denote the flow of net benefits associated to the project in the BAU scenario and in the stress scenario respectively. Equation (14) fully describes our proposed evaluation system. Information needed for it is therefore:

- The rates of pure preference for the present (δ) and relative risk aversion (γ),
- the growth rates in the BAU and stressed scenario, g^b and g^s, with the size of the initial downward jump in the stressed scenario, θ,
- the probability of the stressed scenario scenario π,
- the flows of benefits of the project in each scenario.

We believe that this method is simple and intuitive. This makes the stress discounting method highly operational for project evaluation. Moreover, for a perpetuity with fixed

[15] The numerical simulation provided at the end of section 3.3. shows indeed that adding a Gaussian noise has a very marginal impact on NPV estimations.

δ	0	rate of pure preference for the present
γ	2	degree of relative risk aversion
π	4.36%	probability of the stress scenario
g^b	2.0%	growth rate of consumption in the BAU scenario
g^s	0.2%	growth rate of consumption in the stress scenario
θ	50.0%	initial drop in consumption in the stress scenario
r^b	4%	contingent discount rate in the BAU scenario
r^s	0.4%	contingent discount rate in the stress scenario
Δ	4.0	boost discount factor in the stress scenario

Table 1: Benchmark calibration of the evaluation model. The bottom three variables are derived from this calibration.

payments equal respectively to $B_t^b = \bar{B}^b$ and $B_t^s = \bar{B}^s$, it becomes:

$$PV = (1-\pi)\frac{\bar{B}^b}{R^b} + \pi\Delta\frac{\bar{B}^s}{R^s}, \tag{15}$$

where $R^i = 1-\exp(-r^i)$ is the continuous version of the conditional discount rate r^i, $i \in \{b, s\}$. From this valuation equation, it is easy to recover the key finding of modern asset pricing theory, i.e., of a positive (negative) valuation bonus for assets whose net benefit is negatively (positively) correlated with aggregate consumption. Indeed, define the unconditional expected net benefit $\bar{B} = (1-\pi)\bar{B}^b + \pi\bar{B}^s$, and the value $\overline{PV}$ of an asset yielding a constant net benefit $\bar{B}$:

$$\overline{PV} = \left[\frac{1-\pi}{R^b} + \frac{\pi\Delta}{R^s}\right]\bar{B} \tag{16}$$

It is easy to check that PV is larger (smaller) than $\overline{PV}$ whenever $\bar{B}^s$ is larger (smaller) than $\bar{B}^b$.

3.2 Calibration

The objective in this section is not to propose a definitive set of parameters for this method. It is up to public authorities to choose the parameters setting, in line with the tutelary values that have been defined beforehand. Thus, the calibration described in Table 1 is purely illustrative.

We assume a degree of relative risk aversion equaling $\gamma = 2$, the consensus regarding standard attitude toward risk being between 1 and 4 (Gollier and Hammitt, 2014).[16] We choose a constant $g^b = 2\%$, which corresponds to the trend of growth in the western world over the last century. Using international data on national macroeconomic catastrophes during the XXth century, Barro (2009) estimated an expected drop in GDP between 15% and 64%. We take $\theta = 50\%$. It remains to determine both the probability of the catastrophe and the trend of growth in the stress scenario after the occurrence of the catastrophe. Our stress scenario needs to be worse and longer-lasting than the Barro scenario, to account for the fact that it occurs only once and at the beginning. This translates into a sustained fall in growth, that can be interpreted as a Barro scenario combined with a Gordon-type pessimistic view on productivity gains (Gordon, 2016). In addition, it may be desirable that the asset prices that emerge from this calibration fit observed market prices, in particular the long run risk-free interest rate and aggregate risk premia. Hence, the remaining two parameters are set in order to match the following returns when applying the stress discounting method:[17]

- A risk-free rate $r_f = 2\%$ at a $t = 100$ horizon, consistent with EPA (2023)[18] and Arrow et al. (2014) describing the term structure retained for France, UK and the United States.
- An aggregate risk premium around 2% at a $t = 200$ horizon, consistent with long run risk premia under persistent shocks to growth in Gollier (2016)[19].

The probability of catastrophe must then be equal to $\pi = 4.36\%$, and the rate of growth in the catastrophic state must be equal to $g_s = 0.2\%$. All parameter values are summarized in Table 1.

