Social Discounting

Application to the Risk Management of Climate Change

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Executive Summary

A cost-benefit analysis plays a vital role in important social decision-making. The application of discount rates plays a crucial role in the quantitative portion of this analysis, especially when dealing with issues involving costs and benefits over prolonged periods, which is the case in the assessment of strategies, projects, and investments involving climate change considerations.

This analysis is conducted in the context of a social risk management process. After the expected amount and timing of relevant costs and benefits have been estimated, the weighting assigned to the amounts of expected costs and benefits of each year is made by the application of a set of discount rates, a process referred to as discounting, to reflect the effect and value of time. Where social externalities and co-benefits are involved (that is, costs and benefits not considered in prices in the private sector where one stakeholder's actions impose uncompensated costs or benefits on another party), a set of social discount rates are needed.

Social discount rates applied in a social cost-benefit analysis consider the effect on third parties, including costs and benefits of affected current and future members of the public. A social cost-benefit analysis relating to climate change is a particular social discounting application. Social discount rates applied in the analysis of mitigation and adaptation programs in anticipation of or response to the effects of climate change may differ from the analysis of other social issues because of several factors, including: (1) the social externalities involved, (2) irreversibility of greenhouse gas accumulations in the atmosphere and oceans, (3) its global nature, (4) the time periods involved, often measured in decades and even centuries, (5) its complexity, (6) its size and scope, potentially touching all human endeavors, (7) the uncertainties, especially with regard to tail risks associated with the timing and severity of effects, and (8) its social aspects. Because of the unique aggregation of characteristics of climate change, any analysis of its causes, mitigation efforts or its effects also involves ethical considerations.

The social cost-benefit analysis process includes a series of trade-offs between consumption today and unknown and potentially catastrophic damages in the (possibly distant) future. Because of the sensitivity to its long-term nature, the size of its effects and large amount of uncertainties involved, it is appropriate to use and communicate either a range of social discount rates or a range of values to which a single set of social discount rates are applied.

The objective of this paper is to discuss the factors that affect and should be considered in the development of social discount rates, with a primary focus on social cost-benefit analyses of climate change-related strategies, programs, and investments involving mitigation and ex-ante adaption efforts. These programs/investments involve both mitigation action and adaptation to possible effects of climate change, with the optimal mix differing by country and region. A social cost-benefit analysis included in a comprehensive risk management process can assess a combination of or a choice between mitigation and adaptation efforts.

Its intended audience includes actuaries and others involved/interested in climate change-related issues. This paper not only addresses the fundamentals of the social discounting process, but also some of the most contentious related issues raised, including the role of market rates, the treatment of social externalities, co-benefits, uncertainty, and the scope of the application.

The scope or range of issues addressed here can affect public (government) led projects that only involve the public sector and those public or private sector projects including those where actions in the private sector are driven by government rules or mandates. Nonetheless, many of the concepts discussed here may also apply to the analysis of private sector investments and to social issues with a long planning horizon other than climate change.

Many perspectives have been applied to social discounting, including those of a political and legal nature. However, this paper focuses on economic approaches described in a rich accumulation of literature, within which a wide divergence in views and opinions can be observed. Although actuaries have historically not been particularly active in discussions of this application of discount rates, their experience with discounting cash flows over long time periods in a broad range of applications indicate that they can provide valuable insight to this issue.

As evident by a review of relevant literature, there is no unique or consensus set of social discount rates applicable to climate change-related issues. Partly as a result, this paper does not leave the reader with a specific recommendation for such a unique set of these social discount rates. Rather, its goal is to comprehensively discuss the many considerations and approaches that can be taken to pursue this objective. It should be noted that, although attention is given to the entire cost-benefit analysis process, this paper does not directly address the corresponding estimated cash flows (or equivalents).

The key factors need to be considered in determining social discount rates cover a range of economic concepts, including market-based measures and intergenerational equity, as well as other ethical considerations. The paper concludes that, with certain exceptions (e.g., ex-post adaptation and short-term projects), market-based measures are not appropriate to use for this purpose.

Social discount rates should be less than those used by the private sector because: (1) social externalities and co-benefits are not generally considered in private sector transactions, (2) many significant factors cannot be monetized or be included in a discounted cash flow time-risk framework are important considerations, (3) the (almost) irreversible nature of climate change factors, (4) when future generations are involved, ethical considerations involve the implied social contract between generations, including provision for sustainability of human environment, (5) the global scope of mitigation effects, (6) the sheer size of, severity and long-term nature of the risks and issues involved, requiring in some cases aggregate analysis with especial attention to possible low probability tail events, and (7) the significant uncertainties involved, particularly since the trajectories of mitigation applications over the long-term future remain to be determined. Although not a preferred approach, the motivation for these factors could theoretically also be achieved by increasing the amount of the expected cash flows that the discount rates are applied to.

Economic formulations are covered, including the Ramsey formula, which is a growth model commonly used in the analysis of long-term investments covering multiple generations. Extensions of this formulas, primarily the extension relating to uncertainty, as well as concerns with its application are covered. In addition, the basis for two schools of economic thought (the descriptionists who rely primarily on market-based interest rates and the prescriptionists who rely primarily on ethical considerations) are discussed.

Because of the large amount of uncertainty that can snowball over time regarding the amount and timing of the effects of climate change through the level and volatility of climatic factors such as temperature and precipitation, both uncertainty, asymmetric risks, and risk attitudes need to be considered using hyperbolic (decreasing by duration) discount rates in a time-risk framework.

Due to their many high priority issues, governments may not allocate sufficient up-front investment in climate risk-related programs and projects involving either mitigation or adaptation. Nevertheless, a high priority should be given to addressing this important long-term issue, as indicated in social cost-benefit analyses. As a result of the uncertainties involved and many political and economic options available, analysis of flexibility regarding the timing of implementation of mitigation or ex-ante adaptation plans, the application of real options analysis can be used to assess the effects and desirability of a delay in taking such actions. The effect of these factors (e.g., in response to new information and new technologies, as well as the continued increase in accumulated greenhouse gases in the atmosphere and oceans until implementation of environmentally friendly implementation and resulting damages incurred) should be considered in arriving at appropriate and timely decisions.

The controversial measures of the social cost of carbon and carbon pricing are also discussed. A wide range of estimates of the social cost of carbon generated by the application of the Ramsey formula and expert opinion are illustrated, indicating the high degree of sensitivity of this measure to the choice of the social discount rate used.

Alternative approaches to stochastic modeling, such as scenario and sensitivity analysis and use of undiscounted values compared with relevant benchmarks, can supplement the quantification incorporated in a social cost-benefit analysis, in part to emphasize the importance of non-monetizable items in the analysis. Effective communication of results to the intended audiences, as well as the process, assumptions, and models used, are imperative, because of the complexity of the social cost-benefit analysis process, as well as the climate change process itself, and the many stakeholders and generations who will be affected by climate-related issues and risks.

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> *Global climate change unfolds over a time scale of centuries and, through the power of compound interest, what to do now is hugely sensitive to the discount rate that is postulated.*
>
> -- Martin Weitzman *2007*

Chapter 1: Introduction

1.1: Introduction to the paper

Public policy making requires decisions that (1) are based on objective assessments of the expected future and (2) will affect the future. Methodologies and metrics used, involving numerous assumptions, incorporate estimated costs and benefits spread over what may be lengthy periods of time. A key indicator underlying cost-benefit analyses is the present value of the aggregate of the estimates of, among other things, all net costs and benefits[1] to a single value at a single point in time. In a political context, the process involved is referred to as social discounting, which is the topic of this paper. A focus is placed in this paper on the management of the impacts of climate change[2] through government programs, mandates, and regulations as they apply to the actions of both the public and private sectors.

The objectives of this paper include providing actuaries a background on the significance of and considerations involved in deriving social discount rates. It is hoped that this will spur the profession to become further involved in the discussion of significant social issues that involve consequences over an extended period, an important example being the effects and actions associated with climate change.

There is a broad and clear scientific consensus that climate change has been and will continue to threaten the global environment and the welfare of many people and their property. As a result, there is a need to act to curb the drivers of these changes and to avoid or alleviate the harm that climate change has and will cause. These consequences, discussed in section 3.1, include increased temperatures, greater frequency of extreme temperature events and natural disasters, altered precipitation patterns, and sea level rise. However, because of the complexity of and uncertainty regarding the climate and consequential damage process, a wide range of future scenarios are possible, as well as human/governmental actions in anticipation and in response to this process.

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[1] Throughout this paper, references to ‘costs’ usually refer to outcomes with ‘net costs’, ‘net losses’ or ‘net damages’, as applicable, which can include a combination of positive and negative effects, as they aggregate into a significant adverse effect. Also, net costs and benefits can differ, in some cases materially, by geographic area and population segment.

[2] Although this paper primarily refers to “climate change”, it is the level, trend and volatility of climatic factors that constitute climate risk, rather than the change in the factors per se, that drive damages.

In spite of this need, actions that can be taken to meet this need have to be properly prioritized among the many worthwhile needs of society. A great deal of the debate concerning policy responses to avoid or reduce the adverse effects of climate change is not directed at the question of whether to act, but rather: (1) how much should be spent to eliminate, reduce, or defer the effects of these changes, (2) how much can be afforded for this purpose, especially in less developed countries, and (3) how quickly to take these actions. Lurking in the background of social risk management are the existence of social externalities and co-benefits, discussed in section 2.3, and the irreversibility of the effects of current environmental practice, discussed in section 3.4. An analytic framework, discussed in chapter 9 to reflect needed flexibility because of the uncertainties involved, resulting economic dislocations, and the lengthy periods of time involved.

Thousands of papers, articles, and books have been written over the last century about discounting in a climate change cost-benefit analysis context, in large part because of the considerable influence discount rates have on climate change decision-making. Despite this, a global consensus has yet to emerge as to the most appropriate analytical basis and discount rates to apply. It remains an important topic, as social discount rates that are excessive can result in giving inadequate attention to irreversible damages that will affect future generations, while if too low, they may overweight the far-distant future at the expense of today.

The principle problem is the timing mismatch involved, with most of the costs associated with climate change arising over a long time horizon, while much of the financing of preventive and reactive actions is needed in the near future when resources may be relatively scarce in the face of a broad range of more immediate needs. The objective of climate change risk management that this paper addresses is to determine an appropriate framework to assess the appropriate type, amount, and timing of resources to allocate for this purpose.

This paper explores the underlying concepts and considerations needed to understand the determination and application of social discounting, rather than hard-focusing on the derivation a unique numerical discount rate that would satisfy all involved stakeholders (who are society, businesses, communities, households and individuals), which in any event may be impossible to achieve.

This policy decision-making issue arises partly due to the avoidance of the recognition of the total cost of many products and services. Social risk management can be used to determine the strategies that should be implemented or a program/investment made to reduce these externalities.

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1.2: Discounting – why and how

> *The choice of the discount rate becomes decisive for the whole analysis. A low discount rate makes the future more important, a high discount rate is dismissive of the future.*
>
> -- Frank Ackerman, *Can We Afford the Future?*

Most people are by temperament impatient, not inclined to sacrifice current benefits or to avoid costs in the future, say in fifty or a hundred years. Therefore, almost everyone prefers policies and programs that generate immediate, rather than deferred benefits.

The fundamental issue that discounting (also referred to as deriving a net present value) addresses is how to aggregate and compare costs and benefits that occur at various times. The determination of net present values through the application of a discounting process is the standard approach to economic and actuarial valuations of future financial outcomes, as well as to contribute to the determination of allocation of resources between the short-term and long-term.

The purposes of discounting, according to the International Actuarial Association (2013), include:

1. Recognition of the time value of money;
2. Reflection of or provision for risk in projected future asset cash flows; and
3. Reflection of the opportunity cost of holding an asset (or expectation of earning investment income on wealth).

Discount rates can be used to assign a price to time. A real (nominal less inflation) return can be observed in certain financial markets. For example, the nominal return on 20-year U.S. Treasury bonds was 1.31% on June 10, 2020, with the corresponding real rate of -0.25% based on 20-year Treasury Inflation-Protected Securities (TIPS). This contrasts with the nominal pre-tax return on U.S. Baa seasoned corporate bond rate on June 10 2020 of 3.61%, with an average return on capital of about 6.5% per year over the last forty years.

By discounting, a single number or value is derived using a set of weights (discount rates) assigned to corresponding future points in times, multiplied by corresponding financial metrics (such as cash flows) or the welfare value (measured by an individual's or society's utility[3]) to households, businesses, governments, or generations. They are sometimes based on what has been referred to as pure rates of social time preference, which are used to determine a maximum of a social welfare function. This would be the discounted value of utility of consumption over a specified period, possibly including estimates for a given number of future generations or cohorts. The underlying principle is that individuals are impatient and value time, whether measured in monetary, utility, or consumption terms.

Arrow et al. (2013) described two bases for discounting future benefits: (1) consumption and (2) investment. The consumption rate of discount reflects the rate at which society is willing to trade consumption today for consumption in the future. The investment approach assumes that, if the rate of return on investment is positive, the value of an amount invested today is less than the equivalent nominal amount of benefits in the future. In this case, the discount rate is the annual equivalent rate of

[3] Note that the accuracy and application of utility functions has been criticized by some behavioral economists as being an abstract concept, which in reality is inconsistent with observed human behavior.

return on the investment. Given a fixed amount of total available investment capital, Arrow et al. assumes that increased demand for capital to support private sector climate change investments comes mainly at the expense of other private sector investments rather than consumption, while public sector climate change investments come mainly at the expense of other public sector investments. In addition, in contrast to evidence that the amount of investment is sensitive to interest rates, little evidence exists that current consumption responds to changes in interest rates.

A dual approach is also possible. In response to the needs and purposes of analysis and comparison, the U.S. Office of Management and Budget (OMB) Circular A-94 (2003) required projects involving intragenerational benefits and costs to be evaluated twice: once using a constant discount rate of 3% to approximate the consumption rate of discount (the social rate of time preference) when the rule primarily and directly affects private consumption and, separately, using a discount rate of 7%—an approximation to the real pretax average return on private capital in the U.S. economy, being an approximate cost of capital. If important intergenerational benefits are involved, a lower rate could be used.

Thus, a present value can be used to measure the relative price of similar goods at different points in time or to measure the real return on capital. Especially for the latter application, many corporations use the rate at which they can access market financing, their weighted average cost of capital.

The discounting process establishes a value or comparative values, which can incorporate subjective assessments and weighing of the qualitative considerations involved. Some think, since both intra and intergenerational issues (see section 7.2) are involved, that ethical (or social justice) considerations (see section 7.1) are central to the use and even the determination of assigned values. These considerations include the impact on directly affected individuals, as well as unspecified people including those not yet born, attitudes toward risk and uncertainties over time and space including who is to pay and who will benefit (direct and indirect stakeholders), and the value placed on health, life and property.

This process is made more complex because of the uncertainties associated with the future (see chapter 6), especially the distant future, whether the result of past or future actions. Many theories have been presented to explain the basis for discount rates that have been proposed or used. Most have dealt with supply and demand especially as they relate to market transaction prices, opportunity costs, the cost of capital or stakeholders' willingness to pay or exchange for a particular item. They can involve financial risks, including sovereign risk (in government debt), credit/default risk (as debt) or simple passage of time (intertemporal). The lack of trend or pattern in past rates of return is a purely empirical observation, which reduces the likelihood that a single underlying theory can be used to confidently project the past far into the future. The focus of this paper is not on these theories. Rather, it is on approaches and considerations that can be applied to construct social discount rates, although they are related.

In fact, there is no unique discount rate or social discount rate methodology applicable in all circumstances, although many have tried. This is evident by the thousands of papers on this issue, with no consensus in sight. It remains a multifaceted issue, affected by the perspective, objectives, values, and aversions of those writing the papers and conducting the discounting, as well as their interest in what is being discounted. Especially relating to issues such as climate change, the approach taken should consider the context and application.

Nevertheless, individual professions, such as economists and actuaries, have come to some general conclusions, some of which are discussed in this paper, although there will remain exceptions. In addition, political and personal views regarding competing uses of funds can affect the methodology or assumptions chosen, whether intended or not. Numerous studies have shown that not only can individuals value and discount goods and other resources differently, but these personal values can change over time.

Kane (2012) distinguished four types of discounting: (1) prescriptive pure time preference, (2) descriptive pure time preference, (3) opportunity cost, and (4) growth. However, he concluded that none of these alone can provide a sufficiently justifiable basis for discounting when setting policy for climate change, especially due to intergenerational implications and other ethical issues.

A challenge for a study or prediction of the future in any cost-benefit analysis is the need for simplifying assumptions, with incomplete, relevant, and reliable evidence. Transparency in the model and key assumptions (variables and their parameters) make it necessary to establish and maintain trust by its users in the results.

Especially because of the long timeframes and uncertainties involved and potentially enormous costs and benefits, the selection of discount rates has become a primary source of contention in the debate regarding climate change, as well as the make-or-break factor in policy and investment evaluations. Even minor changes in discount rates can alter policy recommendations regarding the trade-offs between immediate costs and uncertain long-term benefits. The use of a low discount rate increases the relative importance of the large future costs and benefits. If the discount rate used is relatively high, it may be difficult to justify policy or investments that impose costs on society today, but yields most of its benefits 50 to 200 years from now, because greenhouse gases persist in the atmosphere and oceans for a century or longer. Resulting losses and damages and corresponding mitigation and adaptation benefits[4] are measured on different time-scales from those of many other environmental issues, which makes any climate risk decision quite sensitive to the selection of the discount rate.

In contrast to the above discussion, there are some who do not believe that discounting is appropriate at all. They contend that it is impossible to collapse all relevant information and ethical considerations, such as intergenerational equity, into a single number – so one should not try. Although the author agrees that a single number cannot encapsulate all the factors necessary for a sound decision, this does not imply that a rigorously prepared quantification of the effects of climate change that considers the value of time and uncertainty is not relevant. Indeed, it is an essential tool for clarifying the key values-at-risk or that need to be agreed upon. For those who believe that discounting should not be considered, much of the remainder of this paper is not relevant. However, in an actuarial or economic sense, this position can create inappropriate bias and may result in findings that are not economically or actuarially warranted.

Key take-aways from section 1.2 include:

- Discounting is an important process used to recognize the effect of the value of time, especially when a long time horizon is involved;

[4] These not only can lead to a reduction in direct damages due to climate change, but also can include indirect losses and economic benefits generated by the transition to a reduced carbon economy (decarbonization), such as renewable energy industries (see sections 2.2 and 2.3).

- Discounting is expressed as an annual rate that reduces the value of a future item, say cash flows, from the end to the beginning of a time period; and
- There is no unique set of discount rates, as the discount rates may differ depending on the application and uncertainties involved.

1.3: Roadmap to the Paper

A summarized *roadmap* to this paper follows. The Introduction (chapter 1) provides overall background to the subject, including an introduction to the overall topic of discounting that addresses the question of why discounting is relevant (section 1.2) and this roadmap to the paper (section 1.3)

Part A begins the paper by addressing the social risk management process (chapter 2) – it is the over-arching context in which a social cost-benefit analysis is applied. After a general introduction to risk management is given (section 2.1), a discussion of social risk management (section 2.2) and important elements of the latter are given (social values and social externalities in section 2.3) and whether a marginal or aggregate approach is more appropriate (section 2.4). After this stage is set, the major application to which the paper is focused, the key elements of the climate change process (chapter 3) needed in the remainder of the paper is described, with particular emphasis on what is unique about climate change (section 3.3). In addition, the analysis of mitigation and adaptation approaches (section 3.5) to which social valuation as contemplated in this paper is applied is then covered. In developing appropriate discount rates, the context is always important. Note that there are several examples that involve climate change in chapter 2. Readers who aren't familiar with the basic concepts underlying climate change may benefit from a quick read of sections 3.1, 3.3 and 3.5 before reading section 2.

Part B addresses the social discounting process itself. Before it is described, basic principles of discounting are covered (chapter 4). Although most actuaries are familiar with this process, it serves as a baseline from which distinctions between social discounting and non-social discounting are made (chapter 5). Because much of the previously published discussions on this topic have been prepared by economists, chapter 5 also includes a summary of the major economic camps on this topic and the basic formula involved. These key economic viewpoints are presented to provide insight into the social discounting process (section 5.2) and why market-based rates may not be appropriate (section 5.3). Chapters 6 and 7 contain two essential elements that have to be considered in the determination of social discount rates – uncertainty and ethical issues, respectively, the latter of which includes intergenerational equity considerations (section 7.2).

Part C addresses several additional important issues involved with the social discounting process. In several actuarial applications, the structural debate is between the use of a level discount rate and a yield curve. In contrast, in longer-term discounting discussions, the structural debate (chapter 8) is between the use of a level discount rate and a hyperbolic (declining) set of rates (section 8.1.1). Other special issues also need to be addressed (in subsequent sections of chapter 8), including items that present difficulties in the application of discount rates, relevant time periods, and the scope involved (global or local). In addition, the effects of flexibility and optionality that may be available to the decision-maker confronting uncertainties through real options analysis (chapter 9) are useful to recognize. A discussion of a common application in the analysis of mitigation of climate change, the social cost of carbon, is provided in chapter 10.

Part D lays out several related practical issues. These include alternative approaches to the social discounting process (chapter 11) and practical considerations, including communication of its results (chapter 12). A brief conclusion ends this paper (chapter 13), followed by a list of **references**.

Because some readers may not be familiar with the language of climate change and risk management, a **glossary** of selected terms used in the paper is provided, along with two appendices providing a table of discounting rates and their effects, as well as a description of the shadow price of capital approach.

A. Climate Change in the Context of a Social Risk Management Process

Chapter 2: Risk Management and Cost-Benefit Analysis

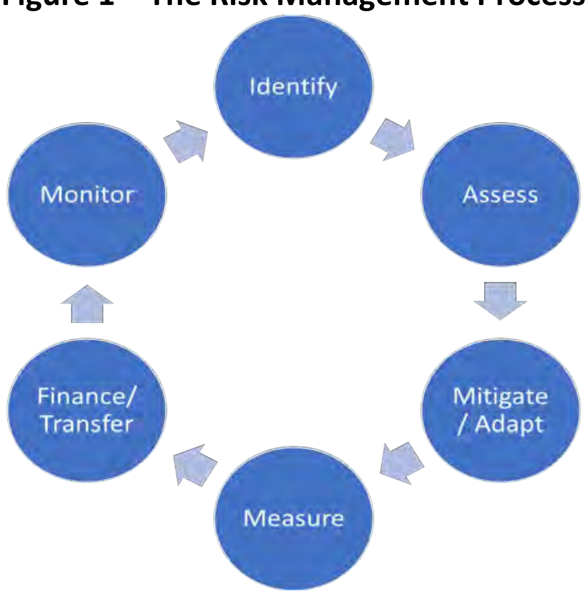
The purpose of this chapter is to discuss key elements of a social risk management process. It begins by focusing on the basic risk management process itself, together with its corresponding cost-benefit analysis in section 2.1. This is followed by an exploration of the special case of social risk management and social cost-benefit analysis in section 2.2. Section 2.3 describes the crucial roles that social value, social externalities, and co-benefits play in a social cost-benefit analysis, while the alternative use of marginal and aggregate approaches is discussed in section 2.4.

Although this process is applicable to the analysis of a vast range of environmental and other social projects and issues, this chapter draws on several examples that deal with climate change, which is further discussed in chapter 3.

2.1: Risk management process

Risk management is a process of identifying, assessing and controlling threats and opportunities that can arise from a wide range of sources, including environmental, economic and market factors. An illustration of the steps involved in this process is given in Figure 1. Not all risk management processes follow the steps in this sequence, and most such processes include feedback loops and multiple iterations.

Figure 1 – The Risk Management Process



A brief description of these steps follows:

- *Identifying* objectives and risks that may threaten health, income, or other resources, usually addressed through a planning process; vulnerable areas and stakeholders, as well as potential opportunities are also identified;
- *Assessing* risk probabilities and their expected severity and timing;
- *Controlling* through mitigation or adaptation to eliminate or reduce the probability and severity of losses or damages, as well as taking advantage of co-benefits and reducing co-costs;
- *Measuring*, by estimating the risks, costs, and benefits involved, as well as their timing on an analytically sound quantitative basis, supported as applicable by qualitative analysis, and being transparent regarding assumptions made enabling independent review; while in many cases precise answers may not be needed, estimates nevertheless should be as realistic as practical, with a range that is not overly wide -- otherwise they may not be trusted nor useful;
- *Financing and transferring/sharing* the risks and expected or actual costs, including those related to mitigation and adaptation, on an ex-ante or ex-post basis; and
- *Monitoring* to identify new risks and opportunities, monitoring risk appetite and developments, and recognizing/reporting on the effectiveness of the process itself, as well as measures in place and actual costs.

A cost-benefit analysis, as applied in a risk management process, is a structured approach that weighs the costs and benefits (advantages and disadvantages) of a policy or investment according to a set of specified criteria defined by the stakeholder(s) for which the analysis is being conducted, often comparing alternative courses of action or recommending the top-ranked projects (with the most beneficial outcomes at the lowest net cost) until available financing is exhausted. Usually, a comparison is made among several possible policies competing for a given amount of available resources (often including a benchmark or business-as-usual scenario), with a view towards improving the future. To make this as fair as possible, consistent (not necessary the same) methodology and assumptions are used. The economic choice would be the one with the highest net present value, reflecting the effects of externalities, co-benefits and other considerations, as applicable. It is used to optimize the value of the net benefits of strategies or projects.

It is important to recognize that the net present value is a single number in the context of what may be significant uncertainty. The range of probable net present values represents a characterization of extent of risks and uncertainties present. In many cases, therefore, the range of these values should be considered rather than just the single number (see chapter 6 for further discussion of the treatment of uncertainty).

Before beginning this analysis, the objectives and constraints of the applicable stakeholder(s) need to be identified, understood, and agreed to. According to HM Treasury (2011), a cost-benefit analysis quantifies in monetary terms as many of the costs and benefits of a proposal as feasible, including items for which the market does not provide a satisfactory measure of economic value. It includes a set of valuation techniques that enable priorities to be established among investment or program opportunities. The objective of the analytical process is to help maximize the expected value of net benefits and costs – probability or risk-weighted values of all possible outcomes, including possible tail results (e.g., disasters and windfalls) that may not be consistent with a pre-determined scenario.

It usually expresses quantitative results in terms of a single number at a defined point in time (evaluation date). Because costs and benefits are likely to occur at various times, an approach such as discounting (for time value) is crucial to derive an appropriate assessment. Expected marginal costs tend to occur early, while expected marginal benefits often occur later in the period covered. This attempts to place all relevant costs and benefits on a common temporal footing. Therefore, discount rates play a crucial role, since results can be sensitive to the discount rates used, especially when lengthy periods of time are involved. The use of lower discount rates encourages investors to adopt projects that offer returns over a long time horizon.

Correspondingly, a cost-effectiveness analysis is defined as an analysis that compares the costs of alternative ways of producing the same or similar outcomes or outputs. Standard private sector cost-benefit analysis practice is to use a large discount rate, often as high as 8% or 10%. This can work reasonably well in most cases (although by no means perfectly) in the private sector when selecting worthwhile projects and rejecting those that are not, as it often seeks relatively rapid returns.

A risk management process includes both quantitative (cost-benefit analysis) and qualitative elements, including opportunity and other non-monetizable costs. This process includes such steps as determining new or revised strategies, identifying inputs and relevant information needed and outputs desired, and measuring and monitoring possible associated risks and outcomes on an ongoing basis. Each step in this process can take several possible forms, depending on the risks involved and the situation, such as the source of information obtained, anticipated mitigation or adaptation actions, approaches taken in considering uncertainty in assumptions made regarding the future, the likelihood of successful implementation, and the application of leading-edge technologies and processes. Human, business and political behavior are important considerations. As inputs to the analysis, the user should understand its degree of risk aversion and a risk/reward tradeoff, as well as the willingness to pay[5] for use of time relative to other competing projects.

Most cost-benefit analyses conducted in the private sector only reflect the costs and benefits that are expected to directly affect the stakeholder conducting the analysis. In this case, the real expected return on capital is used to assess the relationship between the marginal cost of environmental or social actions and their discounted marginal benefits (in addition to distortions caused by taxes and uncertainties reflected in investment risk premiums). Such analyses conducted in the public sector consider additional costs and benefits (see section 2.2 for a discussion of this approach).

Expected costs that may be considered include: the amount and type of resources required, potential damages to property/life/health, hedging and counter-party possibilities and costs, transition costs, lost productivity, and opportunity costs (from the resultant inability to move ahead with competing projects that could provide a different set of goods or services). It includes both favorable and detrimental effects and the value associated with such effects. Expected benefits that may be considered include: loss reduction, increase in social welfare, increases in future revenue, reduction in uncertainty, and co-benefits.

In addition, these costs and benefits can include retroactive charges or constraints, e.g., as a result of stranded invested assets whose value may be impaired, especially in the case of natural resources that result in greenhouse gas emissions. Direct and indirect regulatory costs and risks can also be involved. Regulation can affect either the supply or demand side of fossil fuel use. The supply side involves the

[5] Measured from market transactions or surveys, reflecting in any case the preference of applicable stakeholders.

exploration and extraction of fossil fuels, while the demand side involves their combustion. Usually restrictions apply to emissions within a country's borders. For example, reduced demand tends to lower fuel prices, making exploration and extraction of fossil fuels sufficiently unprofitable that more fossil fuels remain in the ground.

Business models of many private sector companies have often not incorporated the expected future effects of costs, benefits, and risks associated with many environmental and social issues, such as climate change (e.g., the physical, decarbonization, and potential legal costs). However, with respect to climate change, an increasing number of power companies have incorporated an internal cost of carbon into their decision-making processes. These effects include the cost of adapting to the decarbonization process through what has been referred to as a 'just transition'[6] that can either be applied voluntarily in certain industry sectors or as a result of externally imposed mandates.

A wide variety of methods may be utilized. They range in complexity from a back-of-the-envelope to multi-year research effort – the quantification of long-term and social risks can be quite complex and take considerable time and resources. Techniques used can include the use of stochastic modeling or analysis of a range of scenarios, although it can be difficult to quantitively compare alternatives in a completely consistent manner. In addition, expert judgment is usually required, consistent with best practice in a transparent manner – in providing both quantitative input and qualitative context to the issue addressed.

Fredrick Hayek, a twentieth century economist, argued that technocrats do not know enough to properly weight benefits and costs. In spite of this concern, they may be the best to recognize associated uncertainties and to objectively obtain from the key stakeholders their views (see section 6.2 regarding attitudes toward risk). However, value assessments may have to be based on culture, beliefs, and subjective inputs, as appropriate.

It is important to assess asymmetries and tail risk (see section 6.3), that is, worst or near-worst (e.g., disaster scenario – under stressed conditions) outcomes, to ensure that the probability of their occurrence (but if realized the adverse consequences) is minimized and sustainability maintained. These can include economic, property, and social destruction. In contrast, there are some who do not believe that the tail should drive policy; rather, they believe that the expected value should be the driving metric, as long as a contingency plan has been developed to respond to emerging tail conditions.

As a result of significant uncertainty, it can be important to consider project flexibility through probabilistic and real options analyses (see chapter 9 for further discussion). In contrast, standard economic appraisals usually assess the performance of the project over its entire lifecycle without taking account of the value of needed flexibility and valuable delays, when warranted. Use of an unweighted average of the effects of possible outcomes among multiple scenarios can under or overvalue projects, because it does not consider the ways projects can be adapted to various scenarios as they emerge, nor the expected likelihood or timing of the scenarios. The life of a short-term or long-term strategy or a project follows a dynamic process, recognizing the desired need for flexible management, which normally consists of a series of decisions, responsive to changes in conditions, resulting from an ever-evolving world in which new information constantly emerge and unintended consequences and

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[6] Including costs of, for example, re-skilling (through life-long learning or new skill development) and temporary social safety nets for those who lose jobs as a result.

unanticipated results (surprises) regularly emerge. This is similar to an enterprise risk management (ERM) system utilized in the private sector.

If a sensitivity analysis indicates that the choice of discount rate is important (e.g., changes the sign of the project's net present value or relative ranking against alternatives), additional scrutiny of the discount rate used may be called for before a decision is made. This may deepen the understanding of the drivers of that uncertainty or warrant further research to reduce uncertainty and refine the estimates or judgments made.

Before exploring the bases and issues involved in discounting in subsequent chapters, it should be recognized that discounting is just one element of a cost-benefit valuation and process. Other major ingredients, components, and necessary inputs to a comprehensive cost-benefit analysis can include:

- a full understanding of the context of the item/issue under study and the interrelationships with other factors in the system;
- the amount and timing of expected cash flows or cash flow equivalents;
- the uncertainties associated with the amounts being discounted, for example, cash flows and the economic and demographic context;
- the present value of (discounting) these cash flows with respect to time;
- expected behavior of the relevant stakeholders, including political actions, under alternative scenarios, e.g., developed countries may reduce their carbon emissions, while changes in standards of living and thus energy use in less developed countries may increase theirs;
- consequential co-benefits and co-costs,
- expected changes in and effects of technology and national sentiment, for example, toward energy mix used and holistic cost structures, e.g., although batteries will lower greenhouse gas emissions, due to their heavier weight and electricity needs, electric cars may not generate the hoped-for amount of emission savings;
- cost of initiating and replacing infrastructure, especially in less developed and developing countries;
- consideration of qualitative and non-monetizable (non-economic) aspects (see section 8.2.1) and opportunity costs;
- subjective social, personal and political assessments and preferences of the stakeholder conducting the analysis;
- a willingness to take action, where applicable; and
- differentials in costs and benefits among the stakeholders, including those of different population segments and generations.

Time lags in implementing a project or strategy in obtaining results can be considerable. For example, just obtaining a consensus regarding desirable action regarding large social issues or projects can take years, if not decades. Some large-scale mitigation or adaptation efforts can also take that long, if not longer, to begin to achieve observable results. In assessing mitigation, the amounts and lags in costs and benefits of any related or supplementary adaptation efforts also should be considered in modeling or evaluating alternatives.

Key take-aways from section 2.1 include:

- A risk management process can be used to address many issues, originating in both public and private sectors.

- A cost-benefit analysis, usually the quantitative component of a risk management process, can also include qualitative elements, including useful ranges of probable scenarios and expert judgment.
- In most cases involving costs or benefit occurring at different times, a discounting process is usually incorporated in a cost-benefit analysis, which is often important because of the lags between implementation of the item being assessed and the mismatch between costs and benefits analyzed.

2.2: Social risk management and social cost-benefit analysis

Risk management practiced by the public sector is often referred to as social risk management, although certain elements of the latter can also be utilized by the private sector. The social risk management process generally relates to risks associated with a given population or society and is an application of ERM to a social issue. Similarly, a social cost-benefit analysis is a cost-benefit analysis that considers social externalities or a valuation of social value. This section discusses the characteristics of both social risk management processes and a social cost-benefit analyses.

There are common features and similarities between a cost-benefit and a social cost-benefit analysis. For example, a component of any cost-benefit analysis is an assessment of the extent that expected benefits can be achieved in an effective and efficient manner. Each can be used to evaluate both mitigation (to reduce the likelihood) and adaptation (to reduce adverse consequence) actions. In addition, the amount of resources society is willing to commit to a these programs critically depends on the value assigned to the expected sustainability of the expected benefits.