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[16] $\gamma = 2$ is also in line with the French authority guidance, whereas the British authority has set this parameter to 1 (Treasury, 2020)

[17] More precisely, we choose parameters such that the present values given by equations 10 and 14 are the same. For instance, for the risk-free asset, it means that the present value given by equation 16 is equal to e^{-r_f} – with $\Delta = \bar{B} = 1$ whereas the rate r_s and r_g are given by the exact Ramsey rule.

[18] See Figure 2.4.1 p 60.

[19] See section 6, p 77, figure 2. It is also consistent with the observed equity risk premium once equity leverage is taken into account.

	contingent value		expected
	BAU	stress	value
Benefit	3	3	3
PV	0.41	9.86	0.82<1

Table 2: Valuation of a safe project in 50 years.

Under our procedure summarized by equation (14), the flow of net benefits materializing in the BAU scenario must be discounted at $r^b = 4\%$ per year. In the stress scenario, net benefits materializing in that scenario must be multiplied by a boost factor $\Delta = 4 = (1 - 0.5)^{-2}$ and must be discounted at rate $r^s = 0.4\%$. This quantifies in a transparent way the bonus allocated to projects whose net benefits materialize preferentially in the bad state of nature, on top of using a lower discount rate.

As an illustration of this method, let us consider a safe investment that imposes an upfront cost 1 today and generates a single benefit $B_{50} = 3$ in 50 years, which corresponds to an internal rate of return of 2.20%. In the BAU scenario with a contingent discount rate that is $r^b = 4\%$, the contingent PV of this benefit equals 0.41 that is less than 1, hence yielding a negative contingent NPV. On the contrary, in the stress scenario, the contingent PV of the future benefit equals $B_{50}\Delta \exp(-0.4\% \times 50) = 9.86 > 1$, yielding a large positive contingent NPV. In other words, if one would be sure about which growth scenario would prevail, this project should be rejected in the BAU scenario, and accepted in the stress scenario. From equations (3) and (14), the project should be accepted if the expected PV is larger than the upfront cost. It happens that the expected PV equals 0.82, which is less than 1. The project should not be implemented. We summarize these results in Table 2.

Consider now a similar project with a unit cost today and a single benefit in 50 years. It is a risky project which yields a larger benefit in the stress scenario than in the BAU one. We take $B_{50}^b = 2.9$ and $B_{50}^s = 5.2$, so that the expected benefit equals 3, as in the previous example. The conditional PVs are now equal to 0.39 and 17,09 respectively in the BAU and stress scenarios. It yields an expected PV of 1.12, which is larger than 1, so that it is desirable to invest in that project. These results, summarized in Table 3, illustrate again the hedging

	contingent value		expected
	BAU	stress	value
Benefit	2.9	5.2	3
PV	0.39	17.09	1.12>1

Table 3: Valuation of a risky project in 50 years.

value of projects whose benefits are negatively correlated with economic growth.

Getting inspiration from the analysis of Table 2 and Table 3, we can measure the rate at which one should discount safe benefits occurring at different maturities in a world whose macroeconomic uncertainty takes this 2-scenario nature. This is represented by curve "$\beta = 0$" in Figure 1. The parametric uncertainty surrounding the annual growth rate tends to make the term structure of the risk-free rate decreasing, as explained for example by Weitzman (2001) and Gollier (2016). This risk-free discount rate tends to $r^f = 0.5\%$ for very long maturities. But the risk of an immediate drop in consumption magnifies the short-term risk, which massively reduces the short-term interest rate. This yields a hump-shaped curve for the risk-free discount rates.[20]

Suppose that one would apply the standard present valuation approach in which expected net benefits would be discounted at a risk-adjusted rate. What discounting system should be used under this evaluation framework? In Figure 1, we also represented the term structures of the risk-adjusted discount rates that should be used to value a risky benefit $B_t = C_t^\beta$ occurring in t years, with $\beta = 1$ and $\beta = 2$. We use equation (11) to estimate this rates. These risk-adjusted discount rates are increasing in β and tend to 4% when β tends to infinity.

[20]In case the initial drop in consumption is removed from the stressed scenario, the discount rate for a maturity close zero becomes 3.59% for $\beta = 1$ and 3.84% for $\beta = 2$. In case there is no uncertainty at all in the stressed scenario, the discount rate simplifies to 4%.