An example of a risk that can be addressed by means of a social risk management process is climate change, the nature of which is discussed in chapter 3. The reasons it is a useful example is given in section 3.3, particularly because of its potential long-term consequences. Examples of projects that might be assessed are those (1) whose objectives include limiting the amount of greenhouse gas emissions that can help mitigate against climate change and (2) that prepare for and protect against severe flooding, in an attempt to adapt to a time that future disasters might be caused by or be made more severe by climate change. Although applicable to climate change analysis, this process and analysis can also be applied in many other situations as well.

National or local mitigation and adaptation programs and strategies are becoming increasingly common. Although a social cost-benefit analysis is usually conducted over the expected life of the investment or strategy, it should extend beyond this period where longer-term consequential effects are expected. Examples include air and water pollution or litigation (see section 2.3 for further discussion of social values, social externalities, and co-benefits) as important elements of sound governance practice, section 8.2.1 that deals with non-monetizable items, section 8.2.2 regarding the time horizon covered, and section 8.2.3 for a discussion of geographic scope. In contrast, in the private sector where the focus is primarily on investment returns and direct costs of the immediate stakeholders, the scope and time horizon are relatively easy to determine.

A social cost-benefit analysis sets out in a manner similar to that undertaken by a private sector entity to determine whether a class of or a particular project or investment should be undertaken. In addition, it also considers factors relevant to the public domain, that is, contributing or resulting social and macroeconomic costs and benefits. In doing so, the values of these investments consider economic impacts, including their effects on growth in the economy, consumption, and jobs, as applicable. The economic factors used should be consistent with the discount rates used in the calculations.

Public policy decisions are usually based on more than just economic/actuarial analyses, but can also be influenced by qualitative considerations. For instance, in dealing with environmental issues, many considerations are of an intangible, qualitative, or non-monetizable nature (see section 8.2.1), such as those involving air and water quality, life and health, land use, coastal protection, food and water security, waste management, and disaster recovery, as well as the overall sustainability of the environment and, in the extreme, existential risks. The effects of governmental intervention should also be considered, which in some cases can incur costs for the private sector and create economic distortions. For example, although regulation may successfully address a market or other failure, it might also lead to significant compliance costs, which should also be considered in determining whether intervention is warranted.

Weighing the relative merits of quantitative and qualitative findings of a social cost-benefit analysis may be difficult, which can depend on multiple factors . Although in some cases the conclusion is clear from the get-go, others are controversial and challenging, especially in the practical reality of the public sector, which can be affected by political considerations. Decisions ultimately have to consider the benefit/value/possibility of investments supporting a growth strategy (e.g., current job creation and innovation), including such factors as the extent of enhancement of adaptive capacities and emission mitigation, such as a scenario with and without effective carbon capture and storage systems. Framing the climate change debate in terms of economic choices may help the process.

Situations in which both the public and private sectors are involved also arise, e.g., when the public sector imposes rules or requirements on the private sector, such as minimum mileage standards on the automobile industry, maximum greenhouse gas emissions for energy utilities, green-oriented agricultural practices, and investment restrictions on insurance companies regarding to the risk of stranded assets. Rules that require private sector action should consider the same factors as if the action were undertaken solely by government – a similar social discount rate should be utilized in both situations. In contrast, if the same analysis is conducted by the private sector to determine whether to participate in a public program, consideration of such externalities may not be relevant. Although a large amount of implementation costs can be involved, most of these costs are borne by the affected private sector businesses[7] and ultimately, in many cases, their consumers.

In the most general terms, the purpose of government is to manage risks of a non-personal nature to society within its boundary and assist (or in some cases, perform) the provision of public goods and services that are or will be useful to society's members. In planning and managing programs or rules to support this purpose, appropriate information and analysis is developed to formulate soundly-based policy decisions. This contrasts with the purpose of many businesses, whose primary goals are expressed in terms of factors such as its profits, employees, customers, and their own sustainability. It should be a goal of social cost-benefit analysis to enhance social welfare and encourage better means of price discovery and other incentives that can motivate private sector stakeholders to enhance the public interest.

[7] Although much of it may be able to be passed on to their customers because all such businesses are required to comply.

According to the HM Treasury (2011), the scope of government should include all consequential social outcomes, costs and benefits of a project or investment. It is necessary to assess and decide upon the objective(s) of the project or investment to determine the extent to which those objectives are expected to be met, as governments operate in an environment with many objectives, some of which are bound to conflict. It is desirable to develop an optimal mix of resources to meet these objectives in the best way possible given available resources. Often, the analysis conducted is a crucial input to the process of allocating limited resources[8].

The quantitative component of a social cost-benefit analysis forms the basis for normative action and in some cases, provides the time-risk framework within which ethical judgements and social priorities can be established, applied, and monitored. This can also provide the basis for an argument for or against public action that may involve complex public goals, often made by a governmental entity/authority or lobbying groups. If a discounted cash flow analysis demonstrates that a project has a positive net present value, then the project is welfare-improving, representing a sound use of resources. With an effective planning/budgeting system in place, specified criteria based on achievement of societal objectives are used.

These criteria enable comparisons of expected outcomes of alternative courses of action (such as the mitigation and adaptation of climate change, or a combination) with a business-as-usual baseline scenario. Attempting to save money by neglecting or minimizing mitigation action in the management of climate change risk and environmental protection will likely may prove to be false economies, at least over the long-term.

For public sector project appraisals, regulatory impact assessments[9] can provide input to a wide range of governmental or business decision-making. Regulatory impact assessments of large projects and important mitigation strategies generally apply the results of the development and application of the following four components (each consisting of a model). Climate models, for example, are developed based on available experience data and information and then run over prior periods, such as the past century, to compare their output to actual changes in climatic factors. They are then tested out-of-sample to determine whether they are able to replicate very different climates.

The models used in the analysis of a climate change analysis are usually run several times, each reflecting one of a range of scenarios or sets of assumptions:

1. Socio-economic and climate models, incorporating population and Gross Domestic Product (GDP) per capita projections that derive an expected greenhouse gas emission trajectory up to 2300;
2. A model to derive mean global temperatures from the climate change drivers derived in step 1;
3. A model to derive damage estimates from the climate model derived in step 2; and
4. An economic model to monetize damages and discount damages derived in step 3 to the present.

[8] Within the budgeting process, to assess approaches whose objectives are, for example, to increase security, reduce poverty, reduce debt or enhance the environment, human capital, or public health.

[9] For example, as required in the United States beginning in the early 1980s. In March 2017, a Presidential Order repealed guidance for factoring climate change into National Environmental Policy Act reviews. Thus, climate change is, at the time this paper was written, not to be considered in developing or revising environmental policy regulations by U.S. government agencies; there is no scientific reason for such an exclusion.

The outputs from this analysis could be used to derive a range of valuations, such as, for example, a social cost of carbon (see chapter 10) – both in terms of a benchmark (e.g., business-as-usual) scenario and sensitivities to alternative mitigation and adaptation efforts, as applicable. It can also compare against an objective (e.g., a given number of deaths per year or a maximum adverse impact in the tail of possibilities). It is fourth step and in deriving recommendations or the decision in which social discount rates play a crucial role.

Even if many projects prove cost-justified by themselves, available funds, either in total or for a type of use such as involving the environment, to resist changes to the climate (mitigation – such as a project that results in a reduction in greenhouse gas emissions), or to reduce environmental/health harm (adaptation – such as a project to reduce the impacts of climate-induced flooding or storms), may be limited. This leads to the necessity of ranking projects as to their desirability and approving projects to the extent that financing is expected to be available. It should be recognized that, at least temporarily, such investments may displace private or public investments or consumption, or alternatively reduce savings.

A social cost-benefit analysis can also consider the effect on economic growth. Climate change can affect both the level, rate of growth, distribution, and volatility of GDP.

- Some effects of warming will be permanent, e.g., destruction of ecosystems, extinction of species, and deaths from weather extremes.
- Growth rates are partly based on competing resources and crowding-out of other capital investments. Dell et al. (2009) showed that, based on fifty years of historical temperature and precipitation data for 136 countries, higher temperatures reduce GDP growth rates (a 1^{o}C degree increase in temperature reduced growth by 1.1 percentage points for poor countries). Using economic and financial market panel data for 147 countries between 1950 to 2007, Bansal and Ochoa (2011) found that increases in temperature have a strong adverse impact on economic growth - a one standard deviation shock to temperature of about 0.2^{o}C lowered annual GDP growth by 0.24%. Also, their modelling indicated that temperature-related utility costs represent about 0.78% of aggregate consumption, and the total cost of completely insuring against temperature variation would be about 2.46% of world GDP. In 2018, Carbon Brief (carbonbrief.org), based on 70 peer-reviewed climate studies, projected an 8% lower GDP per capital in 2100 if global temperature was 1.5^{o}C higher than pre-industrial levels and 13% lower if 2100 global temperature was 2.0^{o}C higher than pre-industrial levels, compared to a world with no additional warming.
- Since climate change primarily affects those who are vulnerable to its damages, who tend to be poor and less-advantaged, the effects on average GDP growth rates do not translate well to its effects on the well-being of many population segments.

Key take-aways from section 2.2 include:

- Social risk management is an extension, or if you will, a special case of risk management in general, as it takes a broader view of the stakeholders involved. Indeed, a primary purpose of government is to manage the non-personal risks to society.
- In the case of government applications, it also focuses on consequential risks, costs, and opportunities, commonly referred to as social externalities and co-benefits, as well as on the effects on economic growth and social well-being.

- Although social cost-benefit analysis often focuses on quantitative aspects, not every effect can be boiled down to an equation, which also requires consideration of qualitative and intangible aspects.

2.3: Social values, social externalities, and co-benefits

This section focuses on three factors of a social nature: social values, social externalities, and co-benefits. All of them are relevant to the social risk management process and in developing a social cost-benefit analysis.

The social value of an item or program, like the general concept of value that can be based on a subjective assessment of worth by an individual, a country, or a culture, is generally determined based on the value of the item or program to society. It is often established by public policymakers on behalf of a group of individuals who are similarly located, such as those who make up a country. If the social value of a proposed investment or strategy is sufficiently large, it is likely to be funded.

Four general types of managing social risks are:

- *Individual* – it is the responsibility of each individual to manage their own risks;
- *Community* – everyone in a community or population segment voluntarily attempts to protect everyone else in the community;
- *Hierarchical* – leaders manage risks by issuing orders; and
- *Fatalistic* – no one tries to manage risks.

Because of its public nature, the determination of social value, usually based on the second and third types, should be subject to sound social governance principles. These include, where possible, the use of an explicit methodology that is subject to external scrutiny and subject to public input. Sound governance usually leads to decisions that enhance social value, addressing the needs of all population segments, rather than focusing on the average or well-off individuals and businesses.

Since value is ultimately personal, there may be no unique number that is fully descriptive of social value that constitutes the aggregation of heterogeneous views, needs, and desires. Nevertheless, money has been equated to social value as a necessary expedient, although it has to remembered that each currency unit is not of equal value relative to the individual's or society's needs and value system. However, social value can be estimated in several ways, including:

- The difference between the application of the social discount rate (see chapter 5) and the application of the corresponding discount rate not considering social externalities (expressed as cash flows, cash flow equivalents or utils, at corresponding expected points in time) associated with or resulting from the economic activity studied, plus relevant non-monetizable items.
- The social discount factor applied to all applicable time intervals, multiplied by the expected social externalities at those times, plus relevant non-monetizable items.

The first approach is especially useful in the study of programs to combat climate change or its effects through mitigation or adaptation (see chapter 3). Although it is challenging to determine social values, they nevertheless can be useful in designing strategies to better society's life.

In the identification stage of social risk management, externalities, and co-benefits should be identified and later in the process be estimated (measured and quantified). If the risks include potential disasters, then a specific disaster risk management framework/plan/guidance for implementation should be developed and maintained.

An externality occurs when one party's action(s) results in uncompensated costs or benefits received by or given to another party. These costs or benefits are usually, but not necessarily, an indirect consequence of associated economic activity(ies) not reflected in the prices that would be charged for the activity on, say, an open market. These costs and benefits not involving direct stakeholders are referred to as externalities. An example of such a cost rarely included in private sector prices is the effect of greenhouse gas emissions or pollution whose cost the stakeholder is not directly held responsible for.

The set of externalities that this paper deals with includes social goods and services, as well as charges to ensure the sustainability of the environment and affected institutions, which in this paper are referred to as social externalities. However, since the costs associated with these externalities have to be borne by someone, they may ultimate be the responsibility of other parties or society as a whole. As a result, these externalities are rarely[10] included in the price or market value of goods or services or in a typical private sector cost-benefit analysis.

The effects of climate change include numerous social externalities. If, for example, a company does not believe it is responsible for the cost associated with its goods or services other than its cost of production, it will not incorporate its possible secondary or tertiary consequences in its pricing. A classic example is where, in absence of a tax or constraint placed by an external party such as government, a manufacturer or utility that produces pollution as a by-product of its production process does not consider in its price the cost of the health or property damage caused by the pollution. This is because the company does not expect to bear the costs associated with the pollution it produces.

Similarly, if carbon is an intended or unintended consequence of the activities of an industry, for example, a car sold or electricity produced, the price of the car or electricity will not incorporate the total external cost (i.e., the cost of climate change) it was responsible for related to the emissions generated. This is especially the case if most of the adverse consequences emerge years after the product is sold.

Some or all costs relating to carbon emissions could be incorporated in prices, a process referred to as *carbon pricing*. This price equals the estimated present value of the amount of the cost externality or the cost to voluntarily reduce or eliminate its carbon emissions by, for instance, installing effective emission control equipment.

Inclusion of these costs in the price of goods or services sold could provide the consumer an incentive to avoid or to modify socially undesirable behavior that is the result of damages caused by the production or delivery of the good or service, the so-called *tragedy of the commons,* for which global climate can be considered to be a prime example.

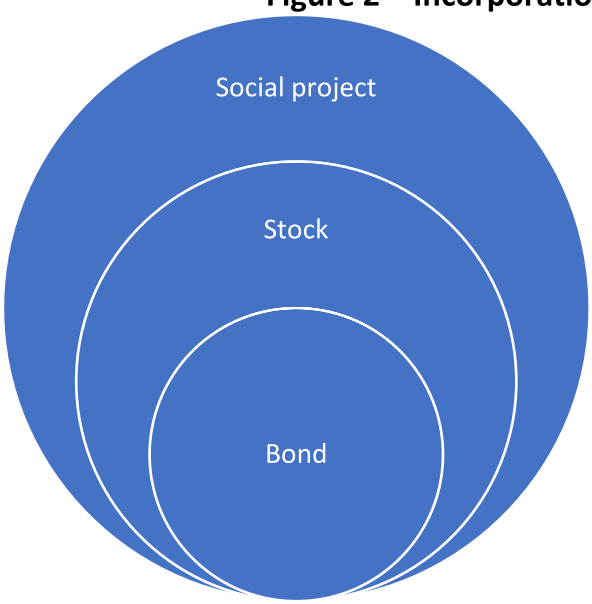
[10] Unless their cost is incorporated as an expected tax or external cost, e.g., as a result of a liability verdict or government requirement.

Interventions usually comes with a cost (e.g., electric power producers may have to install expensive scrubbers and air conditioners must be made with a more expensive or more efficient refrigerant) or certain jobs, such as those of coal miners, may be lost. So, the policy decision may have to be made based on a social cost-benefit analysis, that is, whether the benefits in terms of reduced environmental damage is at least as large as the costs associated with the policy.
These relations are illustrated in Figure 2: the small internal circle represents a closed-end activity in which expected cash flows to the immediate stakeholders are prescribed, such as a bond or good sold. The middle circle represents a semi-open-ended activity that incorporates additional cash flows – in the case of a public company, a stock that may provide for undefined possible future cash flows or a firm's net franchise value. In contrast, the largest circle also includes social externalities and net indirect contingent costs, such as damages due to climate change or liabilities that arise from a company involved in, say, coal mining or coal power plants.

As a result, greenhouse gas emissions have been referred to as a massive market failure because many transaction prices do not consider all associated costs (see chapter 7). Nevertheless, a public entity that will ultimately be responsible for the clean-up or mitigation of further damages should include these costs in its cost-benefit analysis. It is worth noting that, because of inequality and relative exposures, it is the vulnerable (those most at-risk) population segments that will tend to suffer the most.

Actuaries have generally dealt with closed-ended systems. Nevertheless, if asked what are the costs associated with goods or services, most actuaries would incorporate the consequential costs and benefits.

Figure 2 – Incorporation of social externalities



← Includes social externalities and related co-benefits, usually indirect costs, such as green-economy jobs

← Includes related contingent cash flows, e.g., net franchise value of a corporation or reduced air pollution

← Well-defined closed-end analysis

Particularly important in social cost-benefit analyses is the consideration and reflection of the effect of social externalities. These externalities can be expressed in terms of the costs and benefits that are a consequence, usually, but not necessarily, of an indirect nature, of the economic activity or good being assessed not reflected in the prices charged, which the purchaser of the output of the economic activity or good does not normally include or consider in setting a price for that activity or good.

To provide sufficient incentive to change behavior, the costs or benefits of the social externality need to be of sufficient size to grab attention and affect behavior. This can be addressed by law/regulation, taxation, social media messages, or public nudges. Examples include the cost of retraining individuals affected by mine closings, health effects of air pollution, litigation against emitters and the interests of future generations. The total cost of fossil-fuel energy includes pollution-related health problems over the short term and climate change over the longer term. Using taxation (referred to as a Pigouvian tax[11]) may encourage the reduction in the use of carbon emissions more efficiently than a regulator could do by diktat.

Externalities may occur as expected or arise unexpectedly. That is, they may be volatile or follow trends due to unanticipated drivers. For example, an environmental lawsuit may assign legal responsibility for damages to third parties when none was anticipated. In addition, costs and benefits that are social externalities can be the result of secondary or tertiary causes. For example, air pollution[12] can be reduced by means of a reduction in use of coal-generated energy production, an approach also used to mitigate greenhouse gas emissions.

Before co-benefits are discussed, it should be pointed out that internalities[13] are similar to externalities, but their costs or benefits are incurred by the person or entity involved, generally after a long period of time or are currently overlooked. For example, smoking cigarettes or drinking sugary drinks before the fact that they cause ill-health had been established.

In comparison to a social externality, which directly or indirectly results in consequential costs (net losses and damages) outside the direct cost of the good or service, the concept underlying a co-benefit[14] represents a favorable side-effect of the program or strategy being analyzed. It might also be considered a subset of social externalities. These are generally indirect benefits or costs. Reducing carbon emissions (directly caused by, for example, the power, transportation, or agricultural sectors) may at the same time reduce noxious emissions that play a role in many premature deaths resulting from air pollution. In this case, the benefits from reduced pollution would be included in the social cost-benefit analysis conducted to assess the costs that could be avoided by mitigating climate change through reduction in greenhouse gases.

Certain technological innovations in the energy space, such as wind power energy generation, can lead to enhanced energy security through increased energy diversity and ultimately reduced fuel costs, while at the same time being a secondary/tertiary cause. Investments in green-energy can not only reduce carbon emissions, but also begin or enhance entirely new industries, create jobs and grow economies, as well as more effectively using existing resources and adding to economic and environmental

[11] A tax on an economic or market activity or item that generates negative externalities, the effectiveness of which depends upon the level of competition and substitutability of other goods or services, as well as possibly legitimizing bad behavior. Pigou (1920) identified the general problem and solution.

[12] Air pollution is a result of emissions of greenhouse gases such as nitrogen oxides (NOx) and sulfur dioxide (SO_2) that contribute to the formation of fine particulate matter (PM2.5, with a diameter smaller than 2.5 micrometers).

[13] In the remainder of this paper, overlooked, especially those occurring after a long period, are included in references to externalities.

[14] A co-benefit can be favorable or unfavorable (a co-cost), both of which are indirectly related to the item being analyzed.

sustainability. In the analysis of how much resources should be allocated to these energy sources, their relative benefits and related costs are usually considered on a net basis.

Co-benefits (and co-costs) that are a direct result of the strategy, rule, or investment being assessed should be included in a social cost-benefit analysis. Decisions with respect to what is a co-benefit of a direct or secondary/tertiary nature need to be made on a case-by-case basis, although general principles should be established with respect what constitute such a relationship, that is, the strength of its cause-and-effect nature. It is appropriate to assess the strength of the relationship, for example, between climate change and pollution, and pollution and health outcomes. Although preferable to confirm causality, it may be appropriate, after robust transparent independent review, to incorporate those outcomes with strong associations.

These secondary effects might include changes in poverty, wealth creation, labor force participation, consumption, and economic performance/growth. A natural disaster can have significant adverse macro-economic effects. They may take the form of one-time effects, accompanied by offsetting experience in the subsequent period (recovery), or a permanent change. The type of effects may depend on the type or severity of the climate change. In a social cost-benefit analysis, it may be difficult to combine the physical, economic and health effects. Although all are important to consider, they may be best analyzed and disclosed separately to enable effective and relevant decision-making.
The effect of discounting on an analysis is evident if co-benefits are observed earlier than climate change benefits. Politically, it is easier to obtain financial support for initiatives expected to yield a return more rapidly, such as pollution or job creation, compared with climate change itself, with its longer lag period. The benefits of addressing climate change are mostly enjoyed by future generations, while co-benefits can also accrue to current generations (i.e., the electorates that assess their judgment upon current policymakers).

An example of a secondary/tertiary benefit that initially can be difficult to estimate can be gleaned from the assessment of technologies used in the development of the U.S. space program, whose consequential benefits included huge advancements in areas such as improved weather forecasting and miniaturization, which were not likely to have been foreseen or quantified when the program began. There are also potential add-on benefits from herd immunity when assessing the value of a vaccination. Other possible co-benefits include avoidance or reduction of consequential impaired health; food, water, and land insecurity; human suffering after forced emigration; national insecurity; and legal liability.

A social cost-benefit analysis should attribute these co-benefits in an appropriate manner, reflecting applicable probabilities of achievement estimated in an objective and supportable manner, in both setting initial objectives and monitoring performance. This can avoid allocation bias in the findings of a social cost-benefit analysis. In addition, especially since differences in opinion regarding how far-removed certain benefits may be, transparency about the source of these benefits and the amount included (or, indeed, excluded) from the quantification is necessary. Double counting costs or benefits is inappropriate.

The inclusion and estimation of the value of benefits from co-benefits can be controversial, especially if they are difficult to monetize with precision. An example is the December 2018 proposal by the U.S. Environmental Protection Agency (EPA) to not consider the benefits of reducing adverse health conditions as a co-benefit, which in this case was the favorable health effects resulting from a decrease in fine particulate matter that would otherwise adversely affect air quality that occurs when a plant emits mercury pollution. Although the EPA did not contest that there were potential adverse health results involved in current practice, it expressed the view that secondary costs of difficult-to-quantify effects or non-monetizable conditions such as those linked to heart and lung disease did not in this case represent co-benefits that should be incorporated into the quantitative component of a social cost-benefit analysis that form the basis of public policy decisions. There does seem to be a close relationship between the emissions in question and life and health-related costs caused by the emissions (see section 8.2.1 for a further discussion of the difficulties in using the valuation of adverse health conditions and premature deaths in a social cost-benefit analysis).

Key take-aways from section 2.3 include:

- Social value, even though subjective, represents the framework of a social cost-benefit analysis and determinant of whether a project or strategy is appropriate and acceptable.
- A key and necessary component of a social cost-benefit analysis is the inclusion of the value of social externalities and co-benefits, especially if their drivers are shared. It is necessary to determine that they are attributable and related to the issue being analyzed.

2.4: Marginal and aggregate approaches

In most cost-benefit analyses, indeed in almost all private sector analyses, only marginal costs and marginal benefits are considered, that is, fixed or sunk costs and benefits are considered. This is because the investments involved consist of relatively small changes in the overall environment. In contrast, in assessing something as large as climate change-related strategies, costs associated with some of the possible adverse scenarios can be so large that the costs and benefits cannot be considered only on a marginal basis. In such cases, the aggregate effects and interrelationships between the total valuation and between projects also need to be considered.

Even when carrying out a marginal cost-benefit analysis, care is needed when selecting the marginal unit of analysis to be selected. For example, it may be inappropriate to examine the effect of an hour's rate of emissions when the number of operating hours per day doubles as a result of the planned investment. Instead in this case, the marginal unit should be the change in the daily amount of emissions.

Sunk costs[15], such as costs already incurred to comply with a current climate change-related rule, need not be considered in either a marginal or aggregate approach in a social cost-benefit analysis. However, in a review of existing compliance requirements applicable to a business segment, the question of how to treatment fairly those already both in operation and in compliance and new entrants, or in industries producing substitutable products can arise. Although a decision would have to be made on a case-by-case basis, what is important from a social point of view is to require a similar outcome (measured by mitigation or adaptation), independent of the business involved. Regarding the treatment of fixed costs, a marginal cost application would not include fixed costs, while an aggregate approach would.

[15] Costs already incurred that are not recoverable.

Some (e.g., Stern 2015) contend that the scope and effect of climate change will be so large that marginal approaches otherwise used must be modified to assess the aggregate effect[16] of the project or policy using aggregate approaches, including the costs and benefits resulting from economic-environment feedback loops involved in responding to climate change risks and a social welfare function to compare results. The risks include such factors as adverse effects on health, living, ecological conditions, property damage, and reduced productivity, as well as heightened uncertainty.

Observations regarding factors considered in an aggregate cost-benefit analysis include:

- *Application*. The analysis of aggregate versus marginal costs applies to the entire risk analysis and not just to a particular section of the analysis.
- *Fixed and sunk costs*. Relevant future fixed and previously sunk costs and benefits would be considered in an aggregate analysis, while in a marginal analysis only future variable or marginal costs would be included;
- *Factors considered*. Although the manner that factors are considered may differ depending upon the size and breadth of the project being assessed, the same factors on a net basis (costs and benefits) would be considered; the net cost of any subsidies would be considered under either an aggregate or marginal approach;
- *Baseline scenario*. The baseline scenario would be the same under both an aggregate or marginal approach;
- *Transition costs*. If not a one-time investment (e.g., decarbonization – the change from a carbon-based to a renewable energy-based environment), the cost-benefit analysis would include applicable direct and indirect transition costs;
- *Lifecycle costs*. The entire lifecycle of the project/investment/policy and their consequences (that is, including social externalities and co-benefits, e.g., health costs caused by pollution or climate change from coal mining and environmental or liability cost of decommissioning a nuclear plant) would be considered;
- *Relation between segments*. If it involves a segment of an industry, it may be appropriate to consider the effects on the remaining segments; for example, if a fossil fuel (hydrocarbon) powered plant is needed to supplement renewable energy sources because of inconsistent or volatile sun or wind patterns in the absence of an adequate energy storage process, fixed cost associated with maintenance of the fossil fuel plant can increase the average cost considerably, thus increasing aggregate costs;
- *Relation between the economy and the environment*. Interrelations between the effects of overall economic performance and direct environmental damage that affect the analysis need to be considered.

It is difficult to determine the exact point at which a switch from a marginal to an aggregate approach should be made. If in doubt, the cost-benefit analysis should be conducted both ways to determine the significance relative to the findings. An opportunity cost assessment in a cost-benefit analysis should assume the investment or program has been undertaken. To the extent that the project (or series of investments) being considered affects the equilibrium interest rate, the discount rate used should consider the resulting rate.

Key take-aways from section 2.4 include:

[16] The total difference in effect on the economy with and without the effect of climate change, possibly determined through the use of a general economic model. The importance of this is highlighted by the fact that about 80% of global energy use is provided by fossil fuels.

- The size and scope of the costs and benefits involved in analyzing climate change investments, programs, and strategies can be sufficiently large to require aggregate, rather than marginal costs and benefits to be considered in a social cost-benefit analysis.

Key take-aways from chapter 2 include:

- A cost-benefit analysis (1) consists of both quantitative and qualitative components, including some costs and benefits that may be difficult to estimate, (2) is usually conducted on a marginal basis, and (3) is part of a risk management process;
- A social cost-benefit analysis, in contrast, is a study of a social issue or project involving the public interest, usually conducted from a public-sector perspective, including social externalities and co-benefits, with a focus on social value;
- A social cost-benefit analysis can be applied to a wide range of social issues and projects—the issue primarily addressed in this paper is the analysis of what can be done in anticipation of the effects of climate change, although similar analysis could be applied to public and some private decision-making;
- Social discount rates are used in a social cost-benefit analysis;
- Models address the amounts and types of greenhouse gas emissions, resulting climate changes, resulting damages, and economic valuation;
- A range of possibilities is addressed in a cost-benefit analysis, typically either through stochastic or scenario analysis;
- Social externalities include secondary costs and benefits that are outside the direct costs and benefits of a program or project in view of the stakeholders involved and timeframe considered;
- Co-benefits are considered in carrying out a social cost-benefit analysis, especially if their drivers are shared; and
- The size and scope of the costs and benefits involved or at-risk will determine whether a marginal or aggregate analysis is appropriate.

Chapter 3: The Climate Change Process

The purpose of this chapter is to provide an overview of the climate change process and associated risks that are useful to understand the characteristics, considerations and nuances involved in the overall climate change social risk management process. It is hugely important, since climate itself is a global public good that affects all of humanity. A proper background to climate risks and the climate change process (section 3.1) will also aid in the development of a social cost-benefit analysis relating to climate change and to provide an appropriate analytical time-risk framework for analysis of climate-related investments and strategies. It also describes the distinction between the major greenhouse gases (section 3.2), the characteristics of climate change that may warrant its own treatment (sections 3.3 and 3.4), and mitigation and adaptation (section 3.5), the key types of approaches to reduce climate change risk and damage.

3.1: Climate change

An understanding of the basic underlying processes and relationships between greenhouse gas emissions and the overall climate process is useful in understanding the discussions throughout this paper. Greenhouse gases tend to accumulate relatively uniformly around the globe. As a result, climate change represents a global issue (see section 8.2.3) and greenhouse gas emission reductions have become a public good. The overall climate consequences of a ton of emissions of a given greenhouse gas does not depend on the location of the source, whether within or across national borders. A shift in emissions source between locations does not change the extent or effects of global climate, although damages do differ by geographical area.

Although the basic science of greenhouse gas effect is straightforward, estimating all its future effects is not. Greenhouse gases, including CO_2, trap heat within the atmosphere, which prevents it from escaping into space resulting in a greenhouse effect (first identified in 1824), which in turn affects Earth's climate and conditions in the air, on land, and in the oceans. It is the current scientific consensus that human intervention will be needed to avoid further climate changes and to reduce some of their adverse consequences on life and the Earth. At extreme levels (high or low) of concentration, greenhouse gases in the atmosphere can be deadly. The accumulation of gases increases the temperature of the atmosphere and oceans, also threatening natural sinks, like forests and plankton, that have historically absorbed a great deal of these gases.

The United Nations Framework Convention on Climate Change's 21st Conference of Parties' (UNFCCC's COP21) Paris meeting in December 2015 has garnered wide public support for the universally agreed objective to limit global temperature increases to 'well below' 2°C above the pre-industrial average. The Intergovernmental Panel of Climate Change (IPCC) Fifth Assessment Report (2013) concludes with 'virtual certainty' that: (i) the past three decades have been the hottest in 800 years (and likely ever in human history); (ii) the Earth is in positive radiative imbalance (absorbing more of the sun's energy than releasing it); and, (iii) human activity (primarily greenhouse gas emissions) is a significant cause of these historical anomalies. The evidence since has confirmed these scientific views.

The average global temperature in 2020 is currently about 1.1°C warmer than it was before the Industrial Revolution began. The world is on course to exceed 3°C of warming by the end of the century unless significant mitigation action is taken in excess of current national commitments.

Climate is a persistent condition, involving complicated and lagged inter-related factors and feedback loops, such as between ocean temperature, atmospheric and oceanic CO_2 diffusion, CO_2 absorption, and heat absorption by clouds)Not only does it affect temperature, but also other climatic factors such as precipitation, which in certain adverse scenarios might combine to result in such conditions as flooding, subsidence, droughts, spread of disease, food insecurity and famines, deglaciation and water insecurity, and sea level rise[17], as well as reduced productivity of capital and growth, and in turn consumption. Both the level and volatility of these factors are affected. In the aggregate, they constitute potential systemic risk that may affect, say, entire industries or population segments.

The damages from and interactions among these factors, trends in which are often non-linear[18], may involve tipping points and be affected by the heat capacity of the atmosphere and oceans, as well as

[17] Temperature rise will expand the water in the oceans, which is also suffering from increased acidification, due to melting of ice that was once on land; as a result, sea levels have risen by about 25cm since the 1900s and may rise far more rapidly. The possible collapse of vast ice sheets covering Greenland and West Antarctica (the latter has ice that has been estimated to be equivalent to three meters of sea level rise).

[18] For example, as pointed out by Kay and King (2020), the damage from an 80 miles per hour wind is more than twice as great as a 40 miles per hour wind, with outcomes sensitive to initial conditions that cannot be known exactly in advance. The climate system is known as a chaotic system.

being affected by feed-back processes. Warmer air can hold more moisture, thus boosting rainfall, which could in turn cause damage through worsened floods and more severe cyclones that carry with them more rainfall. The time lag between emissions and major damage that will result from today's greenhouse gas emissions might involve years, decades, or even centuries.

Recently, such changes appear to be happening more often as temperatures rise and other climatic factors change. For example, in some cases what was previously estimated to have a 1.0% probability of occurring in a year, now is estimated to have a 4.0% probability in a year[19]. Lehmann et al. (2018) indicated that heavy rainfall events now occur more frequently (regionally, up to 37% more) than they did forty years ago in most of the world, except in Central Africa, where record-dry months have become more common.

Despite these changes in risks, not all the damage from natural disasters can be attributed to climate change. However, it is expected that an increasing percentage of damages will be more, if not totally, attributable to climate change, e.g., which was the case for the lengthy Siberian heatwave of 2020. Care is therefore needed not to overestimate the cost of climate change by including in the associated costs an estimate of all net damages from all climate-related disasters.

Nevertheless, attention to climate change-related net costs may better focus attention and financing toward all climate risk costs, especially for adaptation purposes. For example, the analysis of desired investment aimed at reducing flood risk[20] would appropriately include all costs (and benefits) associated with flood prevention and adaptation, whether or not flooding would be in part or totally due to climate change.

The timeframe over which the effects of climate change can emerge can be categorized as being sudden or slow-onset. The former can be observed by the form of some of the recent increases in the number and severity of natural disasters and storms and will become even more evident if and when a climatic tipping point is reached. They can also include such physical risks as extreme temperatures, precipitation, and increased diseases. Those from a slow-onset condition will involve a longer gestation period or process and can include a condition, such as higher sea levels, increased ocean acidification, or desertification.

The time lags involved have resulted in some viewing the effects that have been widely publicized as being overly-alarmist, although the threats are real and the time it takes to 'fix' the drivers of the process is lengthy. In addition to the consequential costs associated with climate change, indirect economic/social costs will arise, include the effect of a rapid increase in demand for environmental services and safe land and buildings due to climate change, which may lead to a higher than otherwise expected cost for those resources.

A diagram of the climate change process is shown in Figure 3. The process begins with key drivers of greenhouse gas emissions, which are influenced by the size of the population, the size and stage of economic development, and technological changes, all driven by the relative efficiency of energy generation, transportation, and agriculture. Mitigation efforts in this context can reduce the amount and

[19] For flood event risk for the Houston region, as estimated by the National Oceanic and Atmospheric Administration in September 2018.