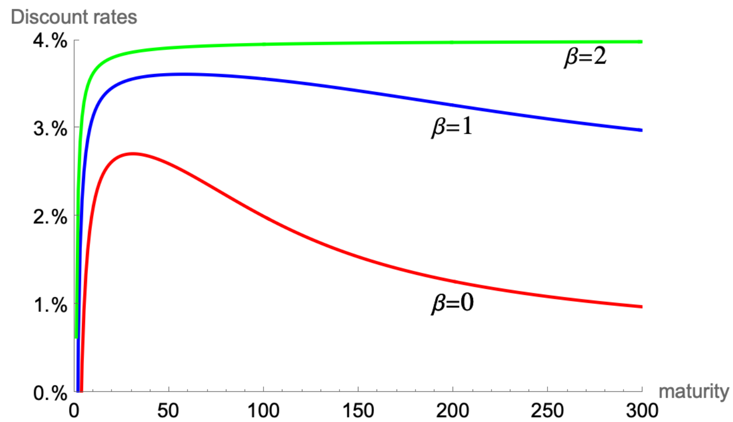

Figure 1: Term structures of risk-adjusted discount rates when consumption grows at 2% with probability 0.9564, otherwise it drops immediately by 50% and then grows at a rate 0.2%. We examine the case of a risk-free benefit ($\beta = 0$), or a risky benefit $B_t = C_t^\beta$, for β equaling 1 or 2.

3.3 Appraising the accuracy of the stress discounting method when the true growth process is i.i.d. with infrequent catastrophes

Our stress discounting method is based on a simple stochastic process in which the uncertainty is immediately resolved. This is of course unrealistic. However, basing it on a more realistic timing of the resolution of uncertainty would make the methodology much more complex. We tackle this issue of realism in section 3.5, by questioning the choice of the parameters retained. In this section, we assume that our beliefs about future growth yields a gradual resolution of uncertainty and we measure the valuation error of the stress discounting approach. We take as a benchmark Barro's model in which the annual growth rate of consumption is an i.i.d. process. In that case, the risk-free rate and the aggregate risk premium have a flat term structure. Each year, there is a probability π of a drop in consumption by a fraction θ. With probability $1 - \pi$, the annual growth rate is randomly selected from a normal urn with mean g^b and standard deviation σ. This stochastic process differs from our stress discounting modeling in two dimensions. First, Barro assumes that a catastrophe can occur every year, whereas we ignore any disaster beyond the one that could occur next year. Second, the growth rate in the BAU is noisy around its mean g^b. We know from the asset pricing puzzles of the CCAPM that this second dimension has a marginal impact on asset prices. In this framework, a future payoff $B_t = (C_t/C_0)^\beta$ materializing in t years has a present value equaling

$$PV_{Barro} = e^{-\delta t}\Big(\pi(1-\theta)^{\beta-\gamma} + (1-\pi)e^{(\beta-\gamma)g^b+0.5(\beta-\gamma)^2\sigma^2}\Big)^t. \tag{17}$$

We retain the parameters from Barro, that is $\pi = 1.7\%$, $\theta = 0.35$, $\sigma = 2\%$ and $g^b = 2.5\%$. Martin (2013) extended Barro's model in continuous time and by allowing θ to be normally distributed with mean b and standard deviation s.[21] We also set $\delta = 0$ and $\gamma = 2$ as previously.

In Figure 2, we estimate the value of a single payoff materializing in $t = 15$ years for different betas in the interval $[-1, 3]$. We compare the valuation obtained with the stress discounting method calibrated in the previous section with those obtained with those two "benchmarks" inspired respectively by Barro and Martin. We also enrich the stress discounting method by adding a Gaussian uncertainty (with volatility $\sigma = 2\%$).

Figure 2 suggests that the stress-discounting method provides a good approximation.[22] Indeed, the four methods give very similar present values, with a maximum difference between the present values computed with the stress-discounting method and the two others less than 10% on the range considered.

[21] $b = 0.39$ and $s = 0.25$ have been set by Martin to match the mean and variance of the distribution of jumps used by Barro.

[22] We consider here a relatively short horizon of 15 years because both the "Barro" and the "Martin" methods are not well-suited for long horizons as they assume independent and identically distributed (i.i.d.) shocks, and therefore a constant term structure. On the other hand, the stress-discounting method was calibrated to fit a decreasing term structure of the risk-free rate consistent with the literature.