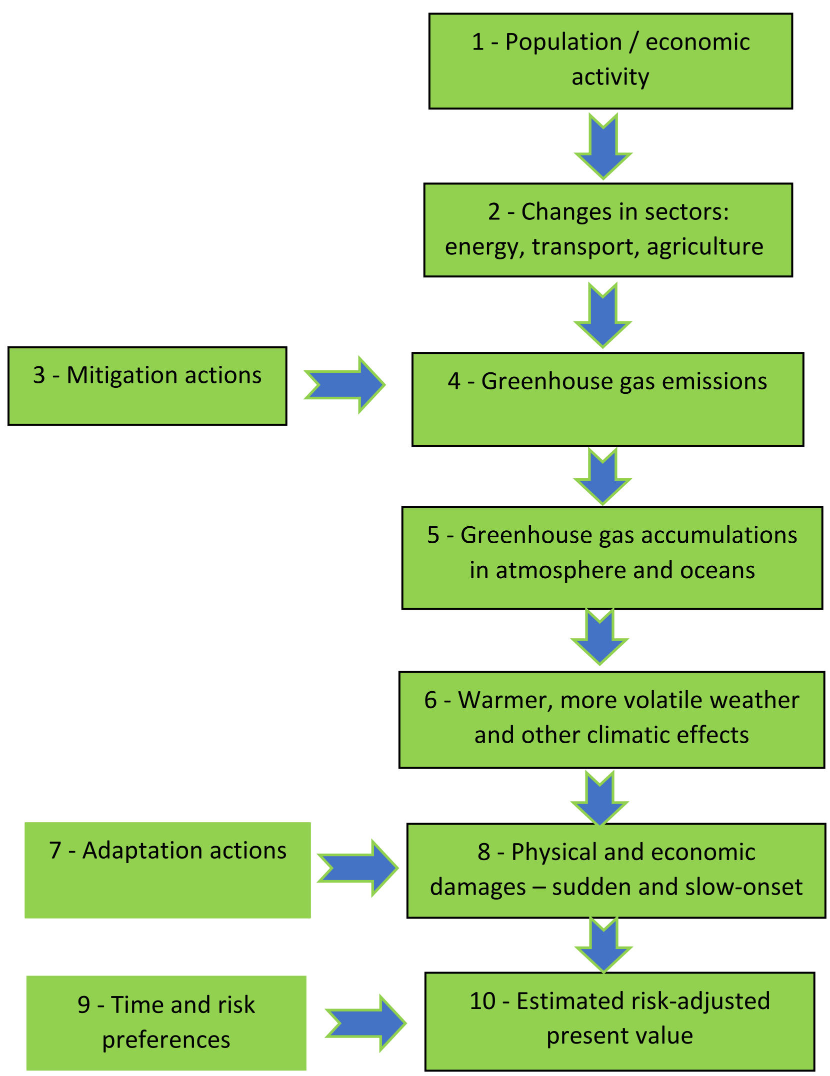
[20] See "Flood Risk", a paper (2019) of the Resource & Environment Working Group of the International Actuarial Association.

type of emissions. In turn, emissions result in the accumulation of greenhouse gases in the atmosphere and the ocean, which can be remain for decades and even centuries.

The net effect of this accumulation results in increases in global atmospheric and oceanic temperatures (among other aspects of climate). This in turn can result in damages from both or either sudden or slow-onset climatic conditions. A society can decide the extent and timing of adaptation to these changes, either prior or after an adverse local effect, although they may have limited choices. The valuation of expected damages by location or groups of locations can be expressed as a social value through the application of applicable social discount rates and uncertainty.

Feedback loops and uncertainties are inevitable among each of these steps. The time, interactions and uncertainties involved, both in the steps in the process and lags between the emissions and ultimate damages contribute to the adverse cost associated with the effects of the social externality of these processes.

Figure 3 – Climate change process



A brief description of the steps shown in Figure 3 follows:

1. *Population and economic activity*. Changes in the number, characteristics and behavior of people and economic activity can drive the amount of greenhouse gas emissions. In addition, the use of technology is among other factors involved.
2. *Changes in sectors: energy, transport and agriculture*. The volume of activity of these sectors are the intermediate factors that are driven by population and economic activity, which in turn drives the level of greenhouse emissions. They can be difficult to decarbonize.
3. *Mitigation actions*. Actions taken to reduce or eliminate greenhouse gas emissions.
4. *Greenhouse gas emissions*. As indicated in sections 3.1 and 3.2, these, among other factors, contribute to their accumulation in the atmosphere.
5. *Greenhouse gas accumulations in the atmosphere and oceans*. An increase in these accumulations can affect global temperature and other climatic factors.
6. *Warmer, more volatile weather and other climatic effects*. Together, these affect human life and property every day and over the long term.
7. *Adaptation actions*. These actions are intended to eliminate or reduce the adverse losses and damages that result from climatic factors.
8. *Physical and economic damages – sudden and slow-onset*. The losses and gains from climate change can have physical and economic consequences.
9. *Time and risk preferences*. These preferences, which can differ by stakeholder, affect the derivation of climatic-related values.
10. *Estimated risk-adjusted present values*. These are the economic values of the outcomes of the climate change process, adjusted for time and uncertainty.

An often-used metric for overall climate change is expressed as the long-term increase in average global temperatures, such as an increase of 2°C over an estimate of the global temperature over the pre-industrial period. However, such an aggregate measure does not capture the true nature of climate change that can differ significantly by region, and can be far greater and more volatile in a local area. These and other differences, including differing effect among population segment and individuals, are captured by a quote attributed to William Gibson, the science fiction author, "the future is already here – it's just not evenly distributed".

The use of an Integrated Assessment Model (IAM) is the most common scientific approach to assess the net cost of climate change. IAMs usually consist of a multiple equation simulation model[21], consisting of three major components: (1) a model that estimates future climatic factors by means of demographic, economic, meteorological, and geophysical factors, as well as their interactions, (2) a model that estimates losses and damages based on the results of the climatic factor estimates, and (3) a valuation model that estimates the value of the losses/damages. IAMs consider the complex interactions between the underlying drivers and other factors involved. An IAM can be used to estimate the amount of optimal reduction in emissions, considering their resulting costs and benefits. Another application is the calculation of the social cost of carbon (see chapter 10). Disaggregated techniques are also used,

[21] IAMs usually include a large number of variables. Many incorporate uncertainty by using either Monte Carlo (stochastic) simulations or fully stochastic programming techniques. Since at least some aspects of these models are random, a stochastic model (or one or more of its components) is repeatedly estimated to generate a range of possible outcomes to provide an estimate of represents a reasonable distribution of outcomes. Monte Carlo studies can provide insights regarding the order-of-magnitude effects of the relationship among and uncertainties associated with multiple model parameters.

explicitly estimating the effects and costs on lives and economic activity, including the effects of environment degradation or investment in mitigation/adaptation.

Broadly speaking, these damages affect both (1) economic activities and (2) natural and human systems. In most economic assessments, damage from climate change can arise by means of reductions in and changes in patterns of economic activity or consumption. These directly reduce social welfare, often expressed in terms of the constant relative risk aversion (CRRA) utility function that is a function of consumption. Usually, the larger the economy, the greater the amount of greenhouse gas emissions, although recently more efficient technologies and mitigation efforts have modified this relationship in some cases in some developed countries.

Losses and damages can be categorized into the following four categories:

1. *Physical risks*. Direct costs associated with adverse effects on physical resources, such as life, health and property, as well as indirect or consequential costs;
2. *Transition risks*. Financial costs that can result from the process of moving towards a lower-carbon economy, referred to as decarbonization (International Actuarial Association 2019);
3. *Liability risks*. These potential litigation actions against businesses or governments can result in financial costs by parties who have suffered loss or damage from the effects of climate change and who seek and obtain compensation -- individuals and organizations have filed more than 1,300 lawsuits between 1990 and May 2019 around the world against businesses and governments, most seeking to strengthen climate policies or enforce existing ones, more than three-quarters of which were in the United States, with the vast majority filed since 2006 (Setzer and Byrnes (2019); and
4. *Economic risks*. There can be considerable loss of economic and business activity, and can include loss of economic and business activity, as well as reduction (or reduced growth) in GDP, productivity and employment.

An increasing percentage of extreme weather events has been attributed to climate change. For example, in a set of studies published by the American Meteorological Society (2018), sixteen out of seventeen extreme weather events (e.g., heat, drought, flooding, and ocean-driven events) in 2017 were either the result of or at least its likelihood had been increased by human-caused climate change by at least half. For instance, the analysis of the record-breaking heat wave that devastated Europe and the Mediterranean in 2017 found that such events are now three times as likely as they were in 1950, with the chance of such an event occurring in a given summer now at 10%. The co-editor of this report indicated that the warmer the Earth's average temperature gets, the greater the sensitivity of weather is to the change. This strongly suggests that climate change is both a future and current risk.

Although most of the discussion in this paper involves the implications of adverse results from climate change, especially in the short- and medium-term, the effects of warmer temperatures benefit certain areas of the globe, particularly in areas away from the equator. In certain areas, sunk cost investments in mitigation activities may outweigh the present value of the irreversible effects of that investment. In addition, climatic factors can affect people differently, depending on such factors as geographical area, degree of mobility, demographic characteristics, and income.

Nevertheless, overall, significant damage has already resulted from recent climate change, including an increase in the severity of natural disasters such as lengthy droughts and wildfires. Over the last several decades of increased study of climate change damages, estimated damages have continued to increase. Currently, nothing has been reported that suggests that these estimates will decrease in the future. This is a problem confounded by significant and ubiquitous sources of uncertainty regarding how much worse it will get over the long time horizon.

Key take-aways from section 3.1 include:

- Climate change is a process, involving fundamental drivers such as population and economic growth, affected by both the use of technology and political will. It is also affected by human-driven mitigation efforts.
- Adaptation, both before and after an adverse event or condition, will affect the amount and type of damages that result from the climatic factors driven by the accumulation of greenhouse gases.
- The valuation of the resulting damages is based on estimates of damages, often derived from an IAM, using stochastic modeling and scenario analysis, both of which incorporate present values expressed in terms of a time-risk framework.

3.2: Distinction between carbon dioxide, methane, and pollution

Up to this point, reference has been made to climate change driven by the accumulation of greenhouse gases. The two major contributing types of greenhouse gases[22] are carbon dioxide (CO_2) and methane (CH_4) emissions. For the purpose of this paper, there are two main differences between them: (1) intensity – methane is a much stronger and more intense contributor to accumulated emissions than CO_2, estimated as being about ten times as intense and (2) duration – CO_2 emissions stay around far longer in the atmosphere, measured in centuries (with what sometimes has been approximated as having an annual rate of decay (dissipation) of 0.5%), in contrast to about an average half-life of 12 years for methane. Significantly greater attention has been given to CO_2, primarily because of its (almost) irreversible effects, with its ultra-long-term nature and impact on the environment, and in turn damages. However, emissions of some of the other gases should not be ignored.

The current concentration of atmospheric CO_2 has reached about 418 parts per million (ppm) in May 2020, compared with pre-industrial levels of about 270 ppm, with no end for this increase in sight[23]. With no change in the rate of future emissions, a global concentration of 750 ppm might be reached. Because of low dissipation rates, even a significant reduction in greenhouse gas emissions will not result in a reduction in concentration for many years and decades ahead. The general equation is given in formula (1):

$$\text{Concentration}_t = (1 - \text{Dissipation rate}) \times \text{Concentration}_{t-1} + \text{Emissions}_t \qquad (1)$$

According to Gerlagh and Liski (2012), the relationship between emissions and temperature is concave, while the relationship between temperature and damages is convex. If these relativities are correct, the result is that the relationship between emissions and resulting damages may be close to being linear (at least up to about 1,000 ppm), in what is referred to as the carbon-temperature-cycle. Gerlagh and Liski

[22] This paper does not discuss other greenhouse gases, which represent a smaller percentage of overall accumulation, although nitrous oxide (N_2O) has an average lifetime in the atmosphere of about 120 years and can have a significant effect on local air pollution.

[23] One gigaton (Gt) of CO_2 emitted into the atmosphere increases the CO_2 concentration by about 0.128 ppm. There is some uncertainty in this value because the CO_2 dissipation rate (in the range of .0025 to .0050 per year) depends partly on the total concentration of CO_2 in the atmosphere and in the oceans. But the relative uncertainty in this relationship is reasonably low. For example, in 2018 global CO_2 emissions were about 36 Gt, so that year's emissions increased the atmospheric CO_2 concentration by about 4.61 ppm = (36Gt) x (0.128ppm/Gt).

indicated (note that other authors have developed alternative estimates) that a typical estimate for atmospheric CO_2 depreciation has been about 1% per year, while for temperature adjustment is about 2% per year. The associated peak in temperature-response would be about 70 years; i.e., peak temperatures with a lag about 70 years after emissions.

This has led to a rule of thumb that has sometimes been used for discounting damages: discounting future damages at a rate of r% per year results, reflected in a discount factor of about 2^{-r} after 70 years. An annual 1%, 2%, or 3% discount rate results in a discount factor of damages of about one-half, one-quarter, or one-eighth, respectively. The emission-damage function with a fat tail of about 16% of emissions are not completely disappear, even within a horizon of 1,000 years. Note that although the amount of CO_2 emissions was stable during 2014 to 2016, it increased by 1.6% in 2017, by 2.7% in 2018, and 0.6% in 2019 according to the Global Carbon Project. Even though the amount of emissions is expected to decrease in 2020 due to the reduction in economic activity that resulted from the COVID-19 epidemic, there will still be an increase in the accumulated greenhouse gases in the atmosphere. This increase underscores the difficulty in achieving a carbon-neutral world.

The effects of CO_2 contrasts with the more intense methane emissions that dissipate in the atmosphere on average after about 12.4 years. At the same time, greenhouse gases such as methane that do not last long in the atmosphere can have centuries-long effects on oceans. A summary of key differences between carbon dioxide and methane are shown in Table 1.

Table 1 – Key differences between primary greenhouse gases

Characteristic / Greenhouse Gas	Carbon Dioxide	Methane
Scientific notation	CO_2	CH_4
Relative intensity[24]	1X	28X
Average period (years) in the atmosphere	100s, thus without capture, almost irreversible	12.4
Principle sources	Power, transportation	Agriculture, natural gas production, and distribution

Although CO_2 emissions dominate the long-term growth in the accumulative gases in the atmosphere, other greenhouse gases can have just as significant long-term effects in the oceans and more intense effects in the atmosphere. The shorter time horizon for methane in the atmosphere may warrant a different approach to determine its social cost and social discounting. In any event, climate change, however produced, has effects that are long-term in nature.

Air and water pollution are significant adverse effects (co-costs) of, for example, unsustainable energy generation, inefficient transportation and less-than-optimal agricultural practices. This contrasts with the corresponding co-benefits of reduced pollution that is simultaneously derived from reduction in greenhouse gas emissions. The main sources of these emissions are thus key drivers of both climate change and air pollution, especially involving the amounts of ozone and fine particulate matter in the

[24] IPCC Fifth Assessment Report (2013). Based on a 100-year Global Warming Potential (GWP), the energy absorbed by a greenhouse gas over a specific period of time. If a 20-year GWP was used, the corresponding ratio to CO_2 would be about 84. For Nitric Oxide, the 100-year GWP is about 265 and the 20-year GWP about 264, with an expected lifetime in the atmosphere of about 121 years; for carbon tetrafluoride (CF_4) – 6,630, 4,880 and 50,000 years, respectively.

atmosphere. However, The change in pollution is generally of more local, while the effect on climate change is global in reach. Therefore, the scale of these resulting problems is far broader.

Key take-aways from section 3.2 include:

- Regarding mitigation of long-term damages, it is assumed that CO_2 has a more significant and long-term effect than methane.
- Due to their different drivers, mitigation efforts regarding these two greenhouse gas emissions need to differ.
- Nevertheless, due to its more significant intensity, methane concentrations cannot be ignored.

3.3: Distinguishing characteristics of climate change

Decisions regarding investment in actions that can reduce or eliminate the expected effects of climate change consider several factors that can differ from considerations taken into account in private sector cost-benefit analysis. Nevertheless, in addition to the unique characteristics of climate change itself, its unique or distinctive characteristics considered in the aggregate suggest a treatment in a cost-benefit analysis different from the analysis of most goods and services, as well as many other social policy investment analyses, follows in this section. They are summarized in Table 2.

Although the causes of disaster risk arising from climate change can differ from disaster risk originating from a large financial or pandemic crisis, some of the effects may also be similar. Output may recover in the short run, but potential economic capacity may also be reduced, with physical, public and human capital destroyed, resulting in lower growth and well-being. This is referred to as a hysteresis effect of shocks.

- *Externalities*. These costs and benefits (see section 2.3) are those ultimately borne by one or more third parties, society as a whole, or other countries (social externalities or co-benefits). The distance (in terms of time and processes) between emissions and ultimate damage can make it difficult, in the absence of external parties such as government), to place responsibility on the originator of the emissions. This distinguishes climate change from most goods and services for which only direct benefits and costs are incorporated in their price.
- *Social*. In contrast to many private sector projects, investments involving public goods, whether in the private or public sector (including cases where the public sector dictates rules relating to the investment or operation of the private sector), affect many stakeholders and both direct and indirect/second or third-order costs and benefits. Projects solely between private sector parties can include social externalities, if for example their operation result in pollution or unanticipated lawsuits by third parties.
- *Tragedy of the commons*. If the actions, or lack of actions, of one party adversely affect others, motivations of each party can be affected. For example, this can arise when another country's mitigation actions can help or hurt outcomes in other countries.
- *Irreversibility*. The underlying drivers of climate change are (almost) irreversible in nature. Most greenhouse gases (see section 3.2), once emitted, do not dissipate for an ultra-long-period, sometimes centuries. In the absence of implementation of scaled effective and efficient carbon capture and storage technology, the aggregate amount of carbon in the atmosphere and ocean with its adverse effects will continue to increase for the foreseeable future (see section 3.4 for further discussion).
- *Global*. Both the contributing causes and damages have been and will continue to be global in nature (see section 8.2.3 for further discussion). In most cost-benefit analyses, the costs and

benefits involve only those incurred within the boundaries of the area involved for which the analysis is being performed. However, in the case of climate change with its sizable impact on many people around the world, both now and in the future, the scope of analysis of mitigation is more appropriately performed on a global basis[25]. This means that quantification, expressed in terms of averaged results, may be problematic. At the same time, its consequences can differ by local area, with those most sensitive to damages also being most vulnerable to them, without the resources needed to 'fix' the problem; they also were not the most responsible for generating the original problem. This contrasts to most other environmental areas that are more local in both cost and effects. Rather, climate change is subject to planetary risk management, with everyone being a stakeholder in its operations.

- *Size* and *severity*. Many social decisions have a large impact on the economy and environment of a single country. This is especially the case involving climate change, which may require an aggregate analysis of mitigation, rather than the marginal analysis applicable in most private sector project appraisals (see section 2.4). Some (including Stern 2007) indicate their opinion that climate change is distinctive because its worst likely implications (in the tail of the probability distribution) could extend to every citizen and everyone alive during the next several centuries. Prevention (mitigation), quantification, and minimization (adaptation) of its effects are all aspects of the risk management of the tail risk of climate change.
- *Timing*. Climate change risk was once thought to be primarily a long-term risk; now the reason it is often considered a 'climate emergency' is that it covers the entire foreseeable future, including short-term damages, with possible consequential costs spread over an even longer period. A great deal of current climate policy and mitigation investments analyzed by current decision-makers will primarily benefit both the current and future generations. and apply to both sudden events and slow-onset conditions. Current climate conditions are consequences of past cumulative accumulation of greenhouse gases. Not only does climate change cover a broad time period, it also involves intergenerational issues (see section 7.2 for further discussion). If discount rates used are too high, expected long-term effects may not materially affect current decisions, while if too low, mitigation efforts may crowd-out other worthwhile shorter-term problems. Meanwhile, its sustainability aspects concern the long-term horizon, in contrast to short-term thinking that emphasizes economic growth over typical political time horizons. Sound political governance practice will consider both the short-term and long-term needs.
- *Free-riding* and *moral hazard*. Although a national strategy that does not include mitigation activities (i.e., by taking advantage of others' efforts) may appear financially 'acceptable' on a short-term local level, it creates both moral hazard and a free-riding position. In considering adaptation, a less developed country (or local area) may be willing to roll-the-dice and pay a high price for waiting for recovery assistance by governments or philanthropic organizations if ex-post adaptation help is needed. Nevertheless, it might be able to take advantage of free-riding if that area is lucky enough not to experience such damage.
- *Complexity*. Modeling each step of the climate change process involves many complex factors as are the methods to derive their parameters. In addition, human behavior, political decisions, and the nature of and interactions among the meteorological and climatic factors involved (simultaneous conduction, convection, and radiation) are really difficult to determine. Moving from aggregate global averages to estimating local damages add an additional layer of

[25] Although public decision-making is primarily conducted at a national or local level.

complications. These all contribute to a significant degree of uncertainty, including effects that are non-linear and involve feedback effects[26].

- *Uncertainty*. Not only is there uncertainty associated with the performance of the project or investment being assessed, but there are also unusually large uncertainties associated with the effects of the climate change process on factors such as economic growth, consumption, and quality of life on local/national/regional/global levels (see chapter 6 for further discussion). This uncertainty is partly due to a lack of reliable and relevant data and experience[27]. Unlike other environmental risks that are generally well understood, possible asymmetric and tail risks, with a lack of independence of certain exposures and unusual cascading risks of severe damage that can adversely affect financial markets, bank solvency, and even the extent of sustainable living conditions. The wide range of possible damage contributes to a more difficult-than-usual social cost benefit analysis. In addition, uncertainties can build incrementally over time, suggesting a need for a regular updating process of any analysis.
- *Incompleteness*. In part because of the multiplicity of feedback loops and non-monetizable effects, it is likely that estimates of costs and benefit are incomplete and underestimated.
- *Avoids harm*. The sole purpose of many investments is to add value. In contrast, the purpose of many climate change-related investments is a reduction in the likelihood or severity of the effects of climate change, which is difficult to measure.

Table 2 – Comparison of characteristics of climate change and those of goods, services, and other investments/projects applicable to a cost-benefit analysis

	Climate change	Most goods and services	Private sector investments	Public sector projects
Contains externalities	✓	✗	Sometimes	Sometimes
Social	✓	✗	✗	✓
Tragedy of the commons	✓	✗	Sometimes	Sometimes
Irreversible	✓	✗	✗	Sometimes
Global	✓	✗	✗	✗
Large	✓	✗	Sometimes	Sometimes
Long-term	✓	✗	Sometimes	Sometimes
Complex	✓	✗	Sometimes	Sometimes
Uncertain	✓	✗	Sometimes	Sometimes
Incomplete	✓	✗	✗	Sometimes
Avoids harm	✓	✗	Sometimes	Sometimes

[26] For example, the associated tipping or inflection points involved are problematic and difficult to predict, as there is limited experience from which to estimate either their timing or what may happen after they are reached.
[27] Because overall, the Earth has not experienced such conditions during the life of humanity and has not had to endure the amount of greenhouse gases or more extreme climatic conditions that may be experienced.

Any one of these characteristics alone will not likely lead to the conclusion that climate change projects represent a unique class of investment. Nevertheless, because of the combination of these characteristics, climate change can represent a unique public policy issue whose causes and effects may need to be treated in a distinct manner.

This does not necessarily imply that there is a single set of discount rates[28] appropriate for all climate change-related projects or issues that is lower than that used for all other projects. If so, this might lead, in the extreme, to a crowding-out of all other projects[29], which may be difficult to support. In addition, it has to be recognized that some investments or projects can serve multiple purposes, e.g., to reduce both climate change and air pollution, the latter of which tends to have more local and shorter-lasting benefits.

If different discount rates would apply to financing climate change projects and development projects of less developed/developing countries, it would be tempting to describe all development assistance projects as being related to climate change. As a result, if different discount rates or financing are applied, it is important to have a carefully crafted set of criteria to categorize such projects, and a granular set of rules in place to decompose such projects into its separate components. An example where a loan should be split is one sponsoring increasing job opportunities offered in the decarbonization process, which could serve both purposes.

What is the difference between a climate change investment and one that involves other long-term social costs and benefits, such as those involving education, health and public security? They all may involve costs and benefits over long periods of time, even involving intergenerational costs and benefits. An example is radioactive waste management, which can share several of the above characteristics, with an even longer time horizon[30]. However, the effects of nuclear waste management are not as complex as climate change (e.g., fewer feedback loops, although accident and leakage hazards are not straightforward), do not involve mitigation and adaptation efforts, and usually involve effects relatively local in nature). They therefore may not share the same set of discount rates.

Although the valuation of climate change-related investments is not directly comparable to that of a typical private sector investment, the social discounting-related question (i.e., why should the value of time differ by type of project) remains. One response is that the discounting process does not solely involve the value of time. It is, therefore, appropriate to explore other relevant issues, which are addressed in the remainder of this paper. In reviewing these issues, the fact that the use of a lower discount rate could be used to favor a certain type of investment based on personal preferences, rather than objective reasoning, should be kept in mind.

Wagner and Weitzman (2015) summarized the issue raised in this section by indicating that the challenge is "almost uniquely global, uniquely long term, uniquely irreversible and uniquely uncertain".

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[28] Or alternatively, a separate set of adjustments to the amounts that would be discounted (see section 8.2 for further discussion of this alternative approach).

[29] Nevertheless, the huge debts incurred from fighting COVID-19 will limit the total available for social causes, making future allocation to any project, including those that might enable better control of climate change and its consequences that much more difficult.

[30] The half-life of nuclear waste is measured in thousands of years.

Key take-aways from section 3.3 include:

- Projects solely related to climate change mitigation are unique because of the combination of characteristics listed in Table 2.
- However, since several other classes of investments and projects share some of these characteristics, and such investments and projects can address multiple objectives, careful categorization is needed if different discount or loan rates apply.

3.4: Irreversibility

The purpose of this section is to consider one of the significant characteristics of climate change, irreversibility, and its effect on the selection of a social discount rate. Uncertainty and irreversibility of some of the drivers of climate change may provide society the push to take earlier and stronger actions, even though some of these actions, once taken, may be irreversible themselves.

An important characteristic of the climate change process to consider in social cost-benefit analyses is the almost complete irreversibility (i.e., extreme persistence) of greenhouse gas emissions that can be difficult, if not impractical, to undo. The most common irreversible adverse effects relevant to current decision-makers include the accumulation of greenhouse gases in the atmosphere and oceans, the acidification of the oceans, destruction of coral reefs, deglaciation, sea level rise, and extinction of species. Trends in these effects have been underway for several decades, effects of which cannot be effectively controlled, at least with current technologies.

Mitigation decisions consider, for example, that CO_2 emissions tend to stay in the atmosphere for centuries. A certain part of those emissions is quickly absorbed by, for example, plants and the upper part of oceans, with the remainder staying in the atmosphere. Thermal expansion occurs when greenhouse gases enter the atmosphere, which in turn causes the air and ocean temperature to rise. In the meantime, some of the heat absorbed into the oceans causes the water to become and remain more acidic, remaining for centuries, effectively being irreversible in our lifetimes.

The lack of future options and flexibility (see chapter 9) with respect to what has occurred already and will likely continue to reduce social value compared to reversible alternatives. For example, lower discount rates may be appropriate in the analysis of investments associated with non-renewable (irreversible) resources compared to those associated with renewable resources.

Many IAMs currently assume that in the near or intermediate term the level of global greenhouse gas emissions will be reduced, with an eventual decline in the cumulative amount of greenhouse gases in the atmosphere. However, this assumption relies heavily on an expectation that, as the effects of climate change become more apparent, an increasing amount of resources will be allocated to developing technologies and agricultural approaches that offset the effects of the climate change process. A potential example could be the development of a practical, affordable, and scalable carbon capture, utilization and storage system (CCUS)[31]. Nevertheless, to date, there is no indication that such

[31] At the current time, negative emissions that result, for example, from carbon capture and storage, do not appear sufficiently cost-effective to result in negative net annual emissions. Both of the two categories of possible approaches, that is, using chemical and biological means, are being developed. However, so far neither have yet been shown to be affordable or scalable to levels needed to make a significant difference in the future. Geo-engineering (e.g., climate engineering, including solar radiation management that reflects incoming sunlight back to space that represents a deliberate manipulation of the earth system to counteract at least a part of the

technologies or approaches will be available at a sufficient scale to make this an effective strategy to reverse the greenhouse gas concentrations. This dearth of viable solutions suggests it would be far more cost- and risk-effective to avoid emissions in the first place.

Beginning in the latter part of the twentieth century, irreversibility was considered separately. According to Dixit and Pindyck (1994), “The irreversibility of most investment expenditures may help to explain why neoclassical investment theory has failed to provide good empirical models of investment performance. Effects of risk are typically handled by assuming that a risk premium (obtained, say, from the CAPM[32]) can be added to the discount rate used to calculate the present value of a project. However, the correct discount rate cannot be obtained without solving the option valuation problem, the discount rate need not be constant, and it need not equal the firm’s average cost of capital. As a result, simple cost of capital measures may be poor explanators of investment spending.” (see chapters 6 and 9 and section 8.1 for further discussion of these issues)

Regardless of the irreversibility of concentrations in greenhouse gases, the types and amounts of consequential damages of the welfare of future generations are at least to some extent uncertain, especially regarding its social, economic, and political consequences. Nor do we know which current actions future generations will deem most important or optimal to have been undertaken.

Because of the unknowns involved, future benefits and risks that justify opportunity cost discounting can be balanced against the sunk cost of future efforts that may prove premature or ineffective. Pindyck (2020) indicates this to be a further irreversible factor, that reducing CO_2 emissions requires sunk costs, i.e., irreversible expenditures. Particularly in areas where long lead times are often necessary (e.g., measured in decades for the steel industry, the largest industrial source of emissions, to conduct research and develop plants that incorporate large-scale decarbonization processes). Nevertheless, if soundly planned investments in climate change mitigation and adaptation strategies or projects are undertaken, irreversible damage may be able to be prevented or reduced, even if resources currently allocated might prove in hindsight to have been better spent on something else (see chapter 9 for further discussion). As a result, in the course of development there is a real option value associated with preserving technological options and avoiding further climate deterioration.

In sum, both irreversibility and uncertainty (as discussed in chapters 6 and 9) raise the minimum investment threshold necessary for action and reduce the discount rate applied.

Key take-aways from section 3.4 include:

- The fundamental nature of the almost total irreversibility of the direct effects of drivers of current and future climate change effects, especially the accumulation of greenhouse gases in the atmosphere and the oceans.
- Although theoretically it is possible that technologies and approaches will be implemented to reduce the drivers of climate change, it is not risk-free to assume that these mitigation efforts will eliminate all or most climate change risks.

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impact of greenhouse gases) is another possible approach, although this could be risky and politically complicated, as it may have unintended adverse consequences, while improved ecosystem stewardship (biological sequestration focused on forest and soil, e.g., reforestation and sustainable agriculture), although worth continuing to explore, currently has a high price-tag.

[32] The Capital Asset Pricing Model is a financial model used to determine a theoretically appropriate required rate of return on an asset, used to make decisions about adding assets to a diversified portfolio.

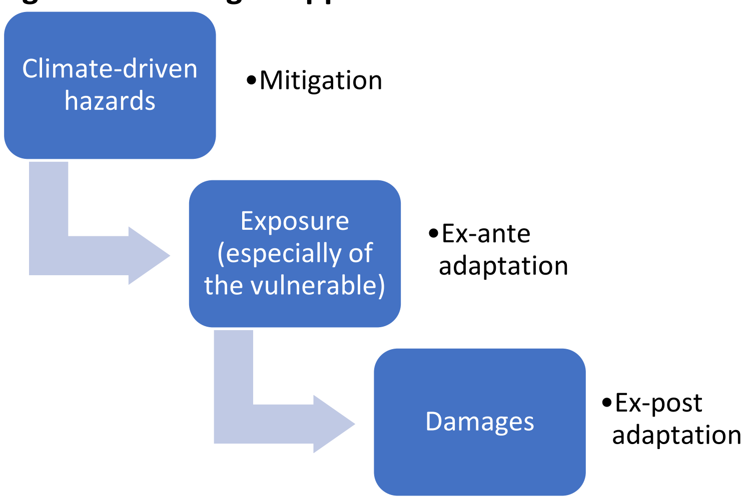
- The (almost) irreversible nature of climate change requires consideration in social cost-benefit analysis and derivation of social discount rates.

3.5: Mitigation and adaptation

The purpose of this section is to explore the distinguishing characteristics of mitigation and adaptation activities. Although some commentators lump them together in a social-cost benefit analysis, there are enough differences to warrant separate discussion.

As indicated in section 3.1, the mitigation of climate change is a global issue, while adaptation is one that is appropriately tackled on either a regional, national, or local level. Adaptation efforts can either be conducted prior to the occurrence of loss or damage (*ex-ante*) or after it occurs (*ex-post*, sometimes referred to this as *loss and damage* or *disaster recovery*). The types of climate change constraints to reduce or, where possible, eliminate losses associated with the process, are shown in Figure 4.

Figure 4 – Timing of approaches to address climate change process



In most cases a combination of mitigation, ex-ante adaptation, and ex-post disaster recovery will form the framework of a comprehensive approach to climate change risk management. Analysis of any of these components will need to consider all three approaches. In addition, their affordability will also be considered. Once the strategy regarding the relative importance of these approaches is decided, separate social cost-benefit tactical analysis of individual investments and programs can be held.

Mitigation and adaptation approaches represent the lines of defense against climate change damages. Mitigation represents the first line of defense – avoidance of the underlying drivers involved and decarbonization. Ex-ante adaptation techniques are the second line of defense, which can increase the capacity to cope with changes in the climate and attempt to eliminate or reduce the amount of damages. Ex-post adaptation efforts seek to reduce the severity of damages once the immediate cause occurs.

The amount and effectiveness of global mitigation actions will determine the extent adaptation is needed in a local area. While adaptation is often locally determined and implemented, strategic planning at several government levels would also be of benefit, where relevant coordinated with others in the region, for example, when related to water resources. In a comprehensive social cost-benefit analysis, adaptation can be viewed as a necessary cost, because it is unlikely that mitigation efforts will succeed in controlling all of the adverse effects of climate change. Ex-post adaptation will be needed when the combination of mitigation and ex-ante adaptation are not successful in limiting damages to an acceptable level.

Efforts to slow climate change may have to overcome political obstacles, as the cost of reducing greenhouse gas emissions must be paid for upfront by businesses and taxpayers, who may not experience much immediate return on their current investments. Ex-ante adaptation, in contrast, can provide substantial benefits, even when it is out of pure self-interest. For instance, homeowners' investment in response to risk, such as purchasing air-conditioning after a heat wave or a community's implementation of flood defenses, are made in expectation of capturing returns themselves through reduced harm to themselves, higher property values or reduced insurance premiums. Adaptation will therefore play a significant role in the response to climate change.

Much of this paper, as do most papers discussing social discount rates, focuses on the assessment of strategies and investments related to mitigation of future climate change, rather than to adaptation techniques used to reduce its effects. A global example of an environmental success is the substitution of certain chemicals for chlorofluorocarbons, which had been destroying the protective ozone layer in the atmosphere. Examples of adaptation techniques include better insulation of old buildings, imposition of insulation standards for new buildings, adoption of land-use and building resilience codes, introduction of more efficient air conditioning systems, increased use of insecticide-treated bed nets, use hardy hybrid crops, enhancement of disaster response planning and health care infrastructure, effective use coastal infrastructure such as dykes to hold back sea or river-level or sea or river-volatility, and relocation of population when needed. Adaption action can take the form of high or low-technology techniques, representing critical infrastructure improvements that can deal with consequential labor effects by use of (re)training, trade and effective public education.