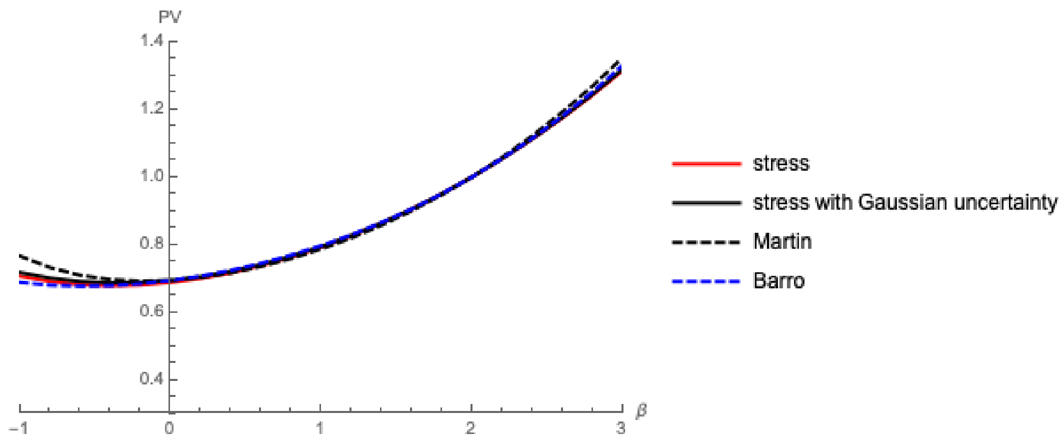

Figure 2: Present values obtained using different methods for a benefit at $t = 15$ years equal to C_t^β

3.4 Public policy relevance of stress discounting

We also compare the results of the stress-discounting method with those obtained by simple methods commonly used by public authorities that do not take into account the risk of the project. More specifically, we apply the methods used in France and in the United-Kingdom, which amount to discount the benefit C_t^β when there is a sure growth at a rate g_b, using the official tutelary values chosen for the discount rate. Over a medium-term horizon of less than 30 years, a constant discount rate equal to 3.5% is used in the UK (as we assume no health effects of the project), whereas the linear equation derived from the CCAPM is used in France with a risk-free rate equal to 1.2% and a macroeconomic risk premium equal to 2% (that is, $r = 1.2 + 2\beta$, see Guesnerie (2021)). Figure 3 represents the corresponding present values when β takes its values in the interval $[-1, 3]$ for two maturities $t = 15$ (left panel) and $t = 40$ (right panel). The discounting method used in the UK underestimates the present value when the beta takes low values (with differences that can exceed 50% for t=15) and overestimates it when the beta is high (in particular for $t = 40$). This comes from the fact that the UK method ignores both the insurance value of projects with a negative beta, and the additional risk borne by projects with a large beta. The method used in France overestimates the present value for low betas and underestimates it for high betas, also with differences of large magnitudes:[23] the role of the beta seems overestimated. It is relatively striking, because we are placing ourselves here on a relatively short horizon. Even then, failing to properly adjust the social discount rate to risk severely distort public investment evaluations undertaken today by governments around the world.

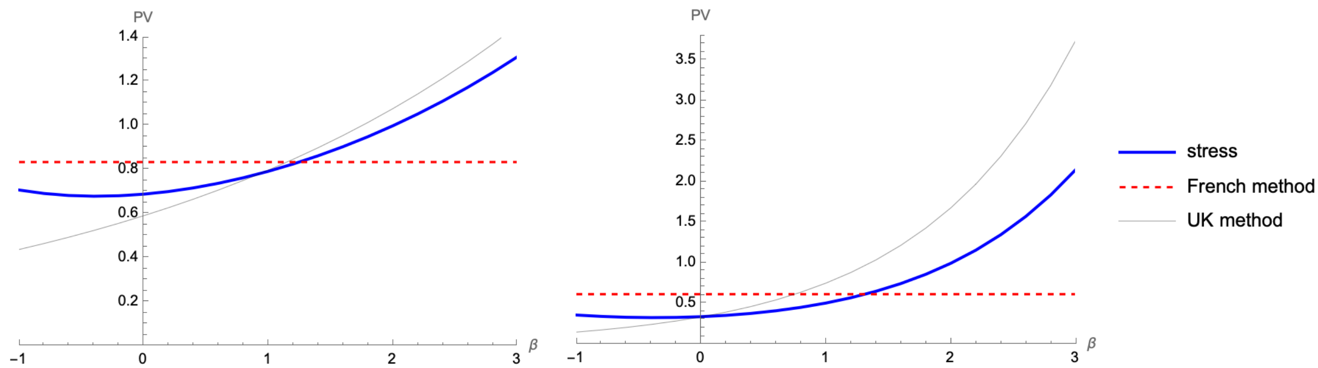

Figure 3: Present values obtained using different methods for a benefit at $t = 15$ (left) or $t = 40$ (right) years equal to C_t^{β}

3.5 Tradeoff between simplicity, precision and realism

Perfection is achieved, not when there is nothing more to add, but when there is nothing left to take away. Antoine de Saint-Exupéry

Two questions naturally arise in the face of the calibration presented above.

First of all, the worst-case scenario can be perceived as “unrealistic”. Unlike a Barro shock, there is no partial recovery in the economy, worse, growth is subsequently maintained at a level close to zero. However, this “unrealistic” aspect does not pose any practical problem a priori for evaluators in a public administration. Whether it is for example an investment in public transport or in a nuclear waste storage structure, as considered in the last section of this document, it is relatively easy[24] for them to recalculate his estimates concerning the

[23] The present values computed with the French method are flat as we consider an economy growing at 2% hence expected benefit grows at 2β % while they are discounted at using $r = constant + 2\beta$.

[24] By "relatively easy", we mean that it is probably significantly easier to value the net benefits in two deterministic scenarios than under uncertainty.

costs and benefits of the project in the event of economic stagnation following a negative shock.[25] Moreover, this subsequent low growth is necessary to obtain a risk-free rate and a long-term risk premium in line with the consensus. One could hope to calibrate the model by choosing the growth rate g^s in the stressed scenario closer to the growth rate g^b in the BAU scenario, and increasing the initial shock (θ) or its probability (π). However, this does not work as the risk-free rate obtained by the stress-discounting method described in this section tends towards r_s in the very long term (see equation (14)) with $r^s = \delta + \gamma g^s$. This requires a low enough g^s. In particular, if we choose the recent estimates from the EPA (2023) for the risk-free rate as a reference, this rate decreases to 1% before 2200 and reaches 0.5% in 2300. Since $\gamma = 2$, this would require $g^s < 0.25\%$ which is what we have ($g^s = 0.2\%$) in the calibration presented in this section. In other words, it is necessary for the stressed scenario to have a persistent impact on growth to obtain an increase in uncertainty over time leading to the decreasing term structure of the risk-free rate.

Secondly, what is the cost of limiting the number of macroeconomic scenarios for the sake of simplicity? To explore this question, we add one more scenario in the analysis. Instead of considering one catastrophic scenario occurring with a probability π in addition to the BAU scenario occurring with a probability $(1 - \pi)$, we study a case with two catastrophic scenarios. Adding a scenario should allow a more precise calibration: here we choose to calibrate in order to obtain a higher short-term risk-free rate (equal to 3% at 30 years) and a low very long run risk-free rate (equal to 0.5% over the 300-year horizon, as estimated by EPA (2023)). We arbitrarily choose that the second catastrophic scenario induces a sudden 50% drop in consumption, as previously, and that the first one does not induce any drop in consumption but results in a lasting decline in growth. Using similar notations, we therefore take $\theta_1 = 0$ and $\theta_2 = 50\%$. We calibrate the probabilities π_1 and π_2 of the two catastrophic scenarios and the subsequent growth rates g_s^1 and g_s^2 so that the risk-free rate is equal to 3%,

[25] This stress scenario is likely to be associated with changes in prices (though not as a result of the project that is marginal). This needs to be accounted for in the valuation that is done of the net benefits in this deterministic scenario.

1% and 0.5% at respectively 30-year, 200-year and 300-year horizons, and so that the risk premium is equal to 2% at a 200-year horizon. We then compare yield curves and present values obtained using the two-scenario and three-scenario stress-discounting methods.

Results are illustrated in Figure 4 with the parameter values given in its legend. It should be noted that, in the three-case scenario, the subsequent growth rate g_s^2 in the worst scenario is negative. The yield curves are correctly fitted to the calibration targets as shown in the left panel by the red and black curves representing the risk-free rate and the risk premium, respectively. Even if the short run discount rates are still not very realistic (which is not a critical problem as we consider investment projects with long- lasting costs and benefits, and the impact of discount rates is relatively marginal on short horizon), this issue is mitigated with three scenarios. The right panel shows the present value of a benefit at 15 or 40 years equal to C_t^β as in the previous figures. We see that the two estimations are very close for $\beta > 0$. The three-scenario method gives less value to projects with a negative beta. This can be explained by the fact that the intermediate scenario is much less serious than the worst-case scenario, and that the latter has a significantly lower probability than the catastrophic one in the two-scenario calibration. There is therefore less risk with these three scenarios than with only two, which reduces the insurance value of the projects with a negative beta.