Although usually resilience refers to physical resources, it also applies to financial reliance requiring increased financial savings needed to survive the after-effects of a disaster. This can help maintain the sustainability of the household, community, or business and could facilitate entrepreneurial pathways for green and clean technology, throughout a decarbonization process.

Even though it can be useful to distinguish them, some efforts are of a dual nature, focused on both mitigation and adaptation. For example, soundly-managed tree planting, wetland restoration, and fertilization reduction can both help store greenhouse gases and reduce damage due to landslide risk and protect soil erosion.

Each mitigation and adaptation project tends to have their own stakeholders and objectives, although both aim to address social, as well as individual needs. Both are extremely important, as it will take a lot of money to meet global objectives and needs for both. Table 3 shows some key characteristics of these projects (the last row will be discussed in the remainder of this paper).

Adaptation strategies are usually designed to apply to a particular type of climate change-related risk. For example, for communities that are at-risk to sea level rise, strategies can take the form of: (1) avoidance, consisting of emigration of population or removal of property from the coast, (2) accommodation, including tactics such as raising heights of structures and flood-proofing, and (3) protection, including dykes and sea walls. Relative emphasis on mitigation and adaptation depends upon such factors as relative vulnerability, level of emissions and available resources.

Research from the Center for Climate Integrity (2019) suggests that building sea walls for all coastal cities with more than 25,000 residents by 2040 will take at least US$42 billion. If all coastal communities are included, that increases to more than US$400 billion. Decisions regarding how to determine which communities to save first remain to be addressed, as both time and money are limited. There is also a growing realization that some communities, even sizable ones, may be left behind. It has been proposed that US$4.6b may be spent to protect Miami from rising sea levels, by means of, for example, sea walls and movable barriers to protect against sea water incursion into local waterways.

Bosello (2009) indicated that there are three types of adaptation efforts: (1) investments in research and innovation for adaption purposes, (2) proactive (or anticipatory) adaptation (ex-ante) to reduce harm, and (3) reactive adaptation (ex-post). Differences between these primarily relate to their timing, with the first type representing investments in developing and enhancing technologies and processes to prepare for a climate change risk, the second representing the implementation of techniques applied, and the last that responds to the loss event or condition. They can take several forms, including being autonomous (triggered automatically when a specified ecological trigger is breached), location-specific, directly or indirectly attacking drivers of damages, or in response to a disaster recovery effort.

Table 3 distinguishes between the first two and the third of Bosello's adaptation categories. These can be categorized between those on an ex-ante basis (in anticipation of potential damages) and those of an ex-post nature (in reaction to a loss that already happened). Because of the nature of the emergence of slow-onset conditions, distinctions between ex-ante and ex-post actions may be blurred.

Certain ex-ante adaptation actions can be taken after some of the damages have been incurred but in anticipation of further damages. For example, sea walls might be constructed (usually considered ex-ante adaptation) after an initial flood surge, but prior to more severe subsequent ones. Although building sea walls could be too late for some especially low-lying exposures, they might represent the only feasible way in which sufficient funding could be obtained to anticipate damages to other exposures. Ex-ante efforts can be categorized as being focused on loss prevention, loss control, or risk transfer (the latter through pooling or sharing). Ex-ante adaptation can also take the form of enhancing the resilience of new or existing buildings in anticipation of severe storm protection – these could be viewed as either disaster prevention or damage minimization.

Some of these characteristics depend on the type, immediacy, and potential severity of damage, particularly those that are of a sudden nature. They can be either complementary or substitutable, depending on the options available and the situation of the country or area. Due to scarce resources, an explicit choice will often have to be made between the extent and timing of each approach. To the degree that global mitigation efforts are successful, the need for certain adaptation efforts may be reduced.

Table 3 – Characteristics of mitigation and adaptation efforts

	Mitigation	Adaptation – ex-ante	Adaptation – ex-post
Objective	Prevent climate change	Eliminate or reduce the adverse effects of climate change	Reduce the adverse effects of a recent or current disaster
Scope	Global	National, regional, or local	Local
Design/ implementation responsibility	National or business level	Global, regional, or national design; often local implementation	National or local implementation
Who pays	Primarily developed countries	Local, with aid provided by developed countries, either alone or through multinational entities/funds	Local, supplemented by national financing, developed countries, or multinational entities/funds, charitable/philanthropic, as needed and available
Drivers	Policy driven	Market- or policy-driven, through price signaling or legal/regulatory requirements	Adverse result of climate change event
Timing	Anticipatory	Anticipatory, although it can be reactive once potential	Reactive, once climate change damages have occurred or become apparent
Term	Tends to be long-term, although benefits may also be medium-term	Tends to be shorter-term, although projects such as dykes and tree planting can be just as long-term	Tends to be shorter-term, depending on the severity or permanence of the damages
Uncertainty (see chapter 6)	Significant over the long term, involving both climatic factors and resulting losses and damages	Applies to both the design and effectiveness of actions taken	Tends to be shorter-term, although can be considerable for slow-onset conditions
Applicability of real options (see chapter 9)	Cost and technological enhancement may be significant during delay period	Not as valuable for long-term damage, but delay may be dangerous for short-term damage	Not applicable
Degree of being subject to free-riding	Being a public good – common	Less common	Less common, depending on the resources and capacity of those affected
Discount rate	Social discount rate, incorporating uncertainty premium	Market-rate during early years, transitioning to social discount rate incorporating uncertainty premium	Market rate, although if long-term damages, may transition to social discount rate

A policy trade-off can arise between the use of funds allocated to, for example, mitigation of greenhouse gas emissions or effective ex-ante adaptation management of damage-control through infrastructure preparedness. From a global perspective, the larger the emitter, the more emphasis should be placed on mitigation. Although damaging events might occur despite mitigation efforts, the probability of an extremely harmful event can be reduced with greater mitigation efforts.

For some smaller emitters, it may be determined that, given limited financial resources, greater emphasis should be placed on ex-ante adaptation than mitigation, especially where there are severe local at-risk exposures and expected damages (e.g., in the extreme case of low-lying islands whose inhabitants face existential risks). In many cases, it may be appropriate to invest in mitigation because of the long lag time between investments and results, with adaption investment made to avoid the more extreme climate tail risks.

In some cases with good planning, mitigation or adaptation actions can be accompanied by significant co-benefits, such as a decrease in pollution or stronger economic development. For example, reducing climate change through reduced deforestation or an upgrade of unsustainable agricultural practices may be enhanced simultaneously with an increase in communities' resilience to a range of risks.

Usually, the more resources allocated to ex-ante adaptation, the less (some estimates are four to seven times) resources will be needed for ex-post adaptation or disaster recovery. Although money might pour in to alleviate the effect of a spectacular media-covered disaster in a less developed country, follow-through on pledges to aid may not be timely. It is prudent to begin preparing for these risks sooner-rather-than-later to enable more cost-effective rapid response through use of ex-ante adaptation efforts.

In modeling, it may be useful to use at least four base scenarios, all including the estimated costs associated with their own ex-post adaptation damages:

1. Benchmark, with no further mitigation or adaptation efforts (i.e., business-as-usual);
2. A fair share of sufficient mitigation to achieve a certain goal, e.g., a 2°C target on a global basis, with limited adaptation investments;
3. A mix of mitigation and adaptation efforts; and
4. Some current mitigation and ex-ante adaptation, while waiting to take additional action when information becomes available to determine when it is the optimal time to act (see chapter 9).

Establishing a rulebook to enable consistent and comparable metrics for adaptation purposes is more difficult to agree upon than to agree upon a set of metrics to measure mitigation greenhouse gas emissions, which was agreed to at the COP24 meeting in Poland in December 2018. This occurs partly because there are so many areas in which adaptation can apply. Nevertheless, this does not mean that such an effort is not worthwhile to pursue.

An important public policy issue, especially for less developed and some developing countries, is how much of their scarce resources should be allocated to mitigation when their maximum possible contribution to overall climate change mitigation efforts might seem trivial compared to global needs. The best response to this question is that everyone should contribute their fair share in support of the global community – the overall global commitment is evident from the total participation in the Paris Agreement, even though the actual contributions by all countries have not been as large as had been hoped. Nevertheless, contributing in some way to the global effort may increase the chance that those countries with more resources will share in an equitable manner, as well as possibly providing assistance to help the least developed countries who are not free-riders to adapt to changed conditions or recover from a disaster.

If developed countries or multinational organizations always finance on an ex-post basis the total damages suffered by those who are vulnerable, the vulnerable will be less inclined (moral hazard) to help themselves by adopting adaptation actions. This disincentive can be constrained if the external organizations or governments demand, as a requirement for financing or assistance, that the original country meets certain criteria, such as developing and following effective risk management practices (see chapter 2 for further discussion of the processes that might be followed).

Adaptation planning is important in any event. For instance, one does not want to have to invent or test a fire brigade after a house catches fire. It is far preferable to have an effective and proven brigade on alert, hoping it will never be used in real life.

Climate change adaptation can be pre-funded, for example, for less developed and developing countries with considerable number of the most vulnerable that have significant capacity constraints. The aim of the Green Climate Fund, an operating entity of the Financial Mechanism of the United Nations is to help achieve a balance between adaptation and mitigation. This considers country-driven strategies and the effectiveness of proposed program designs in view of the needs and priorities of less developed and developing countries. If adequately financed, this Fund can serve as a valuable source of money to enable focused programs to achieve the goals of enhanced adaptation planning on a global scale. It can also provide an immediately disbursable source to meet ex-post adaptation loss recovery needs.

A social cost-benefit analysis can help determine the optimal mix and timing of mitigation and adaption efforts. In some cases, advocates of each type may downplay the relative benefits or practicality of the other and may contend that investment in their preferred approach will be crowded out by the other approach to risk control. For example, greater investment in adaptation may lead to a reduced allocation to mitigation or decarbonization actions. In addition to a social cost-benefit analysis, such trade-off decisions may be based upon such factors as the amount of available funds, relative interest in the financing entity, self-interest, desired attractiveness to potential employees, or relative focus of their social risk management goals.

To assess mitigation activities, an IAM is usually used, while for adaptation, a local or regional cost-benefit analysis model may suffice. In view of the costs and risks involved, a strategy consisting of a combination of mitigation and the two types of adaptation may be best for the situation at hand.

In assessing the costs and benefits in a comprehensive social risk management process where mitigation, ex-ante adaptation, and ex-post adaptation efforts are examined at the same time, some offsets may arise. For example, a greater amount of investment in mitigation will tend to reduce the cost of adaptation, and a lesser amount of mitigation effort will tend to lead to a larger cost of adaptation. As indicated earlier, a similar relationship holds between ex-ante and ex-post adaptation. However, since mitigation involves a global effort, this relationship is not necessarily a direct one. In any case, insufficient global mitigation will result in a greater net cost of local adaptation.

Key take-aways from section 3.5 include:

- Mitigation, focusing on underlying causes, should be viewed on a global basis, while adaptation, focusing on protection against specific losses and damages, should be viewed on regional, national or local levels;
- Ex-ante adaptation includes efforts aimed at reducing the effect of climate change on the individual or entity, while ex-post adaptation focuses on loss recovery once the damage occurs;
- Although individual projects usually address either mitigation or adaptation, a social cost-benefit analysis should assess both types of action, including the need for a proper balance of resource allocation; and

- Due to their different timeframes, social discount rates less provision for uncertainty, will be used for mitigation efforts, while rates closer to market rates will usually be used for short-term ex-post adaptation projects.

Key take-aways from chapter 3 include:

- Climate is a global public good that affects everyone and is a responsibility of humanity.
- The climate change process is complex and has several global and long-term aspects;
- The effects of climate change include those with either a sudden and slow-onset nature, effects differing extensively by region or locality, with potential damages to life, health, property and the environment;
- Greenhouse gases, a primary driver of climate change, consist primarily, but not exclusively, of CO_2 that remains in the atmosphere for a long time;
- The climate change process consists of a unique combination of characteristics, including extensive social externalities, a very long-term nature, a global scope, (almost) irreversible effects on the atmosphere and oceans, and a large potential for catastrophic risk, as well as involving significant uncertainties; and
- It is important to separately plan for mitigation and adaptation efforts in a social risk management process.

B. Social Discounting – Key Elements and Considerations

Chapter 4: Discounting

The purpose of this chapter is to explore the underlying concepts and practical application of discounting in deriving present value calculations, which in turn are used in social cost-benefit analyses.

Restating the framework factors under which discounting is based:

1. People are impatient – time has value;
2. People are averse to risk and even more so to loss; and
3. Discounting is used to compare sets of cash flows (or utils) or their equivalents occurring across time.

In the simple case, a discount rate can be thought of as an interest rate, value of time, or a psychological aggregation that reflects the attitude of one or more stakeholders on day t toward a set of disbursements or receipts of certain amounts of money (utility) on day t+1, compared to a different set of disbursements or receives of a different amount of money (utility) on day t. It is a metric, expressed in terms of an annual rate, that corresponds to the percentage reduction[33] in the value of an item(s) as affected by time.

Discounting results in a value, referred to as a net present value, that may be determined on the basis of supply and demand among relevant stakeholders. In certain cases, the discount rate may be predetermined by an external stakeholder, such as a regulator. The views of the stakeholders involved reflect such factors as expert/non-expert opinions, patience, uncertainties, risk and time preferences, the marginal preference to save, greed, and fear. In a cost-benefit analysis, the process of discounting is conducted to assess whether a stakeholder expects, as a result of a decision or an action, to receive at least a specified amount[34] as compensation for an amount of investment or deferral of consumption. The value can be expressed in terms of a cash flow equivalent amount at the current time (valuation date) or a minimum return on an investment. It is especially useful when a comparison between two or more courses of action is being made, especially when costs or benefits are spread over a prolonged period.

A case could be made that, at least conceptually, a person's or society's time value of money (time preference) is identical under all circumstances. However, the discount rate reflects more than just the time value of money. It can depend on, for instance, the context in which it is applied, that is, what is being discounted and the type and extent of uncertainties involved, the time period over which the discounting relates, and the amounts and preferences regarding risk and uncertainty of the stakeholder.

If expressed in terms of utility (or utils, the unit metric of the economic concept of utility, which relates to the individual or society for whom the valuation is conducted), discounting incorporates the perspective or value placed on the monetary amounts or utils by a specific stakeholder. Stakeholders may have different views, needs, and (time and risk) preferences (see section 6.2 for further discussion),

[33] In the unusual case of a negative discount rate, it would result in an increase in value at time t.
[34] usually net of tax, if applicable.

all of which may depend on their individual circumstances at the time of the valuation, such as wealth, resources, exposure, or vulnerability to the risks involved.

The net present value of all benefits less the present value of all costs, expressed in annual terms, can be described by formula (2):

$$\text{NPV}_o = \sum_{t=0}^{t=N} \frac{(B_t - C_t)}{\Pi\ (1+r_t)\ x\ \sqrt{(1+r_o)}} \qquad (2)$$

Where NPV_t = *net present value*, the current value at time t of all benefits less costs (expressed in utils or cash flow equivalents)

N = *period* over which the calculation is performed

B_t = *benefits* in year t

C_t = *costs* in year t

r_t = *rate of discount* in year t

Π = product of terms from t=0 to t=N

The discount factor is equal to NPV_t determined at the applicable discount rate(s), divided by NPV_t determined at r=0%. Formula (2) assumes that costs and benefits occur in the middle of the year – it can be easily modified if one or more cost or benefit is not expected to be the case. It can be expressed in continuous form (formula (3), as well. It follows that the larger the discount rate, the less an amount at a given time in the future is worth today.

$$\int (B-C)\, e^{-rt} \qquad (3)$$

As an example of the sensitivity of policy decisions to minor differences in discount rates, assume that an investment to reduce carbon emissions costs $5 billion, and is expected to avoid environmental damages worth $100 billion in 100 years. Based on values in Table 8 in Appendix 1, at a discount rate of 2.5% the present value of those damages is currently $8.5 billion, and the project seems appealing. But at the higher discount rate of 3.5%, the present value of the investment drops to $3.2 billion, therefore making the project unattractive. Table 4 provides selected present values of $1,000 in the specified number of years – for instance, the value of $1,000 benefit or cost at 5% per annum that emerges in 100 years is $7.60.

Table 4 – Present value of $1,000 in selected number of years using selected discount rates[35]

Years / Discount rate	2.0%	5.0%
25	$609.53	$295.30
100	138.03	7.60
200	19.05	0.06

Important consistency principles that underlie the application of discounting include:

1. *Costs and benefits*. The same discount rate should be applied to both costs and benefits incurred at the same time.

[35] Further detailed discount rate values are given in Appendix 1.

2. *Application consistency*. The discount rate should be applied in a manner consistent with the cash flows to which it is applied .
3. *Policy option consistency*. The discount rate should be consistent with the policy option(s) being reviewed, for example, the corresponding cash flows or utils.
4. *Scenario-specific*. The discount rate used should be internally consistent with the scenario in which the discounting is applied. In general, if alternative scenarios are being considered (e.g., in stochastic modeling or in stress tests), the discount rate should differ by scenario, as appropriate.
5. *Nominal or real*. If costs and benefits are measured in nominal (or current) dollars, they should be discounted with a nominal discount rate, while costs and benefits measured in real terms (that is, adjusted for inflation) should be discounted with a real discount rate. The usual approach in conducting a cost-benefit analysis is to express all costs and benefits in real dollars and using real discount rates, thus avoiding the need to estimate the future course of inflation.
6. *Currency*. Since interest rates differ by country, it is common to convert both the cash flows being discounted and the applicable discount rate to the same currency or financial market.

Several bases for discount rates approaches have been used or been proposed to be used, including:

- *Risk-free rate*. This rate corresponds to the fixed income financial instrument of the applicable country and duration issued at minimum risk. This is usually sovereign debt. Long-term risk-free rates for developed countries have averaged about 2.5%, although in recent years in low investment market conditions, 10 to 30-year high quality government bonds have been as low as 1.0%, if not lower. The rates for less developed countries have been, in some cases, significantly higher.

Table 5 – U.S. Treasury bond interest rates by quinquennial years

Beginning:	**1965**	**1970**	**1975**	**1980**	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**
Ending:	**1970**	**1975**	**1980**	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2019**
Real rate	1.0%	0.0%	-0.9%	6.9%	5.1%	4.3%	3.9%	2.4%	1.8%	0.5%	0.4%
Nominal rate:	5.9%	6.7%	8.5%	12.1%	8.5%	7.0%	6.2%	4.6%	3.8%	2.0%	2.3%

Source: Office of the Chief Actuary (2020). Average rates for 10-year U.S. Treasury bonds issued during the period; to determine real rates, nominal rates are reduced by the corresponding CPI-W.

There has been a wide range of real risk-free rates of interest – for example, in the United States the average (unweighted) real sovereign interest rates over this fifty-year period has been about 2.3%. However, a different average rate will be obtained if a different time period is selected. If an average rate is being estimated, a fraction of an interest cycle should not be used. These rates differ by country, for example being negative in Japan (-0.6% over the last century) and in certain European countries. The average estimate of future real rates from the Drupp et al. (2018) survey[36] was 2.38% (with a median of 2.00%).

The use of sovereign borrowing rates implicitly assumes that the risk premium on public sector projects is equivalent to the expected cost for credit that the market assigns to the country's

[36] Drupp et al. (2018) reported the results of a survey of over 200 economists who have published papers on the topic of social discounting relating to climate change (see section 5.2.1 for further discussion).

securities. In contrast, the social cost of capital approach assumes the risk premium on public projects is somewhat less than that on private investments, because private investments involve compensation for other factors, such as private sector credit preference or illiquidity risks.

An approach that might be applied in the case of a less developed country is to base the rate used on a recent average of the government's cost of borrowing in U.S. dollars, adjusted for differences in national inflation rates. This approach might be justified by its correspondence to the borrowing cost of the government that would, in most cases, be responsible for financing the project, facilitating consistency between the discount rate used and the corresponding cash flows.

- *Market rate*. This could be based on transaction prices for a set of fixed income financial instruments with little if any illiquidity risk, as traded or issued in a market. It could be the average rate for the entire market or that of a specific type of instrument, such as sovereign debt (for strong economies, these are relatively default risk-free, due to the ability to tax their citizens, with an adjustment for the applicable term premium). A relatively high rate might be discerned from returns from the equity market, as a surrogate for economic growth. Yet it may be difficult to justify the use of such a high-risk return in this context.
- *Real market rate*. This is based on the market rate, adjusted for the current or estimated rate of inflation for the applicable term.
- *Cost of capital* implicit in current or an average of past market rates.
- *Capital Asset Pricing Model (CAPM) rate*. A CAPM is a model that describes the relationship between systematic risk and the expected return on specified assets, particularly stocks. It is widely used in finance to price securities or to determine expected investment returns and the cost of capital of an entity or similar entities.
- *Rate of change in a country's GDP or consumption*. The concept underlying this type of metric is that the role of a discount rate is to adjust future cash flows in line with the rate of growth of economic output or consumption.
- *Social discount rate* (see chapter 5).

Discount rates are often thought of as being based on the corresponding market-based interest rate at the time of the valuation or the historical average interest rates over a specified period. Note that this does not mean that the discount rate used need to be based on one of these approaches. It may also consist of an extrapolation or an average of an historical period, recognizing that financial or environmental conditions at a specific date or during a period may not be similar to the same conditions that will exist in a future period. For instance, "There is no deep reason of principle that allows us to extrapolate past rates of return on capital into the distant future." (Weitzman 2009)

Discount rates can also be based on the output of interest rate models[37], which may have been created to assess financial valuations. They thus may be determined by interest rates implied by financial market prices, modeled, or estimated by other means. These results may also be adjusted, possibly due to uncertainty or social externalities, before being applied as social discount rates (see chapter 5).

[37] These may be theoretically or empirically derived – highly complex or determined largely by expert judgment.

The effect of uncertainty on interest and discount rates is an important issue, as discussed in chapter 6. Interest rates in environments that contain uncertainty do not simply aggregate arithmetically into a certainty-equivalent discount rate. As Weitzman (2007) pointed out, it is not discount rates per se, but discount factors (the cumulative effective of discount rates over a period of time) that are relevant. Thus, if multiple interest rates are assigned probabilities, the resulting average rate declines monotonically over time, closer to the lower than the higher rate of a range.

Interest (real and even nominal) rates can be negative. Recently, this has arisen in part because the application of certain monetary policies (in the family of unconventional monetary policy) can interfere with or constrain the normal workings of a financial market. However, negative rates can also exist even without such interference. This can occur, for instance, especially where severe financial damage has occurred and monetary authorities attempt to provide the economy a boost toward recovery/expansion or when extreme currency strength exists in a country or region. Negative real rates of interest, that is, when a nominal interest rate that is greater than zero is less than the corresponding rate of inflation, can also occur, with a resulting decline in purchasing power over the period. There is no reason to avoid the use of negative nominal or real rates if justified on a sound basis or if they reflect real conditions. Therefore, the long-term interest rate can be quite low, or even negative.

Key take-aways from chapter 4 include:

- Discount rates are the primary metric to aggregate a set of cash flow equivalents spread over time to a single current value;
- Discount rates can differ as a function of the stakeholder's attitudes toward time value, risk, and uncertainty;
- Present values can be quite sensitive to the level of the discount rates used, especially when applied over a long time horizon;
- Discount rates, which can be determined in accordance with the application and scenario, should be consistently applied to correspondingly timed costs and benefits, and should be coordinated with the items being discounted; and
- Several approaches to determining discount rates have been used, including risk-free, market-based, financial-based, consumption-based and social discount rates.

Chapter 5: Social Discounting

This chapter provides an introduction to and covers the basic concepts and framework underlying social discounting. A special case of discounting in which social externalities and co-benefits are considered, social discounting can also reflect society's interests. The issue specifically addressed in this paper involves the social cost-benefit analysis of investments, projects, and strategies relating to climate change, the unique features of which were discussed in section 3.3. Social discounting can provide needed input into decision-making regarding the price society is willing to pay to support a sustainable future.

5.1: Social discounting

As indicated in chapter 4, the discount rate used should be selected in a manner consistent with its application. For example, a market discount rate, used in many actuarial applications, reflects the preferences of those who are involved in current transactions involving financial instruments or other present and future goods and services.

In contrast, a social discount rate is used in a social cost-benefit analysis to help assess whether or to what extent the strategy, policy, or investment under study is an effective (i.e., desirable) use of society's resources from a total social perspective, considering the social value of the costs and benefits involved. Social discounting takes the view that society acts on behalf of individuals and businesses undertakes projects affecting environmental and other social goods and services. A social cost-benefit analysis of the financial effects of these actions incorporates estimates of the costs and benefits expected to be experienced by all directly and indirectly affected stakeholders. It can also be applied by the private sector, for example, private entities that are sensitive to environmental, social, and governance (ESG) factors. It can take the view of a consumer or producer – both viewpoints are discussed in this section. The social discount rate is a key element in decision process, particularly where costs and benefits occur over an extended period.

The application of the social discount rate can indicate whether current consumption can be sacrificed or alternative investments be delayed or not undertaken without lowering social welfare. The determination of whether to undertake a specified investment or strategy aimed at a certain social issue, such as limiting climate change, requires a comparison of, for example, the use of current resources that might otherwise boost current well-being to the discounted value of the effect of the investment or strategy on future welfare. Similar to discounting for other purposes, as indicated above, no consensus has reached as to a single time-risk analytical framework, methodology, or agreed-upon best practice to derive a social discount rate, although many have started with the Ramsey formula (see section 5.2.1).

Although this lack of consensus is partly due to the wide range of applications and societal goals to which social discounting can be applied, it is also the result of a range of views as to the value of what is being assessed. For example, the social discount rates used by various governments or in numerous academic papers and books that have analyzed the effects of climate change have differed dramatically. While some have used something close to market-based rates, others have used rates that deviate markedly. Indeed, choices of low or high discount rates may reflect the entity's or person's preconceived notions as to the importance of dealing with climate change.

In spite of and in consideration of these differences in views, this section and the remainder of this paper address the key factors and major issues involved in social discounting.

As Weitzman (2007) indicated, "there was never any deep economic rationale in the first place for damages from greenhouse gas warming being modeled as entering utility functions through the particular reduced-form route of being a pure production externality … It was more due to an historical accident of stumbling upon a simple understandable analytical form whose parameters could be conveniently adjusted to match various scenarios than the result of serious thought about whether damages from global warming are better specified as multiplicative or additive with GDP, or even entering the utility function as a direct argument."

Gollier (2011) indicated that an optimal social discount rate could be estimated by three primary methods, all of which may derive similar results if the applicable financial market is frictionless and if consumption decision-making is optimized over both an inter and intratemporal basis:

- *Market-based rate*. The interest rate based on market prices. This provides information regarding society's willingness to contribute to the transference of wealth to and consumption in the future. This method is further discussed in section 5.3.
- *Consumption rate*. The welfare-preserving rate of return on savings (social welfare), that is, the return that sets the change in society's welfare to zero. This increases consumption and welfare in later years only if the reduction in current welfare is more than compensated for by an increase in future welfare.
- *Production rate*. The marginal rate of return on productive capital in the economy. An investment is appropriate only if its rate of return is larger than alternative strategies to invest in productive capital.

The following discusses the latter two approaches. First, the *marginal social rate of time preference* reflects society's preference for consumption sooner rather than later. A second measure reflects producers' attitudes and behavior, and is therefore supply-based – the risk-adjusted *marginal social rate of return* from an investment*,* which reflects the return that the private sector sacrifices when resources are diverted to public projects. Thus, while the consumption rate of interest reflects society's preference for a dollar's worth of current consumption rather than at a future time, the marginal social rate of return reflects the opportunity cost of what that dollar could have returned if it had been productively employed for another purpose, rather than used for consumption purposes.

From the consumer's perspective, the social discount rate is the rate at which affected consumers are willing to trade an amount, less than $1 of consumption today, for $1 of consumption in the future. If individuals discount their future consumption (including the costs and benefits resulting from the public policy being assessed) using a consumption-based discount rate, then so should the government[38]. The social discount rate is then based on society's utility function. It therefore determines the conditions under which intertemporal allocation should favor consumption rather than savings. Unlike an individual, whose preference might be determined through surveys or other means, it can be difficult to quantify society's preferences. This determination is an important function of the economic and political decision-making process.

From the production perspective, the social rate determines production allocation over time and thus the resulting type of capital accumulation. The social discount rate therefore mirrors the rate of return on public investment. This approach reflects the idea that, as long as the rate of return on capital is positive, society needs to invest less than $1 today to obtain $1 of benefits in the future.

To compensate for forgone consumption, investment is needed to generate a return (to cover both net direct and indirect benefits, including social externalities) at least equal to the social discount rate. In contrast, a private cost-benefit analysis assesses whether the private entity or sector should implement a particular action (taxes and the private sector cost of capital also affect these decisions). A variant of this situation arises when the public sector uses private resources to satisfy certain social objectives. In this case, the public sector may also transfer risk to the private sector, which then becomes a resource cost.

In sum, social discounting can be viewed either in the context of consumption (the relative price placed on present versus future consumption) or production (opportunity costs in a world of limited capital). It

[38] An example of the application of the consumption rate of interest is given in Appendix 2, in which the shadow price of capital approach is described.

is important to note that the consumption rate of interest and the marginal social rate of return are identical under socially optimal conditions, that is, where consumers are willing to save and producers are willing to invest. This occurs when the investment demanded and its supply are in equilibrium.

However, since this last condition is not always met in practice, many candidates for social discount rates have been put forth, several of which will be discussed in this paper. They include, not necessarily in order of preference):

1. *Social* or *consumption rate discounting*. Aggregate pure rate of time preference of society, based on the assumption that government or government-sponsored investments totally displaces consumption. Thus, a consumption rate would be used – through either a descriptionist or prescriptionists' approach (see section 5.2.2).
2. *Production rate discounting*. Opportunity cost of capital as observed in relevant capital markets.
3. *Opportunity cost discounting*. Considering the cost of mitigation with its foregone benefits as opportunity costs. These investments divert resources from alternative projects that would have generated other benefits for current and future generations.
4. *Social opportunity cost of capital discounting*. Opportunity cost of capital for society, based on the assumption that government or government-sponsored investment displaces private investment.
5. *Between the consumption and production discounting*. Weighted average of the rates of consumption and production (or at least a rate somewhere between them), based on the assumption that government or government-sponsored investment displaces both consumption and private investment.
6. *Time preference discounting*. Based on ethical norms (see section 5.2.2 for a discussion of the prescriptionists' pure time preference discounting), how people think about and act regarding the future. Society's time preference is an aggregation of those of its individual members.
7. *Shadow price discounting*. Shadow price of capital (see Appendix 2 for a discussion), based on the assumption that government or government-sponsored investment displaces both consumption and private investment, with proceeds that could be reinvested rather than consumed in intermediate periods. This uses shadow prices to convert projected cost estimates into consumption-equivalents, accounting for the full opportunity cost of capital and then discounted with the (after-tax) consumption rate.
8. *Growth discounting*. Because future generations will likely, but not necessarily, be richer than our own (using the Ramsey Formula given in section 5.2.1), a larger discount rate reflecting the fact that an extra unit of consumption is worth relatively more, on average, to those currently in need of more current consumption than it will be to those, on average, who will be wealthier in future. As applied to the total economy, based on the elasticity of the marginal utility of consumption with respect to changes in per-capita consumption.
9. *Misogynistic discounting*. Some may not care about future generations as much as they do about themselves, their own generation or population group or direct descendants. Stern (2015) claimed that many of the current generation believe they have an unfettered right to impose its own views on future generations and damage their environment in any way they think appropriate.
10. *Uncertainty/flexibility discounting*. A rate less than the market's real rate of interest by a constant or percentage amount, reflecting project-specific sources of a changing level of uncertainty or availability of flexibility.
11. *Public cost of funds discounting*. The applicable government's cost of funds.

Some (e.g., Stern 2015) have argued that the use of a relatively large social discount rate in a social cost-benefit analysis is unethical. The logic underlying this argument is that, by using the pure rate of discount, ρ, at a rate greater than zero, is tantamount to discriminatory treatment based upon when a generation was born. The use of a positive pure rate of discount, in effect, ignores large costs expected in the distant future that are basically irreversible resource transfers from the future to the present. This argument was considered in the determination of the 0.5% pure social time preference element of the standard Green Book (U.K.) discount rate.

The selection of the 'right' social discount rate remains a challenge. Epstein et al. (2013) developed a useful thought experiment: would you be willing to give up 25% to 30% of your lifetime consumption to help ensure that future generations will have a smaller stock of greenhouse gases in the atmosphere and ocean? Or, what percentage would you be willing to sacrifice?

Several observations regarding the selection of social discount rates less than other observed rates follow:

- It is agreed by many observers that market-based rates are inappropriate (see section 5.3), especially because of the unique features of social decision-making in regards to climate change, especially as they relate to the scope and complexities involved with issues such as deciding on climate change-related actions (see section 3.3);
- the overall uncertainty and tail risk regarding climate change are greater than that of the financial return on most investments for many stakeholders (see chapter 6);
- the issues addressed are more significant to society than those involved in making decisions that only affect the success of an investment or an individual's own allocation of resources, that is, there is more at stake to society (e.g., co-benefits, as illustrated in Figure 2);
- the very long-term implications and asymmetry of adverse consequences of such decisions, that is, overall, society has a longer planning horizon than individuals and private-sector investors;
- based on an overall review of the relevant literature, there is a general consensus that social discount rates should be lower than the discount rate used for an individual business or household, who is unable to diversify risk as effectively as society as a whole;
- because future generations cannot trade in a current market, observable market transactions may not accurately reflect the relative value of traded goods and services between people in the future relative to those currently alive, resulting in goods and services having diminishing marginal benefit over time;
- the need to incorporate interests and values across generations, including those not yet born (each generation, as well as each individual, can be expected to be impatient and to act, at least to some extent, in a self-interested manner), is a reason for the social discount rate to differ from current rates, as average income per capita is expected to increase over time (see section 7.2); and
- studies show a wide range (heterogeneity) of rates and values (observed in market preferences and contingent valuations) among individuals that make a consensus that each participant would accept difficult to estimate and may not be observable.

Differences between social discounting and 'normal' discounting, as summarized in Table 5, can be viewed as including: (1) a social premium that includes a social risk premium, considering the effect of uncertainty (see chapter 6) and of social externalities and co-benefits, i.e., secondary or tertiary costs and benefits not considered by market participants as illustrated in Figure 2 and (2) a sustainability premium, the cost to help ensure the continuation of at least the current level of standard of living, especially for those most exposed and vulnerable to the adverse effects of the social issue being analyzed.

Table 5 – Social Discounting compared

Features	Discounting	Social Discounting
Context	Enterprise risk management process	Social risk management process
Focus	Private sector entities	Public (usually government) entities
Treatment of externalities	Excluded	Incorporated
Preferences—values/risk preferences	Those of individuals or market participants	Those of society, across generations
Social premium	None	Difference between discount and social discount rates
Sustainability premium	Not included or implicit	Included as part of the social premium
How low can it go	Dependent on application, but it can be negative	Typically, lower than discount rate, even if negative
Relative to market-basis	Usually market-based in some way	Usually lower than market-based rates

The following summarizes some of the above considerations. The social discounting process should consider the opportunity cost of public investment, resulting from: 1) alternative investment opportunities, 2) the effects of the investment on private consumption and on public income, and 3) the social opportunity cost of future consumption relative to consumption today needs to be considered. In addition, the opportunity cost of using private sector resources may be greater than the social discount rate. Nevertheless, the relative price of future consumption ultimately depends upon the forces of supply and demand, which in turn depends upon expectations of future productivity and economic growth rates. In sum, if the social discount rate reflects the amount of consumption, the social discount rate will usually be lower than if based upon a cost of capital concept.

Key take-aways from section 5.1 include:

- Social discount rates measure the effect of time in an analysis of the extent that an item is an effective use of society's resources;
- Social discount rates can be thought to take either a consumption interpretation that allocates consumption over time or a production interpretation that allocates the use of capital over time;
- A range of bases for social discounting has been proposed, including ethics-based reflecting an intergenerational resource allocation, pure time value, opportunity costing, shadow pricing, market-based, and growth-focused discount rates;
- Social discount rates are generally less than market-based discount rates, even if the market-based discount rate is negative[39]; and
- Social discounting is used in both intragenerational and intergenerational analyses; and
- The application of social discounting can be viewed as including a social premium that includes a social risk premium, considering the effect of social externalities and a sustainability premium.

What should the basis for a social discount rate be? This question is discussed in the remainder of this paper.

[39] An exception may be if the co-costs are significant, but this case may be unusual.

5.2: Underlying economic concepts

The purpose of this section is to discuss various economic views with respect to social discounting over a long-term period. In particular, a common starting point, the Ramsey formula, is explored, followed by the approach taken by two schools of economic thought that have addressed this issue.

A common approach taken by many economists is to assume that a representative agent (representing society's objectively determined best interests) is able to make rational cost-benefit tradeoffs between consumption and savings that maximizes the present value of future utility from consumption. All items in the analysis are converted into equivalent units of consumption, suggesting a consistent use of a consumption discount rate, the rate at which society through an agent would trade consumption units in a future year for current consumption. Benefits and costs in the analysis are assumed to be certain and determinable (e.g., non-random in nature). A similar approach is to address the question of how much consumption is a current decision-maker (generation) willing to give up to achieve a given expected future gain[40]?

5.2.1: The Ramsey formula

A foundational economic approach often used to derive a discount rate in cost-benefit analyses that covers a long period of time is based upon the so-called Ramsey formula[41] (Ramsey 1928), given in formula (4) below. In this seminal paper, it was applied to compare the values of items related to consumption and savings over time. The resulting discount rate is determined using a neoclassical growth model based on the pure return, ρ, over a unit of time demanded by consumers (or, rather, by a representative agent whose lifetime is of indefinite duration) to optimize their consumption and savings patterns over time. It has been used by many economists to derive a social discount rate to analyze issues involving intergeneration tradeoffs over the long-term, including possible investments that involve climate change mitigation. It has been used in some cases to justify a relatively low social discount rate compared with current market rates.

The resultant social discount rate has been used to determine the minimum acceptable return on safe social investments and projects, valuing social strategy, investments, or projects when a market-based interest rate is not appropriate. It is derived (in the case of CRRA utility) by estimating the terms in the Ramsey formula (formula (4)). The objective is to optimize aggregate social welfare, subject to budget constraints. Those selected are the ones with the largest expected value among those being compared, or at least greater than a benchmark minimum. Measurement can be expressed as the discounted amount of utils of current and future generations or financial value based on an increasing, concave consumption function, including both monetizable and non-monetizable items (see section 8.2.1).

Its two components, shown in formula (4), represent a precautionary effect (ρ) and a wealth effect ($\eta\ g$). Gollier (2011) indicates that the formula estimates an equilibrium interest rate in an economy with perfect financial markets and altruistic investors, by pricing risk-free assets according to a welfare-compatible interpretation of sustainable development. It does not reflect risk/uncertainty (discussed in chapter 6) or taxes. Discounting, according to this formulation, considers two terms: time preference and changes in marginal utility of consumption over time.

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[40] Often expressed in terms of income or GDP.

[41] Also referred to as the *Ramsey equation* or *Ramsey rule*.

The wealth effect assumes that, to the extent per capita consumption is expected to grow (i.e., there will continue to be economic growth across generations), future consumption will be sufficiently large relative to current conditions to have lower marginal utility. In other words, the marginal social value of each new unit of consumption decreases as society continues to grow richer. This effect is captured by the product of the two terms: the annual growth in per capita consumption (g) and the elasticity (η) of marginal utility (social value) of consumption with respect to a change in utility.

Arrow et al. (2012) identified several possible approaches to estimate the Ramsey terms, including: (1) an examination of values implied by society's decisions to redistribute income, such as through progressive taxation, (2) use of a stated preference method determined by examining the implications of actions, such as how much a generation is able and willing to save, although it is difficult to develop an aggregate society-wide preference indicator, and (3) a comparison of alternative values of ρ using current returns on long-term risk-free investments or to historical real growth as surrogates.

As indicated below, there have been several interpretations and extensions of the Ramsey formula (see section 6.1). Algebraically, the Ramsey formula is usually expressed as:

$$r = \rho + \eta\, g \tag{4}$$

where r = *social discount rate* (or social opportunity cost of capital for relevant investors/stakeholders). This is the annual rate at which future consumption (usually expressed as utils or cash flows) is discounted.

ρ[42] = *pure rate of time preference*[43] (risk-free impatience). This term represents the annual rate of decline in the weight placed on a unit of utility in the future compared with an equal unit of utility the year before.

If positive, ρ can be interpreted to mean that one cares less about tomorrow's consumers than today's, or about one's own welfare (or consumption) tomorrow rather than that of today. However, it does not necessarily have to carry with it such a seemingly selfish interpretation.

Stern (2007) assumed ρ has a zero value, as he expressed the view that a positive value represents an unethical perspective (i.e., the current generation does not have the right to damage the environment that would make future generations worse off than ours). Stern suggested that all generations should have equal standing in decisions that also affect them (see section 7.2 for further discussion). In other words, how much should future well-being count, relative to current well-being, in the social welfare function? This view implies that, all else being equal, the further into the future benefits and costs are expected, the less worth or value is attached to the wellbeing of people then living. The challenge to those who disagree is to determine what the pure discount rate in the Ramsey formula should be.

Some commentators (e.g., Stern 2007) have suggested that a component of the pure discount rate should provide for existential catastrophic risk of the human species. This represents the likelihood of an event so devastating that all returns from policies, programs,

[42] Sometimes θ is used instead of ρ.

[43] Has also been referred to as the subjective discount rate, welfare discount rate, or utility discount rate.

or projects will ultimately be zero, such as species' extermination resulting from a major natural disaster such as very large global pandemic mortality, an asteroid strike of the Earth, or a nuclear war. The scale of these risks is, by their nature, extraordinarily difficult to quantify and in their extreme quite scary. The past, in such cases, is not a good guide to the future (see section 6.3 for further perspectives on Stern's choice for ρ).

Most papers in the climate change literature adopt values for ρ in the range of 0.0% to 3.0% per year, with the most popular value cited in the IPCC Fifth Assessment Report (2013) being 2.0%, with many references cited using zero or a number close to zero. However, Drupp et al. (2018)'s survey yielded a mean value of ρ of 1.1% (median of 1.0% and a mode of 0.0%). Thus, it does not appear that the use of a zero rate constitutes a broad consensus of economists.

η = *elasticity of marginal utility*. This term describes how fast the marginal utility of consumption is expected to decline as the utility of consumption increases. η measures the modulation of the sacrifice one generation is willing to make to transfer consumption (or income) to another generation. In other words, the effect on the welfare of one unit of utility is larger when consumption level is lower, thus being concave in nature. It is often expressed as a constant, which could be a placeholder for a more complicated function.

Differences of opinion have arisen in the interpretation of this term. For example, should it reflect preferences of an individual or society (i.e., through a representative agent or social planner) as a whole? Usually, society is considered to be the appropriate reference unit.

Even with a utilitarian social welfare function that merely sums or averages all individuals' utilities within a generation (i.e., when total utility depends on aggregate consumption of the generation), it can change along alternative policy paths. Note that, for a generation, an aggregation would depend directly on individuals' utility functions, as well as on how consumption is distributed.

Determining the weights to place on the interests of different generations involves a comparison of the welfare of different people and birth cohorts (interpersonal justice). Since tomorrow's consumers are expected to be better off overall than today's as a result of economic growth, a greater amount of resources should be allocated to the present, as later generations will benefit more from their consumption because of the decreasing marginal utility of consumption.

Alternatively stated, since future generations will overall be wealthier than the current generation, their future utility should be discounted at a higher rate. This utility will be positively correlated with economic growth (consistent with the Ramsey formula), because they will be able to better afford adaptation. Similarly, if this scenario occurs, the additional future utility would not be as highly valued at the margin and less weight would be given to the utility for the current generation.

In contrast, the almost irreversible nature of the effects on climate caused by the increasing concentration of greenhouse gases in the atmosphere suggests that the range of options available to future generations may be significantly constrained as a result of current actions. Therefore, the expected extent of future growth in the economy should have limited effect on today's mitigation decisions.

r could incorporate flexibility (optionality) in relation to, say, future technological or other developments that could affect future generations. If so, such developments would be directly reflected in the growth (η g) term (see chapter 9 for a discussion of how to reflect option value into an extended Ramsey formula, rather than forcing option values into a term of the original formula). In addition, it is unclear why just aggregate income and consumption are reflected, as they are only a single dimension of desirability and affordability of mitigation/adaptation. In any event, these two terms are weakly related, if at all, to the cumulative expected cost of delay.

Those who could be expected to suffer greater damage (the vulnerable) may be given limited weight in a strictly growth-dominated model. This is because, relative to total resources, their share is relatively small (even though it might be hoped that they would otherwise be expected to experience the greatest rate of growth). Thus, regional discount rates might appropriate (see section 8.2.3 for further discussion), as this term would be expected to differ across time and population segment.

η has been attributed to three factors simultaneously: consumption smoothing, inequality aversion, and risk aversion. However, Lilley (2012) indicated that it is not obvious that a single variable can or should represent the combination of three sub-terms. In any case, the primary assumption is that the utility of an incremental cost or benefit declines as overall income rises. The larger the η, less value is assigned to costs and benefits accruing to those who are better off relative to those not as well off, or to those uncertain outcomes that result in higher incomes. A brief discussion of these factors follows:

- *Consumption smoothing over time*. If society is expected to be richer in the future, the larger the η (and thus the greater the social discount rate), the smaller the desire to save and invest now. In a way, this is similar to the effect of insurance or other risk sharing programs – approximating the amount a person is willing to pay to eliminate financial volatility across time. In this case, the volatility is derived from damage from the adverse effects from a climate change outcome, a contingent outcome, which decreases expected utility. It is also comparable to prudent borrowing, as it makes sense to borrow money when you are young to experience a higher quality of life (e.g., a house purchase with a mortgage) or to improve your personal capital position (e.g., obtaining a job-related education) with an ability and willingness to repay when your income is greater.
- *Inequality aversion*. This is a measure of society's relative aversion to intertemporal inequality, that is, the greater the importance society assigns to equality between generations, the larger the value of this factor. The larger the η, the more that people will want to redistribute resources to help increase the incomes of the relatively poor within a generation rather than to help make future generations even richer (i.e., intergenerational inequity). Many do not believe they should further the interests of the future wealthy, presuming that technological solutions

will be found in the meantime or they will be able to fend for themselves[44]. Because of income inequality, aggregate growth does not necessarily lead to higher incomes or greater satisfaction for the entire population.

- *Risk aversion*. This is a measure of what society is willing to pay today to insure against a potential future loss or reduction in social welfare. It represents a coefficient of relative risk aversion across individuals in each generation and aversion to consumption that is volatile over time, caused by the adverse effects from a contingent event, such as climate change. Its asymmetric effects contribute to a relatively large aversion toward risk. A larger η represents a greater concern or aversion to risk regarding adverse outcomes that leave people worse off. This helps explain why those who are risk averse tend to buy insurance. They are willing to pay a premium reasonably proportional to the effects of the *η* term to eliminate the effects of adverse outcomes, because doing so increases their expected utility.

There has been a wide range of η used or estimated by experts in environmental economics. The choice of value by Stern (2007), for example, was 1.0 – which may be low compared to the observable level of people's rate of savings. Stern (2015) described others' inferrals of η between 0.0 and 4.0. HM Treasury (2011) also assumes a value of 1.0, which implies that a marginal increment in consumption of a generation with twice the consumption of the current generation will enjoy only half the utility that they would gain from a given increment of consumption. Weitzman (2007) indicated a belief that a value of 2.0 is appropriate. The mean value found in Drupp et al. (2018)'s survey of economists was 1.35 (median and mode of 1.0) -- estimates made by the survey participants typically fell in the range of 1.0 to 4.0.

g = per capita growth rate of consumption. This term, expected economic growth, serves multiple roles. It is one of the drivers of emissions, is affected by climate change, and is a component of the discount rate in the Ramsay formula.

Since, according to Anthoff et al. (2009), the effects of climate change tend to grow slower than GDP[45], the effective discount rate is usually greater than the real rate of interest. The expected differential growth rate between richer and poorer countries helps determine the time evolution of the size of the weights used to determine aggregate growth.

Being an economic growth model, an implication of the Ramsey formula is that the social discount rate is inherently linked to the expected growth rate of the economy. This interdependence suggests that the rate used to discount future climate damages should be coordinated with assumptions concerning the rate of economic growth that underlie the trajectory of greenhouse gas emissions and climate-related damages**.**

[44] This assumes that new or enhanced technologies will become available and affordable that will be able to reduce the cumulative amount or effects of greenhouse gases, for example, through carbon capture and storage. In contrast, a totally different type of scenario would involve, for example, extreme climate change, deteriorating economic conditions, or other adverse tail conditions (see sections 3.2, 6.2, and 6.3 for further discussion).

[45] GDP or income growth are not necessarily the same as growth in consumption. Nevertheless, growth in these economic measures have been used inter-changeably here, as the expected effect of the differences is not likely to be significant, at least over the short-term.

During most of the industrial era, greater GDP growth has led to more CO_2 emissions than would have occurred otherwise. This in turn has led to higher global temperatures and consequently to a larger amount of climate-related damage. Overall, greater consumption per capita growth would lead to the use of a larger discount rate. However, over the relatively recent past, this pattern has not always held, because of such factors as emission mitigation activities (e.g., movement to more renewables and more gas-efficient cars). For example, economic growth has occurred in the United States over the last decade, while greenhouse gas emissions have decreased, although this has not always held true in each year (such as 2018). Nevertheless, because emissions have been greater than greenhouse gas concentrations have dissipated (see section 3.2), the total accumulation of these gases in the atmosphere has continued to increase. As a result, this term in the Ramsey formula may be problematic. Whether these changes in pattern will continue is yet to be seen.

The growth in consumption (or income) may not be the best metric to use to represent the relative willingness in all areas of the world and between generations to undertake environmental mitigation or adaptation actions to reduce or eliminate damage from climate change. Nevertheless, this term has the advantage of being measurable and may serve as a reasonable surrogate for the willingness and ability to undertake action.

Stern (2007) assumed a value for g of 1.0%, while Weitzman (2007) used 2.0%. Drupp et al. (2018)'s survey found a mean value of 1.7% (with a median of 1.6% and mode of 2.0%). A commonly used estimate in recent literature appears to be about 2.0% per year, based on average global growth over the past several decades, similar to the average for the last two centuries in the western world (Gollier 2011).

Several variations in the Ramsey formula have been proposed. For instance, Harrison (2010) added a term representing the expected change in the size of the population multiplied by the effect of population growth on the discount rate. Ramsey and most subsequent authors have ignored the explicit effect of population growth on the discount rate, assuming either a constant level of population or a corresponding reduction in the effect of a growing population, which results in a lower discount rate. Other concerns raised with the formula as applied to climate-related analyses, including:

- It ignores the effect of uncertainty, which several authors have adjusted for (see formulas (5) or (6) in section 6.1);
- As described in Heal (2017), it relies on marginal concepts; especially in tail scenarios (see sections 2.4 and 6.3) in which climate change induced damages may be substantial, the effect of reliance on a marginal approach can be problematic;
- A wide range of parameter values have been given to each of its terms by experts (as seen in Drupp et al. 2018) – the lack of economic consensus regarding the development of social discount rates is noteworthy;
- It is primarily consumption-based, which is not the only framework for such a derivation;
- Being a growth model originally designed to address long-term aspects of saving, it may not be an ideal methodology applied to a process involving irreversible and other unique elements (see section 3.3), particularly since exposure to adverse effects of climate change is only weakly related to economic growth;
- Although the objectives of projects to help mitigate and adapt to climate change relate to reducing future climate change-related damages, not all such damages can be directly

translatable to financially equivalent cash flows to which social discount rates are applied (see section 8.2); and
- It ignores the effects of real options (see chapter 9).

A survey of more than 200 economists who have been published on the topic of social discount rates, as reported in Drupp et al. (2018), found a wide range of opinions[46], both regarding social discount rates and the components of the Ramsey formula. The overall resulting mean aggregate social discount rate was 2.27% (2.00% median and mode). About 92% of respondents were comfortable with a social discount rate between 1% and 3%. The opinions regarding the individual components provided in the survey (indicated above) were applied to the Ramsey formula would result in a mean social discount rate of 3.48% (3.00% median). In a prior working paper, Drupp et al. (2015) indicated that there was a relatively low correlation between social discount rate estimates by this survey's respondents and their estimate of the risk-free interest rate (40%), with only a 34% correlation between the three terms of the Ramsey formula and the social discount rate. Thus, many of the responding experts did not rely on the Ramsey formula in deriving their overall opinion. Drupp et al. noted that the broad range of responses suggests that primary reliance on the Ramsey formula may not be appropriate.

Drupp et al., (2018) indicated that a different, similarly structured survey in 2001, found a mean value of 4% (with a 3% median). Drupp surmised that many of those survey participants might have been influenced by the then higher market rates. In contrast to the Drupp et al. survey, Stern (2007)'s conclusions was controversial by asserting a 0.0% ρ, a consumption elasticity of $\eta = 1$ and a long run growth rate of $g = 1.3\%$ per year, which led to a social discount rate of 1.4% per year (including 0.1% for existential risk). Because of the even lower long-term interest rates of 2020, if a comparable survey was conducted then, the resulting estimates may have been somewhat lower.

In the Drupp et al. (2018) survey, respondents provided unprompted additional technical issues that needed to be addressed. These included uncertainty, heterogeneity, and relative prices of non-marketable goods, as well as entirely different approaches that suggest the use of more complex models. Nevertheless, the Ramsey formula represents an easy-to-use and relatively understandable approach using an objective formula (although it is often difficult to obtain consensus regarding the size of its parameters).

The key take-aways from section 5.2.1 are:
- The Ramsey formula is based on a long-term growth model.
- It has often been used in economics literature to represent the long-term time value of money to analyze the discount rate used in the analysis of savings, as well as more recent applications to the social cost-benefit analysis of climate change mitigation efforts.
- Climate change researchers have assigned widely different values to the terms in the Ramsey formula, making its use somewhat problematic as a result.
- In the author's view, at least in this aspect of social cost-benefit analysis of climate change, analysis should look beyond the Ramsey formulation, although it remains the workhorse foundation of economic thought in this area.

[46] The wide range in empirical estimates of the relevant parameters (a reasonable range in parameter values could lead to a range of social discount rates between 1% and 6%) reported in this study suggests that the descriptive Ramsey approach does not resolve disagreement about the appropriate discount rate.

5.2.2: Schools of economic thought

Historically, economists have taken diverse approaches to long-term discounting with respect to its underlying concepts, the components that have been used by their models and their values. In general, two families or schools of economic approaches have been taken (initially described by Arrow 1995):

- *Descriptionists* (also referred to as positivists). Those espousing this approach rely on observable market prices. Descriptionists argue that the most appropriate source of objectively determined discount rates are those derived from prices of market transactions, which reflect the consensus of the preferences of market participants, including intra and intergenerational preferences. These reflect the relevant opportunity cost of capital, characteristics of stakeholders, and what is traded in the market. Information from actual transactions are relied upon, rather than abstract definitions independent of market realities. Their objective is to measure the price that savers demand to defer consumption – in general, they are not concerned with the underlying causes.

  Descriptionists ask: "What trade-offs do people make across time?" This is like asking how and when to allocate resources based on market valuations. Where the prescriptive approach breaks down the components of a discount rate to reach a proper rate, the descriptive approach infers discount rates from saving and investment rates and current expected rates of return. They therefore apply implicit weights to future dates by relevant investors and consumers, forming the basis for a consistent and objectively determined set of discount rates.

  They approximate r in the Ramsey formula by use of risk-free market rates. They interpret the Ramsey formula as a model of how the economy works, by estimating the equilibrium market interest rate, the marginal rate of return to capital, and the rate at which consumers trade or value consumption over time. Some studies have applied the descriptivists' approach by choosing ρ and η values by calibrating the Ramsey formula to market rates.

  However, descriptionists can find it difficult to convert all of the Ramsey's formula elements to consumption-based units, as their preference is to use objectively-derived and observed market prices, at least as a starting point. Because of differing interpretations of the formula's terms, various economists have assigned considerably different values.

  They also do not believe that actual government or consumer decisions have been found to be consistent with the prescriptionists' views, which provide too little emphasis on how investments make current and future generations better off.

  Whether the descriptionist approach calls for the use of the pretax return on capital or the consumption rate of interest depends on whether benefits and costs are expressed in terms of consumption equivalents. They believe that social discount rates should reflect intergenerational issues only to the extent that current marketplace participants consider them.

- *Prescriptionists* (also referred to as normativists or ethicists). They start with a set of normative ethics, deriving by ethical reasoning the pure rate of time preference and the elasticity of marginal utility with respect to the rate of economic growth referred to in the Ramsey formula. Alternatively, they may reflect pre-conceived views on public policy. They ask the question: "How (ethically) should effects on future generations be valued"? The social discount rate they use is based on a social welfare function that reflects the weighting that a policymaker attaches to the utility of current and future generations. It is the rate at which $1 million received by a future generation must be discounted to provide the same marginal utility to the present generation as it provides the future generation. (see chapter 7 for further discussion of ethics in this context).

They generally recommend lower discount rates than the descriptionists. Prescriptionists justify compensation to those who suffer damages resulting from the consequences of today's choices or lack of active prevention. They do not believe market rates are appropriate for this purpose, especially where multiple cohorts or generations are involved. They focus on the amount of aggregate savings needed to satisfy a set of welfare criteria. They usually emphasize a precautionary principle, especially when the damage process is irreversible (see section 3.4) and significant uncertainties (see chapter 6) are involved.

Prescriptionists generally base their Ramsey terms on ethical principles. For example, they set the pure social rate of time preference equal to zero (or very close to zero), with other variables based on the user's value judgements. In fact, they claim any time preference other than zero as indefensible.

In sum, the prescriptionist approach views the terms ρ and η as representing policy choices, while the descriptionist approach bases estimates of ρ and η on market rates of return. Many economists believe that at least a part of both schools are relevant, which results in discount rates somewhere between the rates derived from the application of the approaches of these two camps. A summary of key characteristics of these two approaches is shown in Table 6.

Table 6 – Comparison of Descriptionist and Prescriptionist Views

Characteristic / Approach	**Descriptionists**	**Prescriptionists**
Perspective	Market-based	Ethical-based
Social discount rate	Risk-free market rate	Ramsey formula, usually less than the risk-free market rate
Consider social externalities, such as intergenerational issues	No, unless market participants do	Yes

Of the Ramsey terms, two may be observable (ρ and g) and can, at least in part, be forecasted, while two are unobservable terms involving ethical aspects (r and η) that may be derived from value considerations and judgments. A low real rate of interest in the prescriptive view cannot be justified by a zero generational discount rate alone, but also depends upon consumption elasticity, growth rate of consumption, and population growth. Similarly, in the descriptive view, observations of real interest rates and historical growth rates are insufficient by themselves to determine an intergenerational discount rate.

There has been considerable tension between advocates of these two schools, in some cases possibly related to pre-conceived notions of the need for urgent climate change-related actions. Because of the intensity of their opinions, one approach might be to perform analyses based upon alternative social discount rates, possibly taking an average of the results, recognizing and communicating the two results as a range of possible social values associated with these views.

Just because, as indicated in section 5.3, market-based interest rates are not a proper basis for social discount rates applicable to climate change analysis, prescriptionist-based discount rates are not the only approach that can be used. The two schools of economic thought may serve as useful frameworks from which a rigorous basis of social discount rate can be discussed and agreed upon.

A realistic analysis also needs to account for possible distortions due to taxation, uncertainties and risk premiums, although the effect of tax rules is not explicitly dealt with in this paper. In addition, as Arrow et al. (2012) pointed out, judgment is required no matter what method is used. Estimates should in any case be updated on a regular basis as more information and insight is obtained and changes in circumstances are recognized.

The key take-away from section 5.2.2 is:

- There are two basic schools of economic thought regarding social discount rates: descriptionists that rely upon market observations and prescriptionists that rely upon ethical considerations.
- Since social discount rates determined under these approaches will likely differ (in most cases the prescriptionists will use lower discount rates), it may prove useful to conduct social cost-benefit analyses using rates determined under each perspectives.

5.3: Why not market-based rates

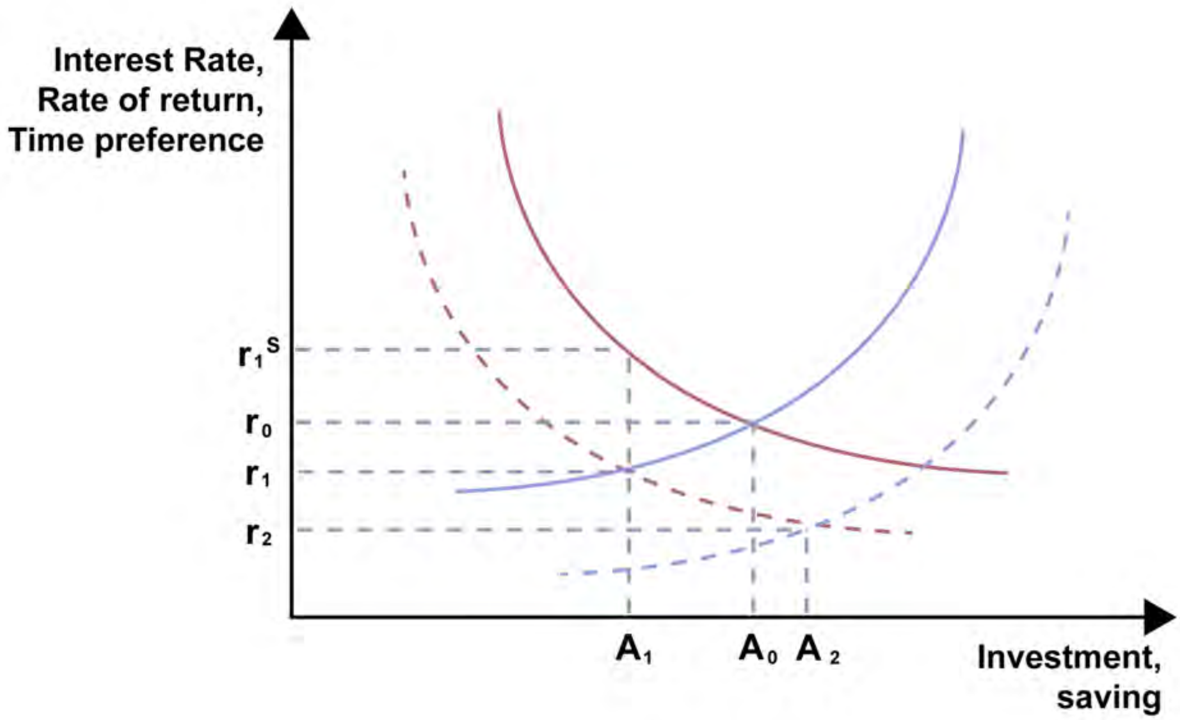
The purpose of this section is to assess whether it is appropriate to use market-based interest rates as a social discount rate, as some (e.g., Nordhaus (2007), who won the Nobel Prize in Economics for his work in this area) have proposed. The following discusses the pros and cons of this position.

Market-based measures reflect market-revealed time and risk preferences of the consensus of market participants as evidenced by market prices, which in turn can be used to infer the discount rate implicit or extrapolatable[47] from observable transaction prices, where willingness to pay and willingness to accept meet. Forces underlying these markets reflect supply and demand considerations, based on generally achievable alternative relevant investments, based on the participants' risk preferences and time tolerances (as well as their incomes and wealth).

This is illustrated in Figure 5, where D represents the investment demand curve, S is the supply curve. r_o is the interest rate (rate of return), and A_o is the socially desirable savings and investment decisions under perfect market conditions. D' and S' are deviated values reflecting adjustments from such conditions. Theoretically, D emphasizes time and risk preferences and S emphasizes the marginal productivity of capital. Changes in D could reflect such factors as social externalities, uncertainties, taxation, and influences from consideration of future generations. These can shift the social time preference to a rate lower than the prior time preference rate. If capital becomes less productive, a shift in S could occur, which would also reduce the social discount rate. Conversely, a higher interest rate, r_1^S, is associated with lower investment demand that can lead to a rate in excess of the equilibrium interest rate, but which is rare and may be unsustainable without a corresponding shift in supply.

[47] Some markets are insufficiently liquid to provide reliable and relevant observable transaction prices, although in some cases external constraints or factors such as liquidity may need to be adjusted for. In such cases, modeling or interpolation/extrapolation of prices relative to overall market conditions may be needed to derive market-based interest rates.

Figure 5 – The effect of supply and demand on interest rates



Based on Song (2017)

One source of observable data at longer durations that could be used for measurement purposes is certain real estate transactions (e.g., difference in prices between leaseholds and freeholds in Singapore and the United Kingdom) of extremely long duration (100+ years). According to various studies, such as Giglio et al. (2016), interest rates of 2.6% or less might be inferred. However, although real estate prices are based on an observable market, they are not usually thought of as a suitable base for market-based rates (that are normally derived from markets involved in financial instrument transactions).

As indicated elsewhere in chapter 5, the use of market-based discount rates can be incompatible with the objectives and applications of social discounting. Although market-based rates can be useful in private sector decision-making where cost and benefit externalities and non-monetizable items are not normally considered, social discounting is more relevant when making public (social) policy decisions, representing the value of the investment from the viewpoint of society in the aggregate.

An example is a situation in which the costs of consequential air and water pollution (social externalities) have historically not been included in market considerations[48]. In contrast, the anticipated cost of required environmental clean-up or operational risks might be expected to have possible serious adverse effects on brand value or sustainability, which have been considered in cash settlements, litigation, and laws/regulations in some cases. In the longer-term example of climate change, external costs associated with emissions have rarely been included in the past, although with increased notoriety

[48] Usually considered as being detrimental, both to the environment and human health.

and enhanced financial statement disclosures, this might change. An assumption that producing emissions can be made for free does not make much sense anymore.

Nevertheless, it is important to understand the case for using market-based rates. A capital market is where inter-temporal financial transactions take place — such as investment, saving, borrowing, and lending. Financial aspects of time and risk/uncertainty preferences of those participating in a market can be observed through a study of its transactions. As indicated in Gollier (2009), the standard arbitrage argument justifies using the rate of return of capital in the economy, as diverting productive capital to invest in projects whose sole, or at least primary, aim is to mitigate the adverse effects of climate change with an internal rate of return below that rate may reduce the aggregate welfare of future generations.

Utilizing a market rate also has the advantage of being capable of being calibrated to publicly available data relating to market prices, although because of the volatility of most markets, its use may result in significant variations in valuations, differing by the date at which discount rates are observed. Although smoothing or averaging may diminish the effect of this problem, the volatile nature of capital markets can in any event unduly affect the expected results of decisions or priorities with long-term consequences.

Nevertheless, descriptionists (see section 5.2.2) view market rates as constituting the best place to start the process of developing social discount rates. They indicate that long-term rates are usually less volatile than short-term rates and it is reasonable to smooth these values, as a small number of transactions may not represent the long-term consensus of the market. Nevertheless, price discovery is an important output of market transaction information. In an era where it seems that almost all governments run budget deficits and many types of projects compete for the same limited resources, the question of using a discount rate different than that used for other public or private sector projects should be viewed with caution. In addition, the context of the application of a social opportunity cost of capital is that available resources are limited, and private and public projects can compete with one another for financing.

Being derivable from and validated by publicly available sources and applied in many types of situations, market-based rates do represent a consistent, objective, verifiable, and practical source of information for determining present values across many types of programs and countries. Willingness-to-pay in the climate change context may be more difficult to derive, as it is often the result of thought experiments or analogous, but different sources. The practicality of obtaining this information on a global basis by direct observation can be problematic, in some cases involving a great deal of subjectivity.

The basis from which prices, and in turn social discount rates, might be obtained, is the amount of utility (social welfare) derived, which in the broadest sense is related to the satisfaction that a person or society derives from consumption of a good or service, or to the change in their welfare or well-being. Because it is difficult to observe utility directly, especially for a large group of individuals, it has traditionally been inferred by observing the choices that people make in related or hypothetical markets. More recently, economists have attempted to directly measure the impact of non-market goods on life satisfaction.

Market rates also reflect the opportunity cost of investing in public (and private) sector projects (opportunity cost discounting). From a financial viewpoint, the case for allocating resources to low-return investments when higher returns are available is weak. However, the issue in the case of climate change-related projects can be difficult to quantify in total. Not considering the effects of potential irreversibility of the opportunity cost of not making mitigation investments because of an artificially high discount rate might make future generations worse off.

Market-based measures are not relevant to many social applications. In contrast, in many actuarial applications, market-based rates (current, prospective, or those for a given existing portfolio) have formed the basis for discount rates. However, this may not be the case in the area of social discounting.

Reasons that market-based rates may not be appropriate as the prime basis for social discount rates include:

- *Time period*. Prices for the period over which social discount rates, especially for mitigation purposes, would apply (e.g., ultra-long term, such as hundreds of years for some climate change risks) are not available, as relevant and comparable financial products from which discount rates can be derived do not exist.
- *Market inadequacies and imperfections*. Markets do not easily reflect such factors as social considerations, uncertainties, non-marginal economic distortions, externalities, non-monetizable items, and political interference or constraints. Imperfections relative to social applications, include illiquidity and short-term volatility that result in rates that are inconsistent with intrinsic values, caused by such factors as size of market, involve multiple sub-markets, change in the mix of participants, and herd trends and over-reactions. Lack of relevant and transparent information can also contribute to imperfections. The use of a low (below-market) rate can overcome some of these concerns.
- *Market participants*. The mix of market participants can differ by term (maturity duration), country of origin, any underlying guarantees, type or extent of liquidity or credit risk, or their taxability. A unique relevant yield curve applicable to the analysis at hand may not exist, even in a single marketplace (although arbitrage or hedging possibilities, if available, can reduce some differences). Especially when comparing interest rates over different time periods and over a range of maturity/call durations, there may be a different mix of participants with differing profiles and needs. Market participants may also have access to asymmetric market-related information, possibly contributing to moral hazard and adverse selection. In addition, as stakeholders, future generations cannot trade on current markets.
- *Multiple market rates*. Size, sophistication, liquidity, and counter-party risks can differ sharply between markets, both within and across national borders, all of which can skew comparisons over time and across markets. Size, illiquidity, and counter-party risks can differ sharply between markets, both within and across national borders, all of which can contribute to differences and skew comparisons over time and across markets. This is especially the case in less developed countries. Types of expected investor returns range from long-term pre-tax real return for stocks/shares to after-tax returns for sovereign and other bonds. Depending upon the credit risk and specific characteristics of the specific project or activity being assessed, rates can differ – a one-size-fits-all private sector discount rate is usually neither available nor appropriate.
- *Externalities* (also see section 2.3). Although conceptually all the costs and benefits associated with externalities and co-benefits, especially those of a social nature, could be reflected in market prices (e.g., by means of comprehensive disclosures and external pressure), it is unrealistic to expect them to be incorporated in transaction prices inherent in private market

pricing. Thus, where externalities are significant, market prices are incomplete and do not incorporate provision for costs or benefits that may not directly affect the owner of the item traded. An example of a social externality is the emissions of greenhouse gases, the emitter of which does not currently bear and certainly does not expect to bear its total ultimate costs or risks, at least in the absence of carbon taxes, are insufficiently large to influence behavior (e.g., as a result of disclosure in an entity's financial statement) or as a regulatory/legal requirement. The tragedy of the commons can also influence overall outcomes. Other examples include increased energy security, greater efficiency, reduced pollution, improved air quality, and the protection of biodiversity and ecosystems (Stern 2015).