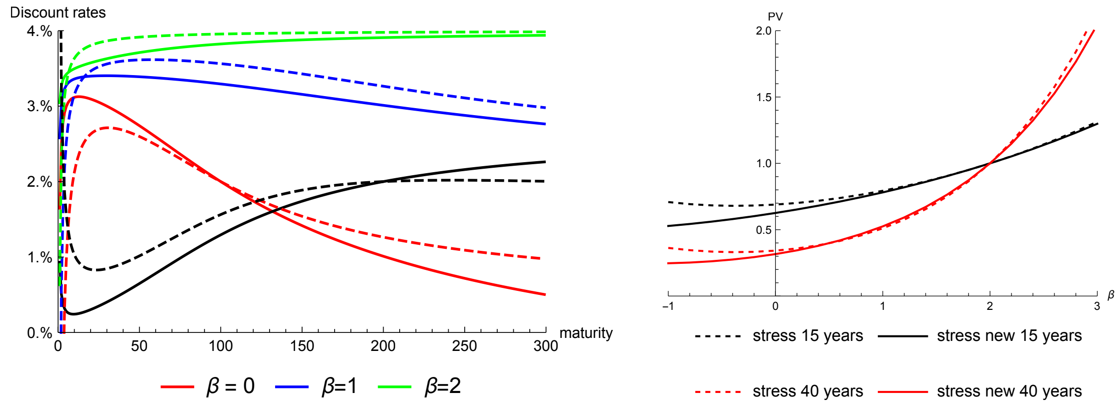

Figure 4: Comparison of the stress discounting method with two (dashed lines) or three (plain lines) scenarios. Left: Term structures of risk-adjusted discount rates for a risk-free benefit ($\beta = 0$), or a risky benefit $B_t = C_t^\beta$ for β equaling 1 or 2. The black curves represent the risk-premium. Right: present values obtained using different methods for a benefit at $t = 15$ or $t = 40$ years equal to c_t^β. Calibrated parameters for the three scenarios method are $\pi_1 = 16\%$, $\pi_2 = 0.6\%$, $g_s^1 = 0.4\%$ and $g_s^2 = -0.3\%$.

4 Application to a nuclear wastes repository project

In France, the second generation of nuclear power plans (1970-2050) will produce a total of 83,000 m^3 of nuclear wastes of high activity or medium activity/long life. The current policy project is to build a geological repository at a depth of 500 meters in the French Ardennes. The site will take 10 years to build, and the wastes will progressively be transferred in the repository over the next century, for a final irreversible closure around 2150. The flow of gross costs associated to this project is described in Figure 5, with a non-discounted sum of 25.5 billion euros. The code name of this project is Cigéo.[26] Its management has been delegated to ANDRA, the national agency in charge of nuclear waste management. There exist various alternative solutions to Cigéo. Many are either not technologically mature or prohibitively more expensive (Bouttes et al. (2021)). In this section, we examine the credible alternative of a Permanent Surface Storage (PSS). The PSS strategy consists in periodically repackaging the nuclear wastes to be stored on surface or subsurface, as currently practiced in

[26]For "Centre Industriel de stockage GEOlogique" in French.

all countries producing nuclear electricity. For France, the annual gross costs of PSS strategy are estimated at 100 million euros. Gross costs do not take account of the elasticity of these costs (labour, cement, land use, capital,...) to changes in GDP. Following (Bouttes et al. (2021)), we assume an income-elasticity of 0.8 for all costs. Notice that this implies that costs will be larger in the BAU scenario than in the stress scenario, and that Cigéo has no hedging benefit if we limit the analysis to the income-elasticity of these costs.