- *Non-monetizable aspects* (also see section 8.2.1). Non-monetizable social externalities, such as the devastation of the natural environment and the deteriorated quality of life of forced immigrants, are difficult to quantify and are rarely factored into market prices.
- *Financial instrument base*. Prices of financial instruments, such as government debt, usually form the basis for determining market-based interest rates. They may not be comparable to the characteristics, such as the uncertainties involved, of climate-related investments, which involve more than the financial effects on the stakeholders. For example, adverse environmental risks cannot be easily compared, either quantitatively or qualitatively, to credit or default risks of financial instruments. Financial instruments are also subject to market perceptions of the credit-worthiness of the debtor and market risks, which may not be as relevant to climate change-related investments.
- *Optionality* (also see chapter 9). Markets do not explicitly reflect the value of the types of optionality relevant to climate change. The option to delay actions, for example, as a result of carbon-free technologies to reduce costs or increase benefits, are generally not reflected.
- *Attitudes* (see also section 6.2). Attitudes towards types of risk may differ. For example, individuals may be willing to join in a collective savings program or diversified portfolio, even if they would be unwilling to save as much in isolation. Market stakeholders reflect supply and demand factors that may not be relevant to the underlying issues associated with a social cost-benefit analysis, which involve different aggregate risk preferences.
- *Heterogeneity*. A wide range of attitudes and views exist (observed, for example, through changing market preferences and contingent valuations, influenced by daily and long-term trends and events) among individuals, businesses, governments and politicians, especially regarding social issues and related risks. This contributes to the difficulty in obtaining a consensus acceptable to the participants in a market as to how to address a social issue. This makes it difficult to estimate long-term values, even in a marketplace of ideas, which in any event does not exist.
- *Public projections and projects*. Public perspectives regarding pricing risk often differ from those of the private sector, where a great deal of analysis is based on market prices or indicators. In large part. this difference is due to differences in objectives, such as public safety and sustainability, and stakeholders involved in and affected by public projects. In addition, overall government financing and debt is fungible, except in areas that are walled-off. Nevertheless, many aspects, particularly the process used in the public and private sectors are similar, with risk and illiquidity costs that can arise in either sector that are more a function of the relative strength of project governance, but can be affected by changing public priorities. Much of the cost of these risks is borne by relevant taxpayers and in some cases program beneficiaries. That said, since the ultimate source of public financing is derived from the government's sovereign

power to tax, taxpayer resources ensure its debt is repaid under most conditions[49]. Social problems are rarely sorted out in a practical or ethical manner by the market.

- *Regulatory effects*. Regulators (usually monetary authorities) can interfere with normal supply and demand market forces that can affect market prices and thus interest rates. One example is quantitative easing that would reduce inferred interest rates.
- *Fairness and free-riding*. Legal, regulatory, or judicial actions can create subsidies to promote affordability or force purchasers of financial instruments to pay at least a fair share of the estimated total net costs or to pass the costs to the ultimate users (see section 7.3 for a discussion of free-riding). In practice, fairness can be difficult to regulate and apply in a consistent manner.
- *Generational issues*. Members of the present generation may be more concerned with the impact of their current activities on (1) themselves or (2) their childrens' generation. As markets generally only reveal the preferences of the current generation and tend to heavily discount concerns for long-term sustainability, current market-based rates may not be applicable, as those currently alive bear some ethical responsibility for future generations (see section 7.2 for further discussion).

As a result of these factors involving the market, many, especially prescriptionists (discussed in section 5.2.2), have concluded that market-derived interest rates do not represent a sound basis for social cost-benefit analysis.

As suggested in section 5.1, social discount rates should in most cases be less than observed or projected market-based rates. The extent to which social discount rates differ from (i.e., are lower than) market-based rates may depend upon one or more of the above bulleted items. For example, the uncertainties involved in climate change risks and the relative importance of social externalities, which may be larger for mitigation than for many adaptation projects and may depend on the time and risk attitudes of the social cost-benefit analysis user. In addition, in contrast to private sector assessments that would use a marginal framework, public sector assessments it may be more appropriate to utilize an aggregate, rather than a marginal framework (see section 2.4).

Robson and Szentes (2014) argued that individuals tend to exhibit more patience if decisions are made collectively, rather than individually. To the extent this is the case, using individual consumption-saving behaviors to implement social policy would be flawed. While individuals choose the amount they accumulate in private capital, the contribution to public capital and public goods is determined in a collective manner. Thus, although a market rate may be appropriate for decisions of an individual or even the participants in a capital market, a social rate would be more appropriate for community or public policy decisions.

The key take-aways from section 5.3 include:

- It is far from clear that the discount rates people use when making financial decisions should be applied to questions of social and environmental policy that will affect current and future global populations.

[49] Unless the government is too heavily indebted relative to its practical ability to collect taxes, in which case interest costs and possibly sovereign risk of the governmental unit can increase.

- A market-based measure is not an appropriate basis for use in a social cost-benefit analysis of climate change projects for a myriad of reasons. These include market failures and market imperfections that do not consider the unique characteristics of climate change, including its ultra-long time horizon, lack of reflection of social externalities, its uncertainties, and the fact that it deals with a public good.
- The desirable approach to social cost-benefit analysis is to apply social discounting to the social cost-benefit analysis of climate change-related projects.

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Key take-aways from chapter 5 include:

- A foundational approach for discounting over a long time horizon has been the Ramsey formula, a growth-related basis to setting social discount rates for safe social investments; it contains both a precautionary factor and a wealth effect;
- Concerns regarding the Ramsey formula that have been raised include its inattention to uncertainty, it assumes that costs and benefits are marginal, and it assumes that the primary consideration in determining social discount rates is the ability to afford an investment, rather than on its irreversible effects;
- A wide range of estimates of the terms of the Ramsey formula have been made by involved economists;
- Two primary economic schools have developed fundamental basis for derivation of social discount rates: descriptionists who rely on market-based interest rates and prescriptionists who rely on ethical considerations, especially as they relate to intergenerational equity and other social externalities; and
- Social discounting, rather than market-based discounting, is appropriate in carrying out a social cost-benefit analysis of climate change-related projects

Chapter 6: Uncertainty

The purpose of this chapter is to explore the effects of uncertainty on social discounting. Uncertainty is a fundamental element associated with the future, especially relating to the many aspects of climate change risk. It will always be with us. Key elements of uncertainty particularly applicable to this discussion include social attitudes toward risk and uncertainty (section 6.2) and the tail portion of involved probability distributions, particularly relating to unusually large amounts of damage (section 6.3). We will not likely be able to resolve these uncertainties in the next several decades, but we can better understand them and may be able to manage some of their consequences.

6.1: Uncertainty and its effects

Although time is a fundamental factor inherent in the determination of social discount rates, risk and uncertainty are also crucial elements to be considered in all cost-benefit analyses. Together, they are the fundamental components of the time-risk framework of decision-making and are intimately related.

In the case of climate change, although social cost-benefit analyses are generally focused on assessing the expected costs and benefits involved, they also need to address uncertainty, ambiguity, and inadequate knowledge of certain underlying processes and of the future. Uncertainty fundamentally affects the willingness of economic agents to defer consumption and can adversely affect future income levels and productive capacities in exchange for reduced climate risk.

However, it can be difficult to decompose the intertemporal and uncertainty aspects of the discounting process. The precise extent of future climate change and its economic and human consequences remain uncertain, as are the political/societal responses to both its drivers and mitigants. It will remain difficult to estimate the timing and severity of these costs and damages.

Dixit and Pindyck (1994) identified three categories of uncertainties:

1. *Technical uncertainty*. Physical factors that contribute to a specified amount of atmospheric greenhouse gases or oceanographic CO_2;
2. *Impact uncertainty*. Losses and damages associated with climate change, and the effects of mitigation and adaptation measures taken; and
3. *Public opinion / risk aversion uncertainty*. Factors involved in deriving value, including attitudes toward uncertainty, are associated with the value of the costs and benefits, including weights associated with intertemporal factors and value statements applicable to various aspects of life and other resources.

Climate policy is all about managing its uncertainties. Uncertainties regarding benefits and costs/damages can affect policy design in at least four fundamental ways, through:

1. *Policy technique*, i.e., whether greenhouse gas emissions are best controlled through a price (e.g., an emissions tax) or a quantity-based instrument (e.g., an emissions quota);
2. *Policy intensity*, e.g., the size of tax, the optimal level of mitigation, or size of insurance premium;
3. *Timing of policy implementation*, i.e., whether it is best to put an emissions tax in place now, or wait several years (increasing currently caused increases in cumulative atmospheric greenhouse gases, offset by enhanced future technologies and a future reduction in uncertainty); and
4. Resources devoted to the *mix of mitigation and ex-ante adaptation*, as well as the consequential ex-post adaptation.

In general, the longer the analytical time horizon, the more important the subtle or all-encompassing trends, catastrophic events/conditions, and discontinuities will be. Such trends, events, and discontinuities are not conditions that fall neatly within a specific range of probable outcomes. Thus, there is an element of significant uncertainty that cannot be diversified away, even by governments. This uncertainty cannot be ignored over the long term, as the range of possibilities can balloon in size and broaden in scope as time goes on. This range can be developed for the assumptions, intermediate values, and outcomes, and be expressed in terms of, for example, emissions, climatic factors, or net present values of the resulting losses and damages.

Therefore, an important question is whether the discount rate for the corresponding costs and benefits should include a risk/uncertainty premium (margin), and if so, how it should be determined and applied. Alternatively, the amounts to be discounted could be expressed in terms of risk-adjusted (certainty-equivalent) amounts, although that approach could be less transparent, flexible and practical. This approach could also make comparisons with alternative investments and strategies more difficult. This is especially true in the case of social discounting climate-related benefits and costs because of their unique characteristics (see section 3.3).

Actuaries are involved in other situations in which the effect of uncertainty could either be (1) expressed as a function of the estimated amounts to be discounted (e.g., cash flows or their equivalents) or (2) reflected as a function of the discount rates. Since the many factors involved in the estimation of the amounts being discounted cover such a long period of time and are so complex involving multiple feedback loops and interrelated, the probability distribution(s), in most cases, the appropriate adjustments may be best expressed in terms of a reduction in the discount rate[50].

Which of the two approaches is used is often determined by the application or the approach historically taken in similar circumstances. Incorporating uncertainty as part of the estimated cash flows (or equivalents) can be more transparent if determined explicitly, possibly as a function of the expected volatility of the cash flows. In any case, the actuary has to ensure that risk and uncertainty are neither ignored nor double-counted (i.e., as part of the cash flows and as part of the discount rate). One approach that has been taken is to use a risk-adjusted discount rate applied to several alternative scenarios, although it has to be determined whether a scenario-specific uncertainty adjustment should be applied. In general, scenario-specific discount rates should be applied, as applicable.

If a probability distribution(s) for the individual assumption or an aggregate set of assumptions or outcomes have been estimated, a value may be able to be calculated by means of a statistical technique, such as at 5% and 95% confidence levels or through qualitative assessment categories according to the extent of confidence in the estimates. The expected cost of risk and uncertainty can be reflected using various methods – in addition to modeling through scenario analysis and stochastic (Monte Carlo) modeling, they include a subjective adjustment of expected costs and benefits for prudence, reducing the social discount rate, overweighting the expected value of tail conditions, and varying the period over which costs and benefits are considered (see section 8.2.2).

Through the latter part of the twentieth century, a common economic approach was to reflect the effect of uncertainty through the use of monetary equivalents, which were then applied to the results of the Ramsey formula, rather than through adjustment of the social discount rate (U.S. EPA 2000). More recently, the tendency has been to adjust the social discount rate.

A typical approach taken in cost-benefit analyses in the private sector is to incorporate uncertainty (and desired return for taking on risk) as an increase in the discount rate. This is partly because investors need, indeed demand, to be compensated for taking on uncertainty, that is, to reflect the possibility that the desired or expected return will not be achieved. Since there is a possibility that those that emit greenhouse gases may be found liable for such actions through litigation or regulatory enforcement, consequential costs may arise. The more distant in time the benefits and costs are, the less weight is assigned to the consequences of actions (and inactions) over those periods. This contrasts with the social discount process, where certain costs (social externalities) are considered that would otherwise not be incorporated. To ensure the proper direction that such an adjustment is taken, a practical check is to view the effect on the result, e.g., if prudency is a desired consideration, the direction of the net effect of costs and benefits should be examined.

[50] Other issues associated with adjusting the cash flows for uncertainty include: the derivation of probability distributions for the cash flows and non-monetizable effects (see section 8.2.1), the significance of the tail (see section 6.3), the interactions of the elements (variables) involved, and how and the extent they affect stochastic modeling or scenario analysis (see chapter 11 for further discussion).

The modern distinction between economic risk and uncertainty was introduced in Knight (1921)[51], who distinguished between situations where the outcomes (1) were unknown but governed (estimable) by probability distributions known at the onset (such as tossing a fair coin) and (2) although likewise subject to stochastic variations (random), are governed by an unknown probability distribution or model. Knight indicated: "The essential fact is that 'risk' means in some cases a quantity susceptible of measurement, while at other times it is something distinctly not of this character; and there are far-reaching and crucial differences in the bearings of the phenomena depending on which of the two is really present and operating… It will appear that a measurable uncertainty, or 'risk' proper … is so far different from an unmeasurable one that it is not in effect an uncertainty at all."[52] Uncertainty, as to the extent that the expected mean of the probability distribution is incorrect, is often referred to as Knightian uncertainty.

In contrast to Knightian uncertainty, some think the major element of uncertainty involved in climate change analysis is qualitative uncertainty/ambiguity[53], in that it is one of timing, rather than of frequency or severity. This suggests that uncertainty would be best reflected in discount rates.

The determination of the social discount rate in a situation in which the amount of uncertainty changes or is expected to change represents a problem of welfare optimization. This contrasts with the original Ramsey-like approach in a cost-benefit analysis where the underlying stochastic process collapses to a stationary distribution as a deterministic variable. The explicit consideration of the stochastic nature of climate change and[54] its underlying volatility is sufficient to justify lower discount rates than are generally used in other project evaluations[55].

In classical economics, both a known probability distribution and an expected utility function are given or assumed. In contrast regarding climate change risk, although information regarding the relative likelihood of certain types of outcomes may be available, a large tail risk (see section 6.3) exists that represent more extreme conditions for which limited, if any, experience data is likely to be available. Therefore, there may not be sufficient nor objective historical information to form a credible and complete probability distribution that is relevant over a long time period. As a result, the focus in this context is on expected values and uncertainty, rather than risk or short-term statistical fluctuations. In addition, since the size of the effect of a tail event or condition might be quite dramatic, such probabilities and severities of future damages have to be considered with caution. Uncertainty is relevant to both descriptionist and prescriptionist schools of economic thought.

Significant uncertainty should induce policymakers and consumers to sacrifice at least some current resources to prepare for a range of possible futures[56]. In a social cost-benefit analysis, the use of a smaller discount rate should result in a government being willing to pay more to undertake a project with greater assurance. On an individual level, it may be proportional to the variance of the growth rate of consumption times the relative aversion to downside risk (see section 6.2 and formula (5)). This can

[51] Further elaborated in Gutterman (2017).
[52] Knight. (1921), 19-20
[53] For the purpose of this paper, the effects of ambiguity are generally included with the effects of uncertainty.
[54] Usually an objectively derived distribution, although in some cases subjective elements could also be considered.
[55] Although much of this paper deals with the effects of the risk and uncertainty associated with climate change, project finance risk (selection and implementation) regarding mitigation and adaptation projects should not be forgotten – these are generally treated in the same manner as any other project finance risk and are reflected in the costs of such programs.
[56] The notion of precautionary saving was first introduced by John Maynard Keynes.

be conceptualized as consumption smoothing (an economic approach) or, as Weitzman (2007) indicated, as to how much insurance to buy to offset the small chance of a ruinous (or near ruinous) catastrophe that is difficult to prepare for by ordinary savings.

Sources or areas of uncertainty directly related to climate change or its consequences, which exist over the trajectory from greenhouse gas emissions to consequential losses and damage, including:

- *Greenhouse gas emissions*. The amount of these emissions, whether from public, private, or natural sources, especially as they result from human behavior or decisions;
- *Climatic factors*. The relationships, feedback loops, non-linearities (e.g., tipping or inflection points) among and within ecological systems, and exchanges between the atmosphere, ocean, and biomass, as well as CO_2 absorption capacity and the impact of clouds involved in the climate change process;
- *Losses and damages*. The extent of the direct and indirect effects, losses, and damages resulting from climate change, including concentration, significant regional differences, and asymmetric and non-linear risks such as natural disasters, which affect economic (GDP) and social costs, property, sea conditions and human health;
- *Mitigation and adaptation*. The extent and effectiveness of mitigation and adaptation actions, which may reduce climate change-related losses and damages and their uncertainty; overall, the extent of climate change and its net damages are affected by human, business, and governmental behaviors in response to incentives and financing approaches, e.g., taxes and trading schemes;
- *Society's preferences and attitudes*. These include society's priorities and risk tolerance, and willingness to pay for effective management of risk, especially with respect to the time scales involved;
- *Technology*. Development and effective application of both low and high technological approaches to mitigation and adaptation. These approaches include new or enhanced sources of carbon-free energy, carbon capture and storage[57], enhanced/smart agricultural and land use techniques, and back-up power generation and alternative planned programs of rapidly getting health care professionals/supply/equipment to appropriate sites during natural disasters. Since most IAMs assume negative net emissions beginning in several decades, it is important to develop technologies that enable this to happen;
- *Economic growth*. Although most of the uncertainty discussed in this paper focus on the losses and damages directly due to climate change, the consequential effects on the economy is also of concern, both in terms of contributions to climate change and its temporary and permanent consequences. Most IAMs make their projections by including a damage function that relates temperature change to lost GDP, but those damage functions tend to be based on judgement. The pandemic of 2020 shows that the economic disruption in local or worldwide disasters can be considerable. It is also an element in formulas (4) and (5) in the Ramsey formula. Nevertheless, it is worthwhile to note that, although the volatility and resulting uncertainty associated with real economic or GDP growth can be significant, average growth over a long-term period (say, 20 to 100 years) may not be as uncertain as the corresponding uncertainty over a short period;
- *Political and regulatory constraints*. The extent to which the strategy or project being analyzed might be terminated or modified prior to achievement of their objectives due to political or regulatory actions, or lack thereof is one example of such possible constraints;

[57] However, if a sufficiently large incentive is provided, increased emissions may occur that could offset at least some of the amount stored.

- *Models*. The multiple assumptions incorporated into climate and economic models require, by necessity, a simplified representation of the real world. This can introduce parameter and model risk[58]. However, the search for increased accuracy by introducing more variables may increase model complexity, which if over-refined, can also introduce spurious accuracy – there will always be a tension between the complexity and accuracy, the resolution of which will depend upon the importance of the model and sensitivity to the assumptions used, suggesting the need for prudent[59] methods or assumptions and transparency; the use of multiple models may help, although weighting the results from such models may not always represent a panacea[60]; and
- *Social discount rate*. Based on the existence of thousands of papers/articles/books on social discounting, a great deal of difference of opinion regarding the proper discount rate itself exists.

Differences in opinion has arisen as to whether climate science or the economic components generate the greatest amount of uncertainty in estimates of value generated by climate modeling[61]. In any case, the three major areas of uncertainties that affect model calculations are arguably: (1) the sensitivity of the climate to greenhouse gases, (2) the level of damages expected over the range of possible temperatures and other climatic elements, and (3) the social discount rate applied. To some extent, the determination of the uncertainty in all three areas have to be based on or at least influenced by the subjective judgement of experts, as society has not experienced the entire range or effects of likely future climate changes. In any case, overall estimates of the value of losses and damages cannot be more precise than the most uncertain component.

The uncertainties involved in mitigation and adaptation s and their effects can differ (see section 3.5). In most cases the degree of uncertainty regarding the mitigation process may be larger than that of adaptation, in part because of its global sources, the different timeframes involved, and the complexity of the climate change process (see chapter 3).

Some of the reasons why these uncertainties differ from those involved in other public policy issues somewhat mirror the unique characteristics of climate change risk, that is, differences between climate change and other projects (see section 3.3), include, based on Pindyck (2006):

- *Complexity*. Exacerbating uncertainty are relationships and patterns that tend to be non-linear, possibly with multiple tipping points. For example, damage is isolated and mostly barely noticeable globally at low levels of climate change, while a tail scenario outcome might be catastrophic. Substitutability and timing of changes between energy sources and other accumulated greenhouse gases can be affected by actions of countries around the world.
- *Irreversibility and social externalities*, including co-benefits. These factors involve accumulated greenhouse gases in the atmosphere/ocean and huge sunk costs needed for mitigation and

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[58] A classic triad of risks consist of model risk (risk that the model is wrong, that is, either the structure of the model or the variables considered), parameter risk (that the variables considered has been assigned the wrong values) and process risk (deviations from expected due to stochastic processes). Over a long-term horizon, it is usually the first two types of risk that are of most significance.
[59] In this case, prudent methods or assumptions can lead to risk margins/prices, such as through the use of a reduction in the social discount rate applied.
[60] Although consideration of multiple models is desirable, a simple average of their results should be used with caution, as several of them may use the same methodology or assumptions. Where practical, a comparison of assumptions and model projections to observation should be made (which may be a challenge due to the timeframes involved) and the sources of the differences explained, with the aim of improving the models.
[61] For a discussion of the uncertainty of combining climate and economic uncertainty, see Barnett (2019).

adaptation. In addition, second order effects, e.g., ocean acidification, sea level rises, hurricane/cyclone intensity, loss of diversity and economic activity, food shortage/famine, pollution, and destruction of ecosystems, can be severe and regionally/locally diverse.

- *Impact*. The range of possible impacts and damage runs from the mere inconvenient to the existential. They can involve intergenerational and intragenerational issues. The effects can include massive health, property, and environmental damage, consisting of short-term (e.g., sudden natural disasters) and long-term / permanent (e.g., sea level rise) impacts. They can result in emigration from a local area or from a country, as a result of famine, drought, or direct or indirect damage. Such mass emigration can not only affect those who emigrate, but also those who remain and the community that receives them. Examples of emigration due to drought include parts of Central America, Africa, and the Middle East. The behavioral responses to a disaster (e.g., due to floods) can range from permanent relocation to rebuilding homes in the same hazard-prone area. Policy actions can have significant and possibly disruptive first and second order regional or global economic and human effects.
- *Asymmetric risk*. Although many other issues create costs that are asymmetric in nature, climate change contains an especially high degree of uncertainty and asymmetry because, for example, there is lack of independence of costs. For example, floods can affect an entire community rather than just an individual house. In addition, there is often chain-of-events risks, where a high amount of rain causes flooding that in turn can cause disease, widespread property damage, and emigration. Damages, especially measured as a percentage of resources, are likely to overwhelmingly affect the most vulnerable, who can least afford the costs associated with climate change. The especially difficult to quantify aspects of the climate change process naturally increases the extent of uncertainty.
- *Benefits*. Although the emphasis on this and related papers is on the adverse effects of climate change, there are some who may benefit from warmer temperatures, especially those who live in moderate temperature zones, and those whose jobs/activities are related to transition, mitigation, or adaptation efforts.
- *Long time horizons*. Most trends actuaries are involved are measured in years or a few decades. In contrast, climate change risks may involve multiple decades or centuries, crossing generations. As a thought experiment, it may be useful to think about the decisions made regarding the desirability of burning coal at the beginning of the industrial revolution less than 200 years ago, that enhanced the consumption and well-being of historical generations but threaten the well-being of future generations.

Some researchers have incorporated the effect of uncertainty into an extended Ramsey formula (5) by including a third term that reflects a precautionary effect. The contribution of this term is usually smaller than the second term. It reduces the social discount rate r, which results in greater quantitative justification or a lower threshold for climate change-related investments involving mitigation or ex-ante adaptation. Generally, if the decision-maker is risk averse or ambiguity averse, that is, the decision-maker acts with (uncertainty) prudence, there is a greater concern and therefor greater propensity for action to eliminate, or at least reduce, the adverse effects of uncertainty and surprises. In any case, an excessive amount of prudence should be avoided.

$$r = \rho + \eta\, g - \tfrac{1}{2}\, P\, \sigma^2(g) \qquad (5)$$

where P = a measure of prudence leading to precautionary saving and the variance of expected rate of growth, $\sigma^2(g)$. Gollier (2011) determined that P should be expressed as $\eta\,(\eta + 1)$, but in most cases can be approximated by the term η^2. Thus, formula (5) can also be expressed as:

$$r = \rho + \eta\, g - \tfrac{1}{2}\, \eta^2\, \sigma^2(g) \qquad (6)$$

Weitzman (2007) included the third term to provide for the uncertain types and effectiveness of future technological changes and enhancements, and for the uncertainty of the discount process itself. Growth, assumed to be subject to independently and identically distributed shocks, is unlikely to materially alter the consumption rate of discount. If, however, shocks to growth are positively correlated over time, this reduction could become sizeable in absolute value over long horizons, leading to the use of a declining term structure of discount rates (see section 8.1.1). Because of its nature, the time effect of uncertainty, although small initially, can become quite large at long durations, possibly even to the point of turning the discount rate negative.

It is problematic to derive a single probability distribution that accurately captures the long trajectory to and sensitivity of damages to a range of varying climatic conditions. It certainly consists of several aggregated and ever-changing distributions. This is partly because conditions, interrelationships, and damage sensitivities can differ radically from those of today. The level, trend, and volatility of these climatic factors, e.g., too little precipitation can lead to drought and famine, while too much can lead to rain bombs, floods, and landslides.

Measures of uncertainty can take several forms, including standard deviation, variance, coefficient of variation, and inter-quintile ranges. One approach to estimating these metrics is to select the riskiest parameters and model inputs, e.g., temperature sensitivity, damage function, growth, decarbonization and discount rates, determine their past values and variability, and estimate how climate change might change their ranges/stresses and volatility. Then use these results to derive estimates of the cash flows or the extended Ramsey formula parameters (or another discount rate model) from estimated deviations from these historical values.

Kelly and Kolstad (1999) evaluated the amount of time needed to significantly reduce uncertainty regarding the parameters influencing climate sensitivity (e.g., the relationship, including the lag, between greenhouse gas concentrations and long-term global average temperature change) by observing the trajectory of global warming. They found the time to be between 90 and 160 years. Leach (2007) conducted a similar analysis that allowed two independent sources of downstream uncertainty. In that case, the time required to resolve the climate sensitivity parameters was found to be even longer.

Pindyck (2006) provided the following to illustrate the effect of uncertainty in the selection of social discount rates. As the discount (non-market based) rate is uncertain, the expected discount factor is greater than the discount factor calculated using the expected value of r, the social discount rate. As an example, suppose a cost-benefit analysis is conducted to evaluate the expected present value of a $100 benefit received 100 years from now, and that the 'correct' discount rate over the entire 100-year period is expected to be either 0% or 10%, each with probability of 50%[62]. If the expected value of the

[62] Although this range may be unrealistic, it was used to illustrate the importance of discount rate uncertainty.

discount rate is 5%, the $100 future benefit will have a current present value of less than $1. If the true discount rate turns out to be 0%, the present value would be $100, while if the discount rate turns out to be 10%, the present value would be close to zero. The expected present value of the $100 benefit would then be ($100)/2 + ($0)/2 = $50. The discount rate when applied to a $100 benefit received in 100 years that would yield a present value of $50 is about 0.7%. Thus, even though the expected value using a discount rate of 4%, this uncertainty implies an *effective* discount rate of less than 1%. Thus, discount rate uncertainty reduces the effective discount rate used to calculate present values.

Stern (2015) suggested that, because most IAMs had historically grossly underestimated the risks associated with climate change and there has been seemingly never-ending worse news about temperature, such as melting of glaciers and natural disasters, a relatively small social discount rate is needed to reduce potential bias in a social cost-benefit analysis involving climate change. In addition, the parameters used in many IAMs may have over-estimated the cost and scalability of new zero-carbon technologies and carbon capture and storage and do not adequate account for co-benefits and non-monetizable effects. Although this argument does not directly relate to uncertainty, it does address the related likelihood of projection bias and the uncertainty involving the derivation and use of current projections. Although two wrongs do not make a right, a possible approach to overcome this problem would be to both develop of an offsetting downward adjustment in the social discount rate and disclosure regarding the qualitative aspects of uncertainty.

The key take-aways from section 6.1 include:

- Uncertainty is a crucially important factor to consider in the application of the time-risk framework underlying the social cost-benefit analysis of climate change-related efforts.
- The sources of uncertainty are inherent throughout the climate change process and can significantly affect the results of a social cost-benefit analysis.
- Although methods used to incorporate risk and uncertainty can be applied to the estimated cash flows or the discount rate applied, because of factors such as the unique character of climate change risk, the importance of transparency concerning the basis of the cash flow projections, and the existence of potentially non-monetizable costs and benefits, in most cases it is better practice to adjust for uncertainty by means of a decrease in the social discount rate applied; and
- Uncertainty can also be considered and communicated through the choice and description of alternative scenarios used or the range of estimates provided.

6.2: Risk attitudes

Risk-bearing is a powerful activity to which most people are averse, especially when subject to a possible loss, i.e., being loss averse. For example, a small chance of a large loss with uncertain timing (even at a distant point in time) can generate a substantial willingness to pay for avoidance, especially if the loss will be felt personally or by one's children. A potential catastrophe represents an extreme loss scenario, although this can be somewhat tempered when viewed from the perspective of being in a developed country with a smaller likelihood and loss potential than being in a less developed country, both in terms of being personally affected and affordable.

Personal and societal attitudes and behavior toward risk and uncertainty (and loss) are important factors to consider in any type of cost-benefit analysis. In determining whether a strategy or program should be undertaken, one of the key questions is: how much risk and uncertainty should an individual or society subject itself. This is especially relevant when asymmetric or tail expectations exist. Risk-related attitudes involve risk preference, risk and loss aversion, risk appetite and risk tolerance. Social risk aversion is the attitude most relevant here. In addition, attitudes toward other factors, including the relative importance given to the economy, environment, health status and quality of life are also relevant to a social cost-benefit analysis.

Some of those in developed countries may not accept the fact that they will incur extreme loss, and do not think about those who are vulnerable and distant, when they are more concerned with their day-to-day security and income. However, fear can be a significant driving force when associated with a low-probability but catastrophically-high damage to future society and economy scenario.

Fairness is also a powerful personal and subjective concept. What is considered fair can be quite different when viewed on an individual, rather than a societal viewpoint. Fairness involves political consideration of the allocation of limited resources between, for example, developed and developing countries, the well-off and the vulnerable (who are usually the most affected), jobs and economic growth for current voters and their future well-being, and multiple generations. In this paper, discussion of the fairness concept is generally avoided, with a focus on the extent and preferences toward risk and uncertainty instead.

When confronting choices, most people and societies are uncomfortable in the presence of (averse to) risk, uncertainty, loss, and ambiguity[63]. Behavior is therefore affected by incentives to avoid risk or loss. The study of such behavior is referred to as behavioral economics. This discipline is particularly applicable to an expectation of loss that is asymmetric in nature, that is, a higher likelihood of extreme rather than limited losses. This is amplified when something of greater value is involved.

The discovery of average societal attitudes can be problematic and may not be usefully expressed in terms of an average of individual views, as in many cases individual attitudes are quite disparate. If this heterogeneity is applicable, it may be useful to study and report on the results of alternative scenarios. In addition, given the high degree of uncertainty in most forecasts of the effects of climate change and the effectiveness of alternative mitigation or adaptation strategies, it is important to consider the risk attitudes and appetites of decision-makers and what they believe to represent those of society as a whole.

Time is also a key factor in deciphering social risk aversion regarding a possible adverse event, comparing one that is expected to occur in 50 years, rather than to occur next year. As indicated earlier, time preference is highly related to risk preference. Time preference is also subject to personal and societal attitudes, which may depend upon the object being discounted. Both risk and time preferences may be more important for non-monetizable items, e.g., the value of a life (or lives), than cash flow equivalents. Psychological experiments suggest that most people tend to overemphasize short-term risks and rewards compared with long-term ones. Similarly, people attach more weight to risks that appear directly in their line of sight, that is, immediately after a disaster or in their immediate area, rather than something that occurred a century ago or far away, especially if it involves a somewhat abstract threat.

A specific level of risk aversion can be viewed as being equivalent to an increase in the amount of uncertainty – how much society is willing to spend now to avoid problems (risk) at a later time. Various approaches have been taken to quantify risk aversion (see section 6.1 for further discussion). The extent

[63] Together, aversion to risk, uncertainty, loss, and ambiguity in this paper are referred to as "risk aversion".

of risk preference and prudence indicates the intensity of the desire to defer consumption and accumulate savings for precautionary reasons. As the level of risk aversion increases, prudent behavior tends to reduce present consumption (or correspondingly increase precautionary savings or invest in mitigation and adaptation) to be in a better position to manage and respond to future adverse circumstances. The greater the curvature (concavity) of the expected utility function, the greater the degree of risk aversion.

As indicated in section 6.1, discount rates are closely related to the risks and uncertainties involved. A smaller discount rate might be more applicable to something of greater importance or value, such as loss of life, rather than loss of a material possession. Since many risks are non-diversifiable[64], their measurement includes the risk of individual projects, as well as systemic risk that affects, say, an entire industry or population segment. Non-diversifiable risk is the project's risk that cannot be diversified away, since it correlates with the aggregate (macro-economic) risk of society's portfolio. Risks that can be fully diversified in a government's portfolio are not relevant to establishing discount rates, since adding them to the portfolio does not change its riskiness. This is consistent with the Arrow-Lind theorem[65] and the CAPM approach.

If a project contains only diversifiable risk and no market risk, an efficient private sector may be able to spread the risk and use the risk-free rate to discount expected project returns. If the risk is perfectly correlated with the average returns on all other investments or if it cannot be reduced by transferring it between, say, the private and the public sector, it is an appropriate risk to reflect. Most private sector and social cost-benefit analyses should use a discount rate or cash flow equivalents that incorporate the risk premium corresponding to the risks borne.

Risk-sensitive and Epstein-Zin[66] preferences can provide for the disentanglement of risk and time preferences, thus rendering it possible to study the effect of a change in risk aversion alone. Attitudes toward risk/uncertainty and time do not necessarily have to be the same. Risk aversion and preferences can differ by individual and country because of such factors as different assessments of uncertainty and

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[64] For example, shocks such as a recession, a sudden discontinuity in overall market returns, or loss of life.

[65] The Arrow-Lind (1970) theorem is based on risk spreading. If all individuals in a society are identical and share all costs and benefits equally, then as the number of individuals increase, the share of the risk carried by each individual decreases, and the individual's welfare cost from the risky project decreases. Arrow and Lind showed that society's total welfare loss from risky project decreases as the risk is spread. When the number of individuals approaches infinity, the randomness of the project does not affect social welfare. In other words, the spreading of risks to many individuals implies, under a number of conditions, that a project can be evaluated only on the basis of its expected net present value. The result questions the need to reflect risks when undertaking a cost-benefit analysis. However, the Arrow-Lind theorem is based on assumptions that are unlikely to be met: (1) in no case can risks be spread among an infinite number of individuals – there will always remain risks borne by society, (2) it is unrealistic to share risks equally by all individuals, partly because in this case climate change damages are not shared equally and individuals cannot transfer all such risks, and (3) the risk spreading argument breaks down if the risks take the form of an externality that affects everyone equally – damages will not be reduced when the number of individuals increases and in fact can increase.

[66] A recursive utility function constructed from a time and risk aggregator with respect to future utility. With Epstein–Zin preferences, the time aggregator is a linear aggregate of current consumption and the certainty-equivalent of future utility, allowing for the independence of the two factors.

exposure to loss, relative reliance on ex-ante and ex-post adaptation, their risk (or loss) preference or tolerance, cultural background, and politics (i.e., who is in charge)[67].

Insurers are compensated for and governments bear the responsibility for many financial risks. In some cases, a simple framework can be developed to illustrate the issues involved and how discount rates, risk aversion and probabilities interact. The complexity of the climate change process can contribute to the difficulty in effectively communicating its effects.

Weitzman (2009) indicated that even a moderate degree of risk aversion can significantly enhance the effect of discounting by increasing the risk-adjusted probabilities of low-productivity scenarios, thereby putting greater probability weight on scenarios with lower discount rates and low endogenously-chosen consumption levels. This is equivalent to a decrease in social discount rate.

Two commonly applied expressions of risk aversion are: (1) expected utility, which exhibits a constant absolute or relative risk aversion with respect to consumption, such as the Arrow–Pratt measure[68] of risk aversion, and (2) hyperbolic absolute risk aversion (HARA[69]), the most general class of utility function applied in practice.

When reviewing the results of risk modeling, findings are often expressed in terms of degree of confidence, in some cases expressed as confidence levels. Where no numerical probabilities are available or quantitatively, the degree of confidence is usually expressed in a qualitative manner, e.g., high, moderate, or low degree of confidence. These expressions of confidence can influence the attitude of the stakeholder toward the need for and risks of the project or investment.

Possible optimism bias, a pervasive tendency for systematic optimism regarding the costs and benefits that often occur when uncertainties are not considered, should be considered. This human characteristic affects both the private and public sectors, especially regarding low probability events. The choice of many model parameters can be affected by optimism, as appraisers tend to overestimate benefits, and underestimate timing and costs, both regarding capital and operations. It needs to be remembered that, although most focus on social risk management is on adverse effects, there may also be favorable deviations from those expected. Downside and upside risks should be assessed and considered in expected value estimates and decisions.

In contrast, prudence may require additional accumulation of capital or a greater amount of preventive or adaptive actions that could be used to fuel growth in excess of its return over the social discount rate. Although usually associated with private sector finance, this perspective can also apply to the public sector, accompanied by decreasing debt and increasing savings and investment in future development of human and physical resources. With no uncertainty, postponing consumption to achieve higher consumption (growth) in the future works only to the extent that the return on the capital committed exceeds the rate of time preference.

[67] Especially politicians who may be more concerned with a short-term time horizon and who might be considered as being populist, rather than on issues seemingly outside of one's ability to influence and are primarily of a long-term nature.
[68] A negative constant multiplied by the second derivative of the utility function, divided by its first derivative – its derivation and application is outside the scope of this paper.
[69] Hyperbolic Absolute Risk Aversion, a characteristic of utility in which the level of risk tolerance, the reciprocal of absolute risk aversion, is a linear function of wealth.

Analysts should explicitly adjust for these aversions and biases where practical. This can take the form of decreasing the social discount rate, increasing estimates of the costs, and decreasing or delaying the receipt of benefits. Sensitivity analysis is often needed to test assumptions about the expected value and range of costs and benefits.

The key take-away from section 6.2 is:

- Risk aversion, especially as it faces the possibility of loss, can magnify the effect of and attitude toward uncertainty, and thus increase the reduction in social discount rates due to uncertainty.
- Where practical, adjustment for personal or societal preferences should be made explicitly.

6.3: The tail

Weitzman (2009) and Pindyck (2006) indicated that what matters in many social cost-benefit analyses of climate change is the tail of the assumed (asymmetric) probability distribution[70], e.g., the significant effects of one or more severe catastrophes or economic contractions over the next century. Pindyck (2020) indicated that it is this tail possibility, even if its probability is low but that society as a whole believes is possible, that might drive society to rapidly adopt stringent emission abatement policies, similar to taking out an insurance policy against that possibility. In light of the extreme damage potential of a tail scenario and the level of confidence associated with its timing and severity, a big question is how much is society willing to pay in the short-term to reduce such tail events or conditions?

The uncertainty, asymmetry, and especially the tail associated with climate change damages are reasons why restricting a social cost-benefit analysis to the quantification of average (expected) values needs to be supplemented by a study of a range of probable or possible amount of damages. While uncertainty and asymmetry are addressed in section 6.1, some important aspects of the tail will be discussed in this section. The economic cost resulting from many unlikely but severe events or conditions can be enormous and can, depending upon the scenario, overwhelm the other more likely but less catastrophic economic costs and benefits in a cost-benefit analysis.

To understand the costs and benefits associated with the mitigation of and adaptation to tail risks, more than one adverse scenario will often be developed. To reflect these scenarios in a social cost-benefit analysis, it is important to identify and report on the range of tail scenarios. This range may be somewhat subjectively chosen, usually relating to where in the probability distribution the tail is estimated to lie (e.g., in excess of the 95th or the 99.5th percentile confidence interval) or for comparison purposes specific IPCC scenarios.

The minimum-tail scenario could represent an estimate of the maximum cost that society is willing to bear, possibly determined on a case-by-case basis. This might consider the condition that society would consider its sustainability being in jeopardy (e.g., of necessary infrastructure, health, and welfare of the population, the amount of resource deterioration and damages, or, say, a 10% decline in global GDP). Consequential damages and co-benefits should be considered and transparently disclosed in the

[70] Although the focus of this paper is on the adverse tail, there is also a possibility of a favorable tail, e.g., as a result of a technological breakthrough. This type of development will not be further discussed, as it does not play a significant role in the types of cost-benefit analysis discussed here that are more directed at mitigating possible adverse effects of climate change.

analysis. Also, because of potential disagreements regarding the correct social discount rates, a range of such conditions or levels might be used.

The lack of experience regarding the effects of global temperatures or other climatic factors at extreme levels leads to measurement challenges and extreme uncertainty, ultimately leading to loss aversion and even fear. According to Gollier (2011), fear of low economic growth can dominate other considerations. Climate change is a sufficiently significant potential factor to turn entire societies risk averse, possibly requiring a significant risk premium and a reduced discount rate.

The precise likelihood or severity of dynamic non-linearities, the serial correlation of risks and damage, and the point at which or where one or more tipping points will occur is not and may never be known. A significant concern is that the effects of some tail events or conditions can have a correlation between all risks converging to one, that is, multiple risks can arise at the same time. To magnify the damages, some changes are cumulative (and in effect, irreversible), with significant short-term random fluctuations, as well as permanent discontinuities, trends, and cycles in climate-related metrics, and geophysical factor interrelationships. Because of the complex nature of the climate change process, multiple probability distributions are involved. Climate models are not sufficiently precise to pick up all of these complexities.

Nevertheless, relying on best-guess parameters, overall forecast ambiguity may be sufficiently manageable for the purpose of a cost-benefit analysis. For extreme cases, substantial mitigation and ex-ante adaptation efforts may be needed to prevent a major economic decline in a country, region, or worldwide. Thus, there is a need for sound governance that includes sound policy planning and effective and timely action, including early warning systems. Due to the many demands on public resources, these may be difficult to obtain and manage on an ongoing basis. They require high quality and objective data and information. However, both the rarity and its potential severe effects imply that it may be virtually impossible to completely recognize the likelihood and severity of damages resulting from a large increase in global temperature (for example, greater than 4^{o}C above the pre-industrial level), where there is limited experience.

Uncertainty regarding the effects of climate change can be incorporated into an augmented extreme value distribution by using multiple climate models or scenarios to generate a series of distributions for each year or period under examination. In addition, it might be feasible to extend this methodology to estimate the willingness to pay for mitigation and ex-ante adaptation to avoid a tail condition.

For example, multinational reinsurance companies may be able to provide estimates of likely market premiums that would be commercially viable, both in terms of price and capacity. Alternatively, an uncertainty margin (to be prudent in view of extreme damage scenario) could be reflected in social cost-benefit analyses by applying flatter probability distributions, with larger probabilities of frequency of occurrence or the severity of scenarios in the tail of the distributions.

In some cases, however, a particularly exposed area may be uninsurable, often because insurance is not available at a reasonable or affordable price. This may occur, for example, where there is a hazard that is likely to decimate an entire city (e.g., through flood or drought risk) or island (sea level rise risk). In this case, there may not be adequate spread of risk for a local insurer at an affordable price (although if a worldwide reinsurer, a proper spread might nevertheless exist). Global reinsurance or public-private partnerships may be able to assist in providing protection. The emergence of this type of situation would be a strong indicator of a need for rigorous public sector-led adaptation planning, including the development and management of sufficiently adaptive/resilient protective techniques or joining a collectively shared community, national, regional or even worldwide private or public risk-sharing system, as appropriate.

Weitzman (2007) emphasized the importance and relevance of climate change-thickened left tail of g (of the Ramsey formula), albeit with a low probability, which carries most of the weight of expected marginal utility in a cost-benefit analysis. Similarly, given the long timeframe involved, lower discount rates tend to dominate higher discount rates, leading to an ultimate discount rate that is quite low. In any event, Weitzman's conclusion was that uncertainty regarding the extent of growth reduces the social discount rate.

In addition, the size, shape and severity of the tail distribution is both important to assess and difficult to determine with much accuracy – some characterize it as mere (educated) guesswork. Nevertheless, today's estimated tail may become tomorrow's regular event and tomorrow's tail scenario may be totally new and unexpected.

In a series of papers, Weitzman introduced the concept of the Dismal Theorem: "[T]he catastrophe-insurance aspect of such a fat-tailed unlimited-exposure situation, which can never be fully learned away, can dominate the social-discounting aspect, the pure-risk aspect, and the consumption-smoothing aspect." Further, "The burden of proof in climate-change cost-benefit analysis is presumptively upon whoever calculates expected discounted utilities without considering that structural uncertainty might matter more than discounting or pure risk. Such a middle-of-the-distribution modeler should be prepared to explain why the bad fat tail of the posterior-predictive PDF (probability density function) is not empirically relevant and does not play a very significant – perhaps even decisive – role in climate-change cost-benefit analysis." Bottom-line, Weitzman strongly suggested that, even though the precise severity of the tail's exposure (IAM's damage function, which he tended to disparage as representing guess-work) is currently quite uncertain, its significance almost demands that action be taken to avoid the great potential damage that this risk could bring us.

In general, Nordhaus (2009) agreed with this theorem, in that under such an extreme scenario normal economic analysis cannot apply. However, he asserted that such conditions only applied under restricted conditions, that is, a very fat tail event, or if the decision-makers are very risk averse. Nordhaus concluded that such a catastrophic result was extremely unlikely, especially because most conceivable climate change catastrophes would likely develop slowly, enabling adequate time to mitigate or adapt to the extreme conditions that might ensue, regardless of the costs involved. Nevertheless, he concluded that consideration of such a possibility should not ignored – rather, should be considered in a qualitative manner.

In contrast, Gillingham et al. (2015) in a study of six IAMs, found that, although the range of uncertainty was wide, there was a lack of evidence in support of fat tails in the distribution of emissions, global mean surface temperature, or damages. This divergence of views suggests that further stress tests of scenarios are needed to confirm the extent of tail risk.

An annual 0.1% probability term was included in the Ramsey formula by Stern (2007) representing the probability of the extinction of humanity[71]. It is the author of this paper's view that incorporation of

[71] For example, due to an asteroid striking the Earth and destroying human civilization.

such a term in a quantitative analysis makes little sense, as it is not necessary or relevant to use such a term as a component of social discount rates. Although certainly an unrelated externality, a quantitative adjustment for such an existential species risk serves no practical value, as it does not affect in any way a decision relating to the relative amount of consumption over time (we can party to compensate for the possible end of civilization?). Not only is it illogical for society to reflect an unrelated global existential risk in a cost-benefit analysis, but the estimation of this term has no supportable basis, other than being a wild-ass guess. It may have been used as a practical expedient to avoid inclusion of undiscounted costs that could not otherwise be justified and the appearance of inconsistency from what was claimed to be an ethical position of using a zero pure discount rate across time and generations. Nevertheless, if the analyst believes that such a result is possible, qualitative disclosure of such a possibility would be warranted. The author does not believe that such disclosure would provide useful information. Therefore, this term will not be considered further here.

An estimate of exogenous catastrophic risk is 1.0% (denoted as L in HM Treasury (2011), Annex 6 as an addition to the traditional Ramsey formula). This allows for a larger set of possible risk factors than the simple species extinction term of 0.1% made by Stern (2007).

Some institutions and people have bought bonds yielding zero or less in real terms partly because they want protection against catastrophic states of a highly uncertain and illiquid world. Thus, the right discount rate for projects expected to eliminate or reduce the tail risks could be quite low, possibly even negative. As tail events appear increasingly more possible, the right way of responding to the nature and scale of possible horrific outcomes is prevention, control, or risk reduction, which can nevertheless be expensive.

The key take-aways from section 6.3 are:

- A wide consensus of scientific opinion supports both the existence of climate change and significant uncertainty regarding its future trajectory;
- in addition, its tail risk may bring with it significant costs and damages;
- It is important to consider and illustrate the potential effects of tail scenarios in a social cost-benefit analysis; it should be done in an objective manner, with care needed to determine the range of tail scenarios;
- Loss aversion associated with adverse tail probabilities leads to an expanded provision for uncertainty, with a corresponding reduction in social discount rates; and
- There is yet to develop a consistent disclosure approach to tail risks, although use of consistent IPCC-generated scenarios might prove useful for this purpose.

Key take-aways from chapter 6 include:

- Uncertainty is an important element in the time-risk framework within which social discount rates are determined and applied;
- Uncertainty is usually recognized in net present value calculations, either in the social discount rates (a decrease) or in the amounts being discounted (an increase), but not both, either of which adds an uncertainty margin in the calculated result, with the former approach representing in most cases better practice and being more common in climate change applications
- Uncertainty can also be considered and communicated through the choice and description of alternative scenarios used or the range of estimates provided;

- There are many sources of uncertainty, including climate change drivers, the climate change process, the resulting loss and damage and the method of economic valuation (discounting);
- Factors leading to a large amount of uncertainty include the complexity of the climate change process, the irreversibility of climate change drivers, social externalities, and the ultra-long time horizon involved;
- If uncertainty is incorporated into the social discount rate determination, it reduces the social discount rate;
- Risk attitudes and risk aversion play an important role, differing by individual and affected by culture, especially with respect to tail risk aversion; and
- Although expectations regarding the extent of tail risk can be based on subjective factors, tail scenarios represent a key driver in consideration in deriving estimates of overall costs of climate change, which leads to a greater use of scenario analysis.

Chapter 7: Ethical Issues

The purpose of this chapter is to discuss the range of ethical issues involved in social discounting of the costs and benefits of climate change-related strategies and projects. Although so far in this paper, the focus has been on the economic basis for discounting over a long time horizon, it is worth reminding the reader that the field of economics was initially an offshoot of moral philosophy, in which economic interests were influenced by moral concern with individuals and society as a whole. This suggests that consideration of other factors, including those of an ethical nature, need to be incorporated into social cost-benefit analyses. Estimates of social value can be made through the application of responsible science within an ethical framework. It is therefore important that both risk and ethics be included as time-risk considerations in the social risk management and decision-making processes in which climate change is involved.

7.1: Ethical Aspects

The social discounting process involves questions of social justice and social value. Stern (2008) argued that the choice of a social discount rate should be based almost entirely on ethical considerations. He indicated that there is no need, for example, to incorporate observed or expected investment returns or estimates of the opportunity cost of capital. Stern expressed the opinion that continued greenhouse gas emissions represent an immoral burden on the future. That is, we all have a fiduciary role and relationship with ensuring the sustainability of the Earth and all its current and future inhabitants on the basis of environmental justice. In contrast, others believe it more relevant to introduce market-based or other quantitative measures, because in order to efficiently allocate resources, rational empirical or technically efficient approaches are necessary. This section discusses these diverse views.

There are several aspects of social discounting that involve or may be affected or influenced by ethical and moral criteria and judgements. This is in large part because public goods, including the atmosphere, land, and oceans, can be adversely affected by significant changes in our climate. Relevant issues include relative costs and benefits between generations, between countries, and between population segments. The Earth, it is argued, is our shared home – it does not belong to a single nation, race, or continent. Looking after the sustainability of our planet and the way of life of its living species is the moral responsibility of us all. Thus, this involves discussion involving the heart or the head. In the long run, it has to involve both.

Ramsey (1928) argued that there is no moral or ethical justification to place greater weight on the welfare of the current generation than that of future generations. He stated, "It is assumed that we do not discount later enjoyments in comparison with earlier one (any $\rho > 0$ is) ethically indefensible and arises merely from the weakness of the imagination." Viewpoints on this are diverse: some believe this to be a universal truth, while others believe it to be inequitable, unrealistic. It has been disregarded by many economists (see section 5.2.1 for further discussion of Ramsey's view).

Trade-offs and constraints in the use and allocation of public or private sector financing of mitigation and adaptation will always exist. Although ex-post adaptation efforts to reduce catastrophic damages are often provided for in some manner[72], the Committee on Assessing Approaches to Updating the Social Cost of Carbon (2017) cautioned: (1) climate change mitigation expenditures can displace investments for other purposes, (2) if the return on mitigation investments is smaller than the return on other investments, allocating resources to mitigation efforts might make both current and future generations worse off, and (3) it is preferable to base resource allocation on tradeoffs made by society on explicit information, rather than being forced to by outside bodies.

Although the following constitutes a brief description of some of the ethical issues related to climate change, it is outside the scope of this paper to comprehensively discuss or recommend a solution to all of them, if indeed they exist, as they often involve value judgments that in some cases can only be made at an individual, cultural, or national/political level.

1. *Intergenerational equity*[73]. What duty does the current generation owe to future generations? Because the costs and benefits associated with climate change cover such a long period, cross-generational equity and intergenerational risks inevitably arise. Those who are older may be more willing to assist in this effort because they may recognize their own vulnerability than those at younger ages due to reduced physical strength and reduced mobility. They may also better perceive and value the effects on future generations, especially if they have children or grandchildren. It may be deemed unethical for decisions with irreversible consequences to be made by the current generation without considering the effects on future generations. These issues are discussed further in section 7.2.

2. *Life and health*. It is difficult to assign specific costs or benefits to public health, premature deaths, illhealth, and other non-monetizable life and health related factors (as indicated in section 8.2.1). One approach to its quantification could be to attempt to answer the question of how much is society willing to spend to reduce the odds of dying, which has at times been derived by opinion surveys. In some types of cost-benefit analysis a subjectively determined statistical value of a life (SVL) is used. This could be related to (1) a fixed amount that, depending upon its use, has been between US$50,000 to US$10 million, the latter generally used by U.S. government agencies, or (2) an estimate of average future wages as a proxy for the economic contributions of an individual that is lost, although this method does not work well for those who are informal caregivers of children or the elderly, or are retired. It is always an ethical challenge to determine the amount attributable to the value of a life foregone or to a reduced

[72] Such assistance efforts are not always adequate or delivered in a timely manner, sometimes grudgingly.
[73] Also referred to as intergenerational fairness or intertemporal justice, being an element of social fairness or social justice.

quality of life. A VSL also does not reflect the willingness or ability to avoid injury and the cost of uncertainty. The value used may differ by country or by application; in some cases, the value assigned has differed by age and health condition, possibly reducing for those at advanced ages. Nevertheless, some have claimed discounting of the value of human lives itself to be unethical, while others suggest that, at a minimum, they should be adjusted using the same or reduced discount rates as financial measures. In any case, it is appropriate to separately consider, document and disclose the amount incorporated in a cost-benefit analysis.

3. *Intragenerational equity*. In many cases, differences in characteristics and outcomes can be more significant within a given generation can be wider than across generations. In fact, the relative adverse effects of climate change on an intragenerational basis can inherently be more unfair and inequitable, especially considering that much of the effects are (or could have been) preventable with rigorously planned mitigation and ex-ante adaptation efforts. The relative sensitivity and vulnerability of certain population segments may be based on long-standing discrimination and lack of basic education, employment, housing, and healthcare infrastructures not related to climate change. Whether having an environment that provides protection against climate risk is a fundamental human right[74] is an underlying issue.

4. *Inequality*. The burden of carbon transition and disaster recovery often lay most heavily on those who are already among the least well off and vulnerable. For instance, fuel taxes are hardest to bear by those in the often-neglected rural areas with few transportation or energy alternatives. Resistance and resentment will likely accompany any change, whether or not well-intentioned mitigation efforts, which generally only reinforces deeply felt emotions, particularly where populism is widespread and deeply ingrained in certain populations. This is similar in many ways to the unequal distribution of income and wealth among or within countries. In addition, in many areas the benefits of much of the recent economic growth have been heavily concentrated in the relatively well-off, as well as has been the cost of the 2020 COVID-19 pandemic that in many countries has particularly hit hard those relatively less well-off, leading to increased inequality of income and wealth. Correspondingly, the effects of climate change often exacerbate inequality, since those less well-off tend to be the most vulnerable and underserved. In contrast, efforts to address and spread the cost of ex-ante adaptation, where affordable, may ultimately help reduce inequality, as such efforts are often primarily directed to help the most vulnerable, as they are usually the first and most affected.

5. *Affordability*. It is difficult to imagine that many less developed countries (i.e., those with limited resources and in a few cases existential climate-related concerns) will be able to afford to allocate the same relative amount of resources toward mitigation as can developed countries. Nevertheless, if there are sufficiently large co-benefits, such as the introduction of new technology such as more efficient and less polluting air conditioners and stoves, the benefits may both be more than offset the costs and be affordable. Also, if a country does not finance ex-ante adaptation, they may end up bearing a greater burden of more costly ex-post adaptation.

[74] The underlying human rights include those involving the right to life, water, sanitation, food health, housing, self-determination, and development, all of which could be at-risk in certain areas and times that would be adversely affected by climate change.

6. *Subsidies*. The allocation of costs and benefits across population segments is of special concern for diverse populations with significant inequality and significant vulnerable population segments. Efforts to respond or to offset the regressive nature of many intended incentive-based approaches (e.g., through carbon-based taxes or reduction in previous subsidies) for mitigation, decarbonization or ex-ante adaptation, may need to overcome huge public opposition. Cross-subsidies may be inevitable and may not be able to be avoided. However, if not carefully designed, these subsidies can lead to incentives that result in over or inappropriate use of certain modes of transportation, poor land use, or ill-conceived construction. For example, below-cost automobile fuel can lead to high use and an excessive amount of greenhouse gas emissions. However, since subsidies have often been implemented to help those in most need, alternative mechanisms may be desired to overcome the regressive nature of such costs or taxes.

7. *Social externalities*. The determination of whether or how to consider the effects of social externalities and co-benefits, such as pollution and consequential deaths resulting from side-effects of greenhouse gas emissions, may involve ethical considerations (see chapter 7 and sections 2.3 and 8.2.1). To exclude secondary or tertiary effects of these climate change drivers from consideration could produce incomplete and misleading findings.

8. *Financing and responsibility*. In many cases, the countries or population segments that have emitted the most greenhouse gases are not necessarily those who (1) are most vulnerable to the adverse damages that result from climate change or (2) can best afford mitigation and adaptation costs to effectively manage these risks. An important international political issue is that those who contribute most to this problem (the developed and certain developing countries) have been asked to finance a great deal of damage avoidance or recovering from the resulting damages of the most vulnerable, as those in the less developed countries and in the most vulnerable population segments can least afford but would benefit most by preventive measures. Standard economic theory suggests that in this type of situation a tax (or its equivalent) based on the extent of the damages and social externalities caused or on the country or industry segment causing it (see chapter 10) would be most appropriate. This can better place the cost on those responsible, thus creating incentives for appropriate behavior. Also, if a country does not make arrangements to finance ex-ante adaptation, they may end up bearing the greater burden of ex-post adaptation. The social responsibilities of individuals, businesses, or governments may include taking on the costs of actions that will also benefit others, whether by 'doing the right thing' or at least taking on one's fair share, including controlling the volume of greenhouse gas emissions and helping others adapt or recover from the adverse effects of climate change.

9. *Free-riding*. A situation in which those who benefit from certain common resources, goods, or services do not pay their share. It is a form of moral hazard, which can arise in the climate change context when a country does not participate by paying its fair share of mitigation costs, even though it receives corresponding benefits from others' contributions (see section 7.3 for further discussion).

10. *Sustainability*. Not only is sustainability of the environment and social values at stake, but sustainability of other key elements of civilization and quality of life should also be considered. Not only is existential risk, such as sea level rise to the population of a low elevation island, but other severe effects to a population segment are also of similar concern, such as long-term drought and famine. Although the cost to support a sustainable system might be able to be estimated in a quantitative manner, qualitative considerations can be of equal or greater importance, especially over a long-term horizon. The factors considered as being aspects of sustainability of a social system can include social and community cohesion, family security, financial institutions, infrastructures, and biodiversity. These effects are particularly difficult to quantify, let alone discount.

11. *Uncertainties*. It is difficult to devise and manage proper mitigation and adaption decisions when relevant and reliable knowledge regarding the feedback loops and sensitivities of the climate process is evolving (see chapter 3). The author emphasizes that this lack of knowledge does not refer to whether climate change will occur or what causal factors are involved, but rather, the type and severity of its effects. This current ambiguity might justify delaying decisions regarding mitigation or ex-ante adaptation in the hope that technologies will emerge that will solve these problems in a timely manner (see chapter 9). Nevertheless, the irreversible effects (see section 3.4) in the climate change process may in the meantime become unstoppable and overwhelm possible solutions. This set of natural and behavioral uncertainties can affect the accuracy of estimates of future costs and benefits, especially regarding the size of the damage tail (see section 6.3). The result of a social cost-benefit analysis can be forced, as a result, to use a relatively subjective range of assumptions, potentially increasing the importance of ethical-based arguments. It is also important to consider that living in a state of continual uncertainty, especially when possible outcomes become extreme, such as fear of the unknown or uncertainty, can lead to mental health problems and irrational responses.

12. *Reliance on market values*. Particularly those who are passionate about the importance of climate change strongly argue against the use of market-derived discount rates, which rarely reflect social externalities or non-monetizable items, nor whose relevance to social discounting is especially strong (see section 5.3 for further discussion).

13. *Social discounting*. Some believe that, in addition to intergenerational considerations, the most suitable approach to analyze climate change is not to discount at all, as this only represents a minor consideration in social decision-making (see chapter 11 for a discussion of alternatives to discounting). In contrast, others (e.g., Stern 2015) express the opinion that the use of a positive pure rate of time preference (ρ) would be unethical and could lead to over-saving.

In quantifying and applying a social discount rate, value judgments are inevitably involved. The basis for and/or the assumptions made will inevitably at least in part may depend upon the values and prejudices of those who are prepared the analysis and who are making needed decisions and direction. As indicated elsewhere in this paper, preconceived notions regarding priorities applicable to climate change may influence the choice of the social discount rate applied, which is one reason to consider using and documenting multiple sets of discount rates.

A challenge in moving forward is building sufficient societal consensus[75] regarding the relative importance of addressing the climate change process, financing mitigation and ex-ante adaptation efforts, and dealing with its uncertainties, as well as the value of addressing this issue with a sense of global responsibility. Safeguarding the future is not just about the science or methodology used, but also about management on a day-to-day level in manner consistent with its long-term ethical underpinning.

The key take-aways from section 7.1 are:

- Ethical considerations are inter-related with financial considerations in conducting a comprehensive social risk management process.
- Qualitative aspects that should be addressed in many social cost-benefit analyses include ethical features such as equitable treatment across and within generations, non-monetizable items including human life and health, social externalities, and long-term sustainability, all of which can be difficult to quantify, but important to consider.
- Affordability and responsibility for financing also need to be considered in the design of approaches to address mitigation and adaptation.

7.2: Intergenerational equity

The purpose of this section is to discuss how the interests of future generations can be considered in a social cost-benefit analysis of climate change mitigation and ex-ante adaptation efforts. This is important because the effects of many of the possible climate change-associated catastrophic risks will reach far beyond the lifetimes of current stakeholders. In fact, one reason climate change is such a difficult issue is due to its multigenerational implications. In this discussion, intergenerational issues are compared with intragenerational issues.

Most social cost-benefit analyses are conducted in an intragenerational context in which very long-time-horizon issues are not especially important, that is, where the costs and benefits for future generations are ignored quantitatively or are discounted heavily. Even though many other environmental issues also have a long timeline, because their characteristics and damages are relatively well understood, they usually aren’t considered in the same way in a social cost-benefit analysis.

When ultra-long periods are involved, especially when accompanied with a significant amount of uncertainty, such as in the case of a climate change-related analysis, intergenerational issues and equity need to be considered, as the interests of future generations should have a claim on our attention. For instance, in general, benefits from reduced atmospheric warming accrue over decades and centuries, whereas the cost of mitigation, that is, cutting emissions, is primarily paid upfront by businesses or taxpayers who may not receive much return on mitigation efforts in their lifetimes (although in some cases, there may be a short-term return for ex-ante adaptation projects and mitigation projects with co-benefits). The social discount rate is the usual means to aggregate the social value of future utility or consumption and current utility or consumption for effective intergenerational comparisons.

Ramsey (1928) and Stern (2007) maintained that little or no pure time discount should be applied in addressing issues involving intergenerational allocations. Stern expressed the opinion that the only justification for the inclusion of a pure time discount in the decision-making process is to allow for the possibility that a global calamity may prevent any benefits from a project from being realized. Ramsey

[75] Based on the best current scientific consensus.

stated that the well-being of future generations should be given the same weight as that of the present one, as discounting the interests of future people is "ethically indefensible and arises merely from the weakness of the imagination".

The National Academy of Public Administration (1997) presented the following four fundamental principles regarding obligations of one generation to another that remain applicable:

- *Trusteeship*: Every generation has an obligation as a trustee or fiduciary to protect the interests of future generations. Nevertheless, it can be felt that the current generation needs to provide the opportunity to lead a better life.
- *Sustainability*: No generation should deprive future generations of the opportunity for a quality of life comparable to its own, whether applicable to the entire society or certain population segments such as those most vulnerable. In other words, each generation should serve a stewardship function for future generations.
- *Chain of obligations*: Each generation's primary obligation is to provide for the needs of the living and succeeding generations. Near-term likely hazards have priority over long-term hypothetical hazards.
- *Precautionary*: Actions that pose a realistic threat of irreversible harm or catastrophic consequences should not be pursued unless there is a compelling or countervailing need to benefit either current or future generations.

These are based on the desire that the future should not be harmed because of current actions, which should help ensure that the lives of future generations can lead at least as good a life as the current one. Future generations should not be saddled with an irreversible adverse climate trajectory that increases climate-related risks and which can decrease the quality of life for many and challenge our physical resources. The choice of a social discount rate based on one's duty to posterity, based upon the objective, or constraint, of sustainability, would avoid an overly large discount rate that might otherwise be used if growth is the sole goal. In contrast, a Rawlsian approach[76] would have a society optimize the economic well-being of the poorest generation, even if that is itself.

There is likely no unique answer that will satisfy all potential stakeholders in answering the question of how best to share or allocate costs among generations, i.e., can a fairness principle be devised to address this issue? And if it can, how could it be measured? Of course, the demarcation between any two generations is somewhat arbitrary. The sharing or allocation process can also be based conceptual in nature. None of the possible approaches, including the utilitarian one[77] that indicates that the best approach is one that provides the greatest good for the greatest number of people, what some believe to be an acceptable rule. In practice, an answer could at a minimum consider the welfare of both the current and future generations.

These issues and considerations are relevant to a wide range of social policy issues, including provision for retirement, public infrastructure, research and development, and education, and are especially important when assessing climate change, as indicated in sections 3.1 and 3.3. The author's conclusion is that we owe an obligation to future generations not to leave a world in an irreversibly deteriorated condition, or at a minimum leave as much societal capital as we inherited.

[76] Based on views expressed by John Rawls, the twentieth century American political philosopher.
[77] The utilitarian school of philosophy, with prominent authors including Jeremy Bentham and John Stuart Mills.

Of course, concerns regarding future costs and damages are amplified when they affect one's own children and grandchildren. Prior generations have usually shared this goal (and hopefully future generations will continue to do so), even though they have not always acted in a manner consistent with it. The objectives of shared responsibility, altruism, and concern with sustainability all point toward the need to invest to improve the future, including mitigation of and ex-ante adaptation to climate change.

In addition, future climate change issues are not just about money (although GDP or income could serve, with appropriate caveats, as a surrogate for social value), as damage could cover items not easily assigned a cash flow equivalent (see section 8.2.1), including loss or limitation of life and health, property, and agricultural resources.

It is also possible to take what could be thought of as being a selfish position that benefits the current generation at the expense of those in the next generation who, on the whole, should be better able to afford the costs involved. However, unless technology will be able to offset the adverse effects of what currently seems to be irreversible, that is, greenhouse gas accumulation in the atmosphere, future generations will be stuck with the results of the current generation's actions, whatever their income. In light of this responsibility and legacy regarding the irreversibility of the outcome, the current generation should be held to a high standard of behavior and decisions.

Social value (welfare) attributable to a given amount of goods and services tends to decline as the income of people increases. If an economy continues to grow in the aggregate, its future population will tend to become relatively better off, i.e., possess or use more goods and services. Thus overall, the greater the economic growth relative to the diminishing effect of the elasticity of marginal utility, the larger the social discount rate should be[78]. Nevertheless, this will not always be the case for all population segments in all countries, and at all points in time. Indeed, overall economic growth and standard of living increases do not mean that the poorest or more vulnerable segments will become better off. Indeed, the issues for the intergenerational issues for many population segments differ and continued improvement for all is not guaranteed. In fact, inequality risk itself can lead to the conclusion that a lower social discount rate is appropriate.

Time preference can be deeply personal and can represent a significant factor in determining society's values. Nevertheless, it is difficult to agree upon a quantitative assessment of the reduction in current consumption that will adequately and fairly protect future generations from the effects of climate change. This is complicated by the practical issue of alternative use of funds and even the definition of a generation, as they continuously overlap. There is no objective demarcation between generations that can lead to an other-than-arbitrary rule or formula. Nevertheless, it can be seen that the greater the desired weight given the public welfare and the uncertainty in the longer-term, the greater an intergenerational equity adjustment to the reduction in the social discount rate is needed.