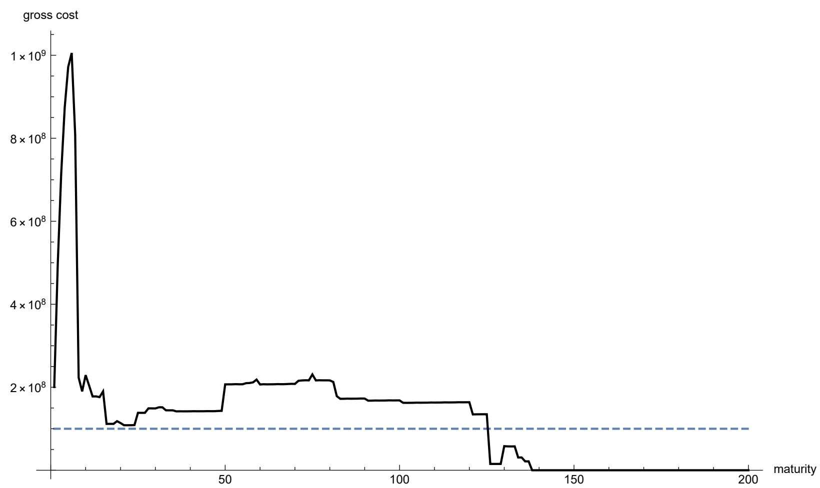

Figure 5: Flow (to be extrapolated to infinity) of the gross costs (in euros per year) of Cigéo (geological repository, plain curve) and PSS (surface storage, dashed curve). Source: ANDRA.

In Table 4, we summarize the stress discounting procedure to evaluate the competing options Cigéo and PSS. In the BAU scenario, the contingent PV of PSS costs is much smaller than the contingent PV of Cigéo costs. This is due to the observation that with a discount rate as high as $r^b = 4\%$, the PSS option is very attractive given the postponment of most expenditures. If one were sure that the BAU scenario would prevail, Cigéo should not be implemented. But the opposite conclusion should be made contingent to the stress scenario, because of the much smaller discount rate $r^s = 0.4\%$ combined with the large penalty $\Delta = 4$ to be used when evaluating costs in that scenario. When taking the expected value of these two pairs of contingent PV costs using the stress probability $\pi = 4.36\%$, we obtain a higher PV of the cost for Cigéo, hence an advantage for PSS.

	contingent value		expected
	BAU	stress	value
PV Cigéo	10.19	51.73	12.00
PV PSS	4.22	95.05	8.18
PV PSS with damages	4.22	242.23	14.62

Table 4: Valuation (in billion euros) of Cigéo and PSS costs. In the last line, we add a permanent flow of health and environmental damages $\bar{B}_s = 150$ million euros/year materializing in the stress scenario if the PSS option is implemented ex ante.

As a sensitivity analysis, we explore the consequences of a negative shock that occurs later: we have conducted a simulation where we have a 1.5% growth of over the next 20 years, followed by two scenarios either BAU or stress (with parametrization that is otherwise similar), generating a time-varying discount rate in the stress scenario.[27] As expected, due to the very long horizon considered, it does not drastically affect the results (see Table 5 in Appendix) .

An important piece of the story is missing in this comparison of the two options to manage nuclear wastes in the long run. The geological repository is used as a passive natural barrier to radionuclides. On the contrary, the surface storage of nuclear wastes requires an active maintenance to guarantee its safety. Cigéo has thus an important safety benefit compared to PSS, in particular in the stress scenario. Such a scenario is likely to be associated with a degradation of our democratic institutions and their ability to maintain the right level of supervision, protection and maintenance of the surface storage, as well as cope with the potential adverse consequences of a nuclear incident. To model this idea, let us assume that in the stress scenario, a permanent flow $\bar{B}_s$ of health and environmental damages is incurred by the local population if the PSS option had been selected ex ante. The contingent PV of these damages equals $\bar{B}_s\Delta/(1-\exp(-r^s))$. Multiplying this contingent PV by the probability π of the stress scenario yields the additional PV of costs of the PSS option. We do not have an estimate on this point, but it is logical to assume that the damage caused by a nuclear leak, induced by the abandonment of maintenance of the surface storage, is significantly greater

[27] The growth parameter of 1.5% is chosen so that the risk-free rate remains similar to that used for calibration, in particular, a risk-free rate of 2% over a 100-year horizon.

than the cost of this storage system. Suppose for example a flow $\bar{B}_s = 150$ million euros with an income-elasticity equaling one. The contingent PV of this flow in the stress scenario is about 150 billion euros. Consistent with equation (15), this adds about 6.5 billion euros to the expected PV costs, thereby inducing a preference for Cigéo. The safety issue associated to the PSS option means that Cigéo is an insurance for future generations, and Table 4 makes that apparent. Although the risk of a chaotic evolution of our society is small, Cigéo should be implemented because of its insurance benefit against the large health and environmental risk of the alternative option.

Imagine how the project analyst would have proceeded if asked to use the standard CCAPM approach to evaluate Cigéo, using PSS as the default option. This analyst should first estimate the CCAPM-beta of the net benefit of Cigéo. It would include the positive income-elasticity of the costs and the negative beta associated to the safety issue examined above. The global CCAPM-beta of Cigéo depends on the CCAPM-betas of all the costs and benefits of the project. Since costs, in particular, are of a different nature depending on the state of completion of the project (with mainly construction costs at the beginning -first 10 years- and costs of dropping the radioactive parcels later on -next 120 years) the global CCAPM-beta varies in time. This term structure of the beta should be used to determine the maturity-specific Cigéo risk-adjusted discount rates using the term structures of the risk-free rate and aggregate risk premia examined in Section 3. Then, the analyst should estimate the flow of expected net benefits of Cigéo, using the information about the distribution of future incomes and the income-elasticity of the costs that include health and environmental damages. Finally, this flow should be discounted using the maturity-specific discount rates. It will generate a positive NPV for Cigéo. However, this standard approach is complex and does not provide the essence of the argument for why Cigéo should be implemented.

5 Concluding remarks

Nearly no public administration around the world applies modern asset pricing theory to adjust the discount rate to projects' risk profile. Most of them recommends using a single discount rate. Ignoring the key role of risk in capital allocation is a serious source of inefficiency in resource allocation in our economic system. The OMB has released in 2023 a new version of the Circular A-4 which recognizes the role of risk in the evaluation of projects. It recommends to take account of each project's risk by discounting the flow of certainty-equivalent net benefits at that risk-free rate. However, this is unlikely to generate a coherent methodology as it completely ignores (i) the deep inter-relations in the price of time and risk in welfare economics, and (ii) the standard asset-pricing puzzles that any certainty-equivalent methodology would face.[28] Moreover, this circular has been revoked and the previous version that has been reinstalled does not address this issue. We recognize the challenges faced by any serious attempt to integrate risk and uncertainty in policy evaluation. In this paper, we propose a radical simplification of the valuation approach. One of the key messages from the recent economic literature is to recognize the role of extreme events, which have impacts on risk valuation that are one or two orders of magnitude larger than gaussian noises. From this observation, we propose to require evaluators to value projects under two radically different growth scenarios, either business-as-usual, or chaotic. This should forces them to recognize one key risk characteristic of projects: Do they generate more net benefits in the worse states of nature? Do they have an insurance benefit for Society? Providing them with two discount rates, one relatively large for the business-as-usual scenario, and one much smaller for the stress scenario (both consistent with the state-specific use of the Ramsey rule), the intertemporal welfare is increased by a project if and only if the expected NPV over the two scenarios is positive. Although it is imperfect because of the simplicity of the stochastic process describing growth, we showed in this paper that this simple and intuitive methodology will generate a much better allocation of capital than when using a single discount rate. However, in some cases it may be useful to consider more than two scenarios, in particular when considering carbon abatement projects where two types of risk come into play – economic and climate. We leave this for further study.

[28]In particular, in the absence of macro-catastrophes in the modeling of economic growth, the certainty equivalents are likely to vastly underestimate risk premia.

6 Appendix

	contingent value		expected
	BAU	stress	value
PV Cigéo	12.02	32.87	12.93
PV PSS	5.61	69.19	8.38
PV PSS with damages	5.61	179.95	13.22

Table 5: Valuation (in billion euros) of Cigéo and PSS costs when the negative shock occurs after 20 years. In the last line, we add a permanent flow of health and environmental damages $\bar{B}_s = 150$ million euros/year materializing in the stress scenario if the PSS option is implemented ex ante.

Do note that the costs in the stress scenario are lower compared with the ones obtained when the catastrophe occurs at the beginning. This is mainly due to the discount rate that is higher during the first 20 years.

This does not change the hierarchy between the two solutions, i.e. CIGEO remains more attractive once the flow $\bar{B}_s$ is taken into account. However, the gap is narrowing because the present value of those potential health and environmental damages is reduced (due to the higher discount rate during the first 20 years). Ultimately, this additional risk posed by the PSS, modeled here simply by the parameter $\bar{B}_s$, appears to be decisive.

7 Declarations

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