In sum, some of the key differences between intergenerational and intragenerational are shown in Table 7.

[78] According to the Ramsey formula, this is the case as long as the rate of growth exceeds the rate of reduction in the marginal utility of consumption; the opposite conclusion is reached if the reverse holds.

Table 7 – Key differences between treatment of intergenerational and intragenerational risks

	Intergenerational	Intragenerational
Emphasis	Compares treatment across generation for the same population	Compares treatment within the same generation among different population segments
Primary focus	Mitigation and to a lesser extent, ex-ante adaptation	Ex-ante and ex-post adaptation
Social discount rate	Lower than rates applied to analysis within a single generation	Similar to other social discount rates

From a practical perspective, a social cost-benefit analysis that discounts benefits for future generations differently than future benefits to the current generation may create time inconsistencies, especially when generations overlap. Further, a dollar invested over a period of time, in whatever manner, does not know or care whether it is an intragenerational dollar (i.e., part of a group's lifecycle savings) or an intergenerational dollar. Because it is difficult to draw a distinct line or precisely differentiate between generations, it is also difficult to set quantitatively-based distinctions. Do future generations include only those who have yet been born, include current children or …? So, where needed, practical expedients by calendar year groupings are usually used. In any case, any differentiation by generation would be approximate, at best.

It is difficult to imagine what future generations' views regarding their values will be regarding climate change, or what values those generations will hold as important, although one could surmise that, if mitigation efforts are unable to achieve a 1.5°C temperature increase, concerns will be greater than that of the current generation. One can only use the current set of preferences or be as neutral as possible.

Arrow (1995) concluded that discount rates represent the relative weight placed by society on the long-term and short-term benefits accruing to itself. A responsible society assigns a reasonable balance to the weights, recognizing that those in future generations have no 'vote' on current actions, and that current decision-makers must act with fairness considering the expected needs and circumstances of all generations.

Key take-aways from section 7.2 include:

- Intergenerational issues should be considered in setting social discount rates, although a zero time preference is not necessarily appropriate;
- It is a social obligation for each generation to leave the Earth in at least a comparable condition as when it was its steward, or at least not leave the world in an irreversible deteriorated condition; and
- Intergenerational equity primarily relates to mitigation efforts, while intragenerational equity primarily, but not exclusively relates to adaptation efforts.

7.3: Free-riding

Free-riding exists where those who benefit from certain resources, goods, or services do not pay for them. In general, it describes what an entity, be it a country, industry, business, or household does when it does not provide its fair share of the costs associated with an activity, such as reducing greenhouse gas emissions, whose favorable benefits provided by others are shared widely. Convincing all that everyone's stake is worth the investment can be difficult while everyone has many other priority issues, most with a much shorter time horizon. Partly because damages caused by climate are primarily the result of others' actions rather than the individual country, business, or household, this can result in a strong incentive to free-ride on the sacrifices of others. It is a type of moral hazard.

Since curbing climate change can benefit all countries and is thus a global good or service (see section 8.2.3), when a country does not contribute its fair share of mitigation costs, either in resources or financially, it is in essence taking advantage of what should be addressed through a global social risk and resource management process. All countries should share in these costs and risks, just as it receives corresponding benefits from others' efforts. Without everyone pitching in, it becomes a *tragedy of the commons* problem.

Examples of free-riding include: (1) actions by an earlier generation that contributed a large part of the accumulation of greenhouse gases that will eventually lead to a degraded environment and a reduced level of consumption by subsequent generations, (2) countries that take no action themselves or make no contribution to others, but rely totally on others to reduce global emissions or bear the resulting cost, (3) everyone benefits from the use of a healthy atmosphere, whether or not they help control pollution, (4) when the cost of social externalities and co-benefits are not reflected in prices, and (5) if the allocation of cost is unfairly conducted.

At least superficially, free riding can seem desirable through pursuit of one's self-interest, especially when there is huge pressure to meet the current needs of one's own population and economy. Indeed, there will always be winners (that is, those who benefit from climate change due to particular geographic area) and losers (most of us, especially the most vulnerable). In some cases a stakeholder can be both – for example, free-riding others' greenhouse gas emission reductions, while at the same time conducting research on new greenhouse gas reduction techniques.

In certain cases, it may be felt that a country's scarce resources (especially in a less developed country) would be better applied to climate change adaptation rather than toward mitigation, or applied to disaster recovery (ex-post adaptation) at a future date rather than in advance planning as it how to reduce damages in the distant future (ex-ante adaptation), even though in the long run those might not represent optimal decisions. Free-riding can also be taken by less developed countries, as by necessity, they benefit from the right type of technological development.

To some, using scarce resources to help those in other countries or in a future generation may be overly altruistic and counter to one's own self-interest. A certain amount of free-riding may even be necessary if, for example, applicable infrastructure is not available nor affordable. This is especially relevant if it is felt that other countries are also not doing their fair share in the mitigation process. However, on an overall basis, this view may turn out to be short-sighted.

Some believe that free riders should incur a penalty for their inadequate action. However, there are currently no binding rules, nor means of enforcement at the global level, that would require a country to undertake mitigation actions. Transparent information regarding needs, promises, and outcomes obtained by third parties through increasingly available technology may nevertheless provide information that will goad a country to appropriate and needed actions. Where practical, remedies could include making certain actions mandatory or provide sufficient incentives and penalties. In many cases, loss of reputation (i.e., shaming) as a global citizen with regards to climate change can adversely affect popularity with the voting public. Free-riding can indicate a narrow view of responsibility, a lack of sound governance, and may affect the global sustainability of our environment.

Developed countries may face what can be a moral dilemma regarding whether to factor in others' share of potential damages in determining how much of their own resources to allocate, for example, by switching to more renewable energy and conducting mitigation research and development. In these cases, the beneficiaries will ultimately be the entire global population. Doing one's fair share is made especially difficult if other countries are not doing so.

In spite of some of the above, the conceptual best approach is for everyone to share in and contribute to the solution, based on their ability to take action. To adequately address global problems such as climate change, global action by all who can do so is needed and desirable from everyone's perspective.

The key messages of section 7.3 are:

- Free-riding is an advantageous (indeed, in some cases selfish) short-term strategy, with others having to make up for the inaction, especially if global objectives are to be achieved;
- Although free-riding can be voluntary and selfish, such as not spending money to mitigate one's greenhouse gas emissions while others are doing mitigating their own emissions, or can result from others' actions when the resources needed are not available, such as conducting research and development in climate change technologies; and
- There is usually no recourse available to others if a country free-rides, other than transparent communication of the extent of free-riding.

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Key take-aways from chapter 7 include:

- The determination of social discount rates involves consideration of several ethical issues, although it is problematic as to what extent and how these issues should be reflected;
- Several ethical issues serve to decrease the social discount rate, including intergenerational equity, long-term social externalities, sustainability of environmental and social values, and numerous non-monetizable items.
- Intragenerational ethical issues are also relevant to social risk management decision-making, including treatment of vulnerable populations and inequality – not only in the quantification of the need for a program, but also the allocation of the direction and allocation of costs, especially in adaptation efforts.
- Free-riding, although not illegal, may not only be unfair to the rest of the world that is sharing costs and risks, but also can be viewed as being unethical. Global action by all in response to global problems to the extent they can is the best approach.

C. Social Discounting – Special Issues and Application

Chapter 8: Social Discount Rates – Special Issues

The purpose of this chapter is to examine several important issues involved in the determination and application of social discount rates. Section 8.1.1 focuses on the question of whether a constant discount rate or a declining set of discount rates over time (hyperbolic discounting) be used, primarily arguing for the latter approach. What they are applied to (section 8.2) and their scope, i.e., the time period covered and geographic spread (e.g., local, national, or global) are covered in sections 8.2.2 and 8.2.3, respectively, can be just as important. In section 8.2.1, the effects of items that cannot easily be monetized into cash flow equivalents are discussed.

8.1: Structure

Discount rates are usually expressed in terms of effective annual (or annualized) rates, for example, when based on observed transaction prices from trades or issues of financial instruments (e.g., government/sovereign bonds) in a capital market. It is thus common and convenient to express them in equivalent exponential form, that is, a level or levelized rate over the period of the instrument over which discounting is applied. In fact, there is no principle requiring this practice[79]. However, investment rates or discount rates are normally expressed as a single rate for convenience and ease of communication and comparison, whether in financial applications or in terms of opportunity costs.

The need for coordinated and consistent treatment of the discount rate and the items being discounted (usually cash flow equivalents) is an actuarial principle. This relates to issues such as consistency of costs and benefits (see chapter 4), treatment of uncertainty (see section 6.1), currency of the cash flows (see section 8.2), consistency of methodology and assumptions in a comparison of alternatives being analyzed (see section 2.1) and among scenarios in a scenario analysis (see chapter 11). Note that the social discount rate applied should be scenario-specific (see chapter 4).

It is common in private-sector cost-benefit analyses to increase the discount rate to compensate for profit[80] and for undertaking financial risk and uncertainty. Note that it is not trivial to derive a conceptually sound increase in the discount rate and the resulting risk and profit premium[81], just as it is difficult to develop appropriate scenarios and the probability distributions of their frequency, severity, and timing. As a result, the increase is usually a subjectively selected rounded number or set as a corporate objective.

Alternative methods can be applied, possibly in an ad hoc manner, to reflect risk and uncertainty. The form of adjustment can include: increase the expected costs, lengthen the period over which costs are considered, decrease the expected benefits, shorten the period over which benefits are considered, or adjust the discount rate depending upon the pattern of the expected costs and benefits.

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[79] Fixed rate bonds pay a periodic coupon based on the coupon rate, which is constant over the life of the bond. In contrast, floating rate bonds pay a periodic coupon based on the rate then in effect. Even when spot or forward rates are unequal over their duration, often an average effective rate over the term is referred to.

[80] Considering profit is not applicable in the case of a public sector cost-benefit analysis.

[81] Although such a margin could be derived from a desired cost of capital or internal rate of return approach. Alternatively, it could be derived based on industry practice or an historically set benchmark.

One test regarding the appropriateness of sign of the adjustment to discount rates is whether the adjustment results in a larger or smaller present value. Since the benefits involved in a cost-benefit analysis are usually later in time than the corresponding costs, the sign of the adjustment made usually reduces the discount rate. In any case, the cost (charge) associated with taking on risk and uncertainty is positive.

Because of what can be multiple types of items (i.e., not all can be expressed as cash flow equivalents) being discounted, a question can be raised as to whether it is appropriate to apply alternative (or a range of) discount rates to different items, depending upon what is being discounted. For example, it may be appropriate to discount expected monetizable cash flows or their equivalents differently from those items that cannot be monetized, such as premature deaths, or are social externalities. Additionally, discount rates could differ if, for example, distinct set of cash flow equivalents are associated with different levels of risk and uncertainty, the decision-maker has a different risk aversion to the alternative components, or the strategy being assessed that includes both private and public investments. Usually, at least for convenience, the same set of social discount rates are applied throughout a social cost-benefit analysis.

There is no fundamental reason that social discount rates cannot be negative, whether because: (1) the level of nominal rates in a country are negative or quite low, (2) there is an expected negative growth rate, although this is quite unusual because of the long-term nature of the cost-benefit analysis, or (3) there is a large adjustment for social externalities or risk and uncertainty.

Given the relatively large amount of uncertainty associated with climate change-related issues, it needs to be remembered that applying too large a downward adjustment for uncertainty can also result in an excessively large and possibly unacceptable decrease in economic growth, which can correspondingly result in other adverse consequences. Therefore, a practical balance between the theoretical and practical is usually called for.

Key take-aways from section 8.1 include:

- Several structural issues may need to be addressed when considering the choice of a social discount rates;
- The need for consistent treatment of discount rate and the items being discounted (usually cash flow equivalents) is an actuarial principle;
- Social discount rates should be scenario-specific, that is, reflecting the expected character of the cash flow equivalents being discounted and expected economic conditions; and
- A decision is needed regarding whether to discount all cash flow equivalents or non-monetizable items at the same rate.

8.1.1: Hyperbolic discounting

In most of this paper to this point, reference has been made to discount rates as if a constant annual discount rate is used over the entire period of analysis. However, this does not imply that a single annual rate should necessarily apply over many years. In fact, many believe that it is more appropriate to use discount rates that decline over time.

Hyperbolic discounting (using a decreasing rate structure, usually stepwise for practical reasons) is an alternative discounting structure that contrasts with exponential discounting, where a constant rate of time value over each period is applied. Although technically the hyperbolic discounting methodology refers to the application of discount rates that follow a hyperbolic curve[82], it has more generally been used to describe any set of discount rates that decrease over time. This section discusses the key arguments surrounding hyperbolic discounting.

Several economists (e.g., Arrow et al. 2012) have expressed a preference for declining discount rates over time on theoretical, behavioral, and experimental grounds. This was supported by the IPCC Fifth Assessment Report (2013), which indicated that "a consensus favours using declining risk-free discount rates over a longer time horizon."

Arrow et al. (2013) indicated: “The decline in the certainty-equivalent discount rate over time follows from the assumption that the discount rate is uncertain. In the more general case, in which future discount rates are uncertain and may vary from one year to the next, the change in certainty-equivalent discount rates over time depends on the joint probability distribution of the yearly discount rates. If the yearly discount rates are independent and identically distributed, then the certainty-equivalent discount rate is constant; low rates in one year, uncorrelated over time, tend to be offset by high rates in another. If there is correlation among the forecasted discount rates, there is a high chance of lengthy periods of persistently low discount rates and an associated high present value of benefits, thus certainty-equivalent discount rates will decline over time.” Therefore, if interest rate shocks are positively correlated, the discount rate should decline because serial correlation increases future consumption risk.

A declining discount rate also reflects the effect of uncertainty regarding future time preferences. Weitzman (2010) showed that the risk-free rate declines over time because of a ‘fear factor’ associated with a catastrophic, low-productivity growth environment. Other studies usually show that most people exhibit decreasing impatience (time preference), although that has not always been the case at the individual level (Attema et al. 2016). Consistent with exhibited impatience, people don’t always perceive the passage of time in a manner consistent with an exponential equation.

If an individual’s discount rate decreases over time, the collectively determined social discount rate would also be expected to decrease, as the efficient collective utility discount rate is a weighted average of individuals’[83] utility discount rates. The weights used are proportional to each individual's tolerance to volatility in consumption. It is thus economically more efficient for the most impatient members of society to receive a larger share of consumption initially, which then decreases over time. Also,

Two approaches based on a consumption approach have been developed:

- *Through the cash flows*. Benefits and costs are converted to consumption units. They are then discounted at a rate (based on the Ramsey formula) at which society would trade consumption in the future for current consumption. If the rate of growth is subject to positive correlation over

[82] For example, assuming a 50% probability of a discount rate being 7% or 1%, the certainty-equivalent discount rate over a one-year time horizon is about 3.96%, declining to about 1.69% after 100 years and about 1.17% after 400 years.

[83] In determining certainty-equivalent discount rates, the average of discount factors, rather than an average of discount rates, is used.

time[84], the uncertainty term in the extended Ramsey formula (formula (5)) may become significant, leading to a declining risk-free discount rate.

- *Through the discount rate*. Weitzman (2001) showed that uncertainty reflecting a probability distribution under exponential discounting should induce policymakers to use a certainty-equivalent declining term structure in an expected net present value approach.

According to Arrow et al. (2012), a declining schedule of social discount rates is appropriate if shocks to relevant interest rates (and therefore to the consumption or productivity growth rate) are persistent. Christian Gollier and Martin Weitzman, both prolific economic authors on the topic of climate change, agreed that where uncertainty regarding the discount rate is persistent[85], the certainty-equivalent (effective) discount rate declines over time, ultimately to the lowest possible positive value (Gollier and Weitzman 2009; Gollier 2009 under conditions of risk aversion and utility maximization[86]).

Because the discount factor would be a decreasing convex function of r[87], the certainty-equivalent discount rate declines over time, to the lowest possible discount rate in a distant period (several papers by Weitzman, e.g., Weitzman 2007). Wagner and Weitzman (2015) indicated that, although we do not know the 'right' discount rate, the right rate is likely to be very low.

Gollier (2014) showed that, for example, if the policymaker is risk averse, uncertainty about future consumption accumulates faster than on a symmetric random (geometric Brownian) basis. Because shocks to economic growth rates tend to be persistent, future discount rates should take on a decreasing structure. Gollier though, found that risk-adjusted discount rates should increase if the beta of future benefits is larger than half the effect of relative risk aversion.

Hepburn and Kounduri (2006) separately applied autoregressive and regime-switching models of real-interest rates to determine certainty-equivalent discount rates for Australia, Canada, Germany, and the United Kingdom. They found that their regime-switching model better fit past interest rate performance for all four countries. The application of this model produced a more rapid decline in certainty-equivalent discount rates.

How fast the hyperbolic discount rate certainty-equivalent interest rate should decline partly depends on how the uncertainty and risk preference involved vary over time, as well as on the persistency of shocks to interest rates and growth. In addition, it is difficult to imagine the extent of growth that will accompany climate change over the course of centuries. This skepticism and uncertainty could also, consistent with the Ramsey formula, lead to a declining social discount rate.

A practical structure for a declining schedule of rates would be for the discount rate for the short or medium-term (e.g., 20 to 40 years) to be somewhat similar to discount rates used for most intragenerational analyses and reasonably consistent with market rates, albeit somewhat lower, for this

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[84] In contrast with repeated independently and identically distributed shocks, which should not significantly affect the consumption rate of discount.

[85] Since the discount rate relating to a distant future period is so uncertain, averaging discount factors over time lowers the resulting discount rate, with the lower discount rate scenarios dominating, also leading to declining discount rates.

[86] If the aggregate consumption path is optimized and is sensitive to news about future interest rates.

[87] Based on Jensen's inequality that states that the expectation of a convex function is always larger than the function of its expectation. In this case: $E(e^{-rt}) > e^{-E(r)t}$.

period. Subsequent to this period, decreasing rates would be applied. This blended set of discount rates results in a more consistent time-risk analytical framework to enable comparison among a broader range of projects or strategies. Alternatively, the discount rate for the initial period could be consistent with the rate used for other social cost-benefit analyses for other projects.

Social discount rates resulting from this hyperbolic discounting structure appear more compatible with empirical observations of human attitudes, time preferences, and behavior. Empirical evidence suggests that people discount a far-off future period at a rate far less than for the near-future (e.g., the discount typically applied between the 200th and the 201st year is less than the discount applied between the second to the third year).

Lowe (2008) indicated that a declining set of discount rates should be incorporated into a social cost-benefit analysis covering a very long time horizon (at least 50 years) where a project involves substantial and irreversible wealth transfers between generations (see section 7.2 for further discussion).

Thus, the use of a hyperbolic approach can recognize both uncertainty and intergenerational equity. In addition, applying the blended approach described above may be appropriate because the applicable expected costs and benefits may also include shorter term objectives and social externalities (including a provision for sustainability) that may be more relevant at longer durations.

Disadvantages of hyperbolic discounting include its relative complexity, as the initial rate, as well as the speed and pattern of the decline, and ultimate rate have to be determined. Being more complex, it may be less understandable than the exponential method to some stakeholders, although with spreadsheets and current programs they are equally easy to calculate. The empirical evidence of hyperbolic discounting has been dismissed as a mere intellectual curiosity and as time-inconsistent. That is, a future generation might have to use a different set of declining discount rates. Nevertheless, being a dynamic process, such analysis performed at a different time might use an entirely different set of assumptions in any case.

Based on the assumption that the distribution of the discount rate is independent and identically distributed, the certainty-equivalent constant discount rate could be solved for, with time weighting based on the specific pattern of costs and benefits being analyzed. However, the use of a single level discount rate would then result in different discount rates for each project and may require a revision to the level rate at different stages of the project. This approach is not recommended.

Note that, if uncertainty is reflected in the expected cash flows or utils (e.g., using a risk-adjusted or prudently determined cash flows or a fatter probability tail) instead of being reflected in the discount rate, the case for a hyperbolic discounting is reduced, and an exponential discount rate may be acceptable.

Where hyperbolic discounting is applied, the decrease in rates would generally move from a positive initial rate to a smaller positive rate (possibly even close to zero). However, it is possible that the initial rate is negative or very possibly quite close to zero already. There has been little discussion in the literature regarding whether the trajectory of future discount rates should move toward zero or even be negative. The answer is that it should not matter whether the initial discount rate is positive or negative – the rates would decrease.

In sum, unless uncertainty is reflected in the expected cash flows or cash flow equivalents, hyperbolic discounting should be used in social cost-benefit analysis relating to climate change. In addition, its higher discount rates in closer-in years could be more consistent with cost-benefit analysis of other (shorter-term) projects, including some ex-ante adaptation projects and co-benefits that may not have the same level of uncertainty. However, if the initial rates are close to zero or even negative, further research may be needed to confirm how best to implement the above discussion about discount rate trajectories.

Key take-aways from section 8.1.1 include:

- Methods used to reflect uncertainty and risk aversion include an increase in the asymmetry of the probability distributions of costs, a longer time horizon, or a decrease in the social discount rate – usually the latter approach is used;
- Hyperbolic discounting (declining discount rates over time) can be an appropriate method to reflect the ever-growing level of uncertainty on theoretical, behavioral, and experimental grounds, including reflection of the uncertainty of the discount rates themselves; and
- A practical approach is to use as a discount rates a rate that is similar (although somewhat smaller) to medium term (up to the maturity period of a significant amount investments) risk-free sovereign bonds, declining thereafter to the time horizon of the cost-benefit analysis.

8.2: Application

Just as if not more important as the social discount rate are the items that the social discount rate is applied to. The purpose of this section is to explore these items and their interrelation. Important aspects of these items are addressed in the remaining sections of this chapter. Section 8.2.1 discusses several categories of items that cannot easily be converted to cash flow equivalents. The time horizon over which the social cost-benefit analysis would cover is covered in section 8.2.2, while the geographic scope of the cash flows or their equivalent are discussed in section 8.2.3.

In any cost-benefit analysis, it is important to understand the context in which discount rates are applied. This is especially the case in a refined social cost-benefit analysis where climate change is involved, with (1) considerable social externalities, co-benefits, and non-monetizable items, (2) significant uncertainties, (3) both mitigation and adaptation involved, with (4) all exacerbated by an ultra-long time horizon.

In most situations in which actuaries are involved, the calculation of present values reflects the expected timing of various (positive or negative) expected cash flows (or monetary equivalents), expressed in a particular currency.

Economists also use units of utility (utils, economic welfare) or units of consumption, although these are sometimes converted to cash flow equivalents. The use of a utility function may be somewhat problematic, in that the utility function may differ with each stakeholder and can be difficult to agree on. In this case, discounting applies decreasing weights to the economic welfare (measured by utility rather than cash flows) of households or generations as timing become more distant. Alternatively, it could involve units of consumption – the Ramsey formula, for example, assumes the expected time of consumption, while a net present value calculation ascertains a single equivalent consumption value as if made at the time of valuation.

Another way of viewing the value of risk and the results of the present value calculation in formula (6), which is similar, but restates basic formula (2):

$$\text{Value of risk} = \text{PV (vulnerability x likelihood x consequences)} \qquad (6)$$

As applied in all areas of actuarial practice, it is important to discount both expected costs and expected benefits using the same set of discount rates. Failure to do so can introduce bias solely because of the discounting process, which can result in misleading findings or comparisons. This would be the case even though risk aversion is not linear (e.g., loss aversion is usually more intense than attitudes toward possible favorable results), although it can be tempting to apply a larger discount rate to expected losses rather than to gains. Nevertheless, the risk characteristics of each project, including the uncertainties of successful completion, need to be considered.

As indicated in chapter 6, the effect of uncertainty can be reflected in either: (1) the discount rate or (2) the expected cash flows (or their equivalents). Uncertainty should neither be ignored nor double-counted in either. Usually in the climate change context, uncertainty is reflected in the discount rates, although it could alternatively be incorporated in the expected cash flows (e.g., in deriving the weights given to the costs and benefits of each scenario in stochastic modeling or in the determination of the expected cash flows for each of the scenarios used).

The amounts and timing of the benefits and costs in expected cash flows from low-frequency high-severity events and distant scenarios are difficult to estimate, especially because of their diverse and uncertain nature. For example, a natural disaster with losses in excess of a certain size is not only a low expected probability event (say, 1 in 100 years or 1 in 400 years, also expressible in the terms of a 1.00% likelihood of happening in a year or 0.25% per year, respectively), but at the same time is directly or indirectly affected by climate risks for which limited experience is available. In any case, the effect of alternative discount rates can be enormous.

Although Weitzman (2007) expressed the opinion that Stern (2007) used a discount rate lower than he (Weitzman) felt appropriate, he reached similar conclusions because the effect of his larger discount rate offset his higher expected losses due, to a great extent, to his recognition of more extreme potential catastrophic (tail) scenarios.

By their nature, net damages due to climate change can differ from the expected cash flows usually associated with, for example, project finance. Some are social externality costs incurred across the globe and by future generations, while others are costs avoided (e.g., the cost of adaptation to a changing environment or recovering from an adverse situation), which would not ordinarily be incorporated into the assessment of a project or investment. Damages can also include non-monetizable items (see section 8.2.1), including costs associated with vulnerable populations, both in the country and elsewhere, who tend to represent a greater share of the victims of the effects of climate change.

Along with the principle of consistency between the measurement approach used to derive discount rates and what is being discounted, care is needed to ensure that inflation and currency are treated properly and consistently. That is, if costs and benefits are expressed in terms of current monetary values, discount rates should be expressed in real terms. Conversely, if costs and benefits are expressed in nominal monetary values expressed in a particular currency, discount rates should be similarly constructed.

Key take-aways from section 8.2 include:

- The amounts to which discount rates are applied can be at least as important as the discount rates themselves.
- Discount rates and the items to which they are applied should be developed in a coordinated manner, for example, the uncertainty involved should be neither double-counted nor excluded.

8.2.1: Non-monetizable items and qualitative aspects

As indicated in section 8.2, social discount rates are usually applied to either cash flows, cash flow equivalents, consumption units, or utils. Social discount rates cannot easily be applied to items or units that cannot be equated to one of these units[88]. Nevertheless, there are many types of monetizable and non-monetizable costs, benefits, or related items that are difficult to quantify in financial terms, but are still relevant to the application or development of social discount rates over a long time horizon, as well as increasing the uncertainty involved. Identification and treatment of non-monetizable items are the focus of this section.

The Ramsey formula assumes that an appropriate utility function can be identified and quantified. In practice, however, where a particular cost or benefit cannot be quantified, it may be ignored or included as a footnote or discussion item in a cost-benefit analysis report. Even when a valuation of these items is made, the values assigned can differ dramatically by the individual analyst and stakeholder that asked for the report, as well as on qualitative factors such as the culture and environment involved.

Non-monetized or non-monetizable items include those not normally bought or sold. Price discovery, often available where a market in the item exists, is generally not available for observation or valuation for these items. In addition, the assignment of a value under calamitous conditions, such as in an extreme environmental event is problematic, at best. When available, information that can provide input or insight into the determination of their values might be gleaned from markets for related goods (revealed preference methods) or on direct information based on people's preferences as obtained from surveys or other sources (stated preference methods).

The types of items that can be difficult to equate to a financial equivalent include the following:

- *Human life and health* (see section 7.1 for further discussion). A quantitative economic valuation of a human life or of the financial or psychological effects of deterioration in health is naturally subjective[89]. Although values could be assigned or the effect on economic growth (e.g., foregone wages) might be estimated, they are at best arbitrary and personal. In addition, employment productivity, families, educational opportunities, food production, and neighborhoods / homes (rather than property values) are other examples of aspects involving human life and health that may be affected. Although life can go on if a family, neighborhood, or region is forced to emigrate from homes due to a natural disaster, famine, desertification or higher sea levels, deterioration in the quality of life can differ dramatically and be drastically affected for several generations.

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[88] This does not include an economic benchmark to which the net present value or annual cost can be related for comparison purposes, e.g., a specific percentage of a country's or world's GDP.

[89] Unless set by legislation or regulation – the type and level of value can be quite sensitive to these amounts.

The value of life and adverse health conditions could be expressed in terms of premature life-years lost (relative to expected mortality or health without the intervention of climate change), time-adjusted future premature deaths, or simply the number of deaths by year or grouping of years. Needless to say, there is no definitive or agreed-upon cash flow equivalent that corresponds to how much a life or its quality is worth, no matter what ages they are (particularly problematic for those in their fetal state and those who are elderly) or their socio-economic status. It is impossible to predict the real current or what-if future value of people who may succumb to premature death, ill-health (physical or mental), or disability.

In spite of the difficulty in attributing the number of premature deaths to climate change or to mitigation/adaptation activities, those in (physical or mental) ill-health, or who become disabled, this information is important to incorporate in a transparent manner, as this effect may be important in making decisions and are valuable in comparing alternative possible courses of action.

- *Quality and stress of life*. Increases in mental stress will occur as a result of, for example, the publicity, exposure, and even fear of a future adversely affected by extreme damages due to climate change. For instance, living in a flood plain bears with it more than direct physical property damage possibilities – there are also accompanying psychological uncertainties and stresses involved in losing a home and community. This type of damage can take on various forms, such as increased food, water, or disease insecurity, catastrophic life trajectories in refugee camps that can result from needed emigration and conflicts in extreme situations, which take cost to new and higher levels. Such intangible costs may be impossible to estimate for any purpose and certainly in a social cost-benefit analysis of mitigation or adaptation actions. The value of and existential threats to a household or community and the value of its needed support systems are unquantifiable – these are likely to be at-risk in the more extreme adverse scenarios related to climate change. Although expected property damage might be increased by a percentage factor could be used, this or other approaches are arbitrary at best. Adaptation of the physical condition may reduce the amount of expected damages and associated uncertainties that in turn may reduce this concern.

- *Environmental and ecological items*. Although there are many components of our environment that can be assigned a value that can be estimated, others cannot be. The latter includes potential loss of or deterioration in ecosystems such as breathable air, drinkable water, rainforests and coral reefs, national parks and recreational areas, ocean quality such as acidification that affects marine life, air and groundwater pollution, and species biodiversity, to name a few. Food and water insecurity are added costs with consequential damages. The incalculable value of heritage assets can also be at-risk.

- *Social externalities and co-benefits*. These include such factors as sustainability of the environment, avoidance of disease, and food security. What is the value of developing and maintaining the sustainability of institutions, human capital (through education), households, communities, public culture, the environment, and public welfare? To what degree will climate change contribute significant damage to the area/country’s financial system, food and other supply chains, public health, or transportation infrastructure? As can be gleaned from the 2020 global pandemic, the economic costs of global disruptions can be impractical to determine, let alone project. While direct costs are difficult enough to estimate, the value of the potential harm secondary and tertiary damages contribute is problematic, at best, to determine. Their intangible aspects contribute to this difficulty.

- *Morality and ethics*. A quantification of the intergenerational and intragenerational effects of some of the ethical issues involved, as discussed in chapter 7, such as on inequality, poverty, and lack of affordable health care, is difficult if not impossible. Although the effect of these factors could be approximated by a reduction in the social discount rate (e.g., through the use of a zero value of ρ as discussed in section 5.2.1), an alternative approach would be to consider them in a separate section in a social cost-benefit analysis report, addressing such factors as the percent of the population expected to be affected and their significance. However, such a section could, if care is not taken, become like a boiler-plate full of platitudes, which may be ignored as a result.

- *Security*. In addition to water, food and shelter security, which are basic to life, other areas of security can also be at risk. These include energy, sanitation, and national security.

- *Technological and information developments*. Changes in human knowledge or new applications of currently known (and unknown unknown) techniques are difficult to identify in advance, let alone to estimate their effects. These are examples of co-benefits that, if and when quantifiable, would be incorporated in a social cost-benefit analysis. Those that are not, should be noted as qualitative costs or benefits.

The cash flow equivalents of these costs or benefits, if any, may also depend on the context. The value assigned to each of these categories can differ dramatically based on time, location, social/cultural/ethical values of the user(s) and scale. Opportunity and other intangible costs will also inevitably arise, e.g., avoidance of direct or consequential damage, and have to be considered.

Alternative approaches to reflect these non-monetizable costs and benefits include:

- Quantify, to the extent possible, in cash flow equivalent terms, in the discounting process;
- Disclose relevant metrics, where possible, and severity of concern regarding possible damage and risks associated with non-monetizable items, e.g., expected number of premature deaths over a specified number of years or a range of health and longevity impacts of increased food insecurity, with an indication of their associated uncertainty;
- Disclose time-adjusted factors applied to quantitative metrics, such as a current time-adjusted number of additional premature deaths;
- In a separate discussion section of a social cost-benefit analysis report, qualitatively describe other significant items likely be affected, in terms of the expected types of loss/damage, frequency (as an expected rate of loss), severity, timeframe, and level of confidence; and
- Reduce the social discount rate used, e.g., through a disclosed schedule, with a range of, say, 0.1% to 0.5%.

Clear communication of the assumptions used for these items is important for the users of social cost-benefit analysis findings.

In summary, since discounting is fundamentally a quantitative process, it is difficult to apply such a process to items that cannot be expressed in a non-financial, non-monetizable or non-estimable manner. It is hoped that decision-makers act in a manner considering these important and relevant qualitative and non-monetizable effects of the investment or strategy studied, as well as quantitative and monetizable analysis aspects. All of these should be included in a social cost-benefit analysis.

Key take-aways from section 8.2.1 include:

- There are several types of non-monetizable items (i.e., not translatable into cash flow equivalents, such as heritage assets, ocean quality, and human lives) and difficult to quantify areas (e.g., quality of life and health, intangible social externalities and systems sustainability) that should be considered in a social cost-benefit analysis;
- There are several possible approaches to reflect these items, either in a quantitative manner (e.g., lives, percent acidity) or a qualitative manner expressed in terms of expected frequency, severity, timing, and their degree of confidence;
- One approach is to time-adjust the applicable metric or to decrease the social discount rate.

8.2.2: Time Period

Two key time periods are addressed in this section: (1) in applying hyperbolic discounting, a constant discount rate might be applied for a relatively short initial period and (2) the time horizon over which expected cash flow equivalents should be included in a social cost-benefit analysis. There is no unique answer to either. In practice, a somewhat arbitrary period is usually used for both.

1. *Initial period*. One approach to implementing a hyperbolic discounting methodology is to utilize a constant discount rate over an initial period (Appendix 1 shows a range of thirty to forty years is used for this purpose in Denmark, France, Norway, and the United Kingdom), which is the period of what is often the longest period of available government bonds. A shorter period, say between ten and fifteen years, might better represent an average period over which comparable investment time horizons cover.

   Climate risk-related investments or projects compete for limited resources with projects of shorter expected lifetimes and objective horizons. In some cases, the investment or strategy being analyzed has multiple, possibly disparate objectives and expected benefits. For example, the objectives of investment in renewables may simultaneously include a contribution to climate change mitigation, reduction in air pollution, enhanced industrial efficiency and green-job creation.

   Real discount rates for an initial period of, say, ten or twenty years, may be based upon corresponding market-based prices for financial instruments, adjusted for uncertainty and social externalities. The discount rate over this initial period could be similar to the period used in a social cost-benefit analysis of other competing social investments.

2. *Time horizon*. The period over which costs and benefits should be considered in a cost-benefit analysis can be quite important, especially in an environment with relatively low social discount rates.

   The first question to address is whether a fixed period or an infinite horizon is more appropriate. Although some economists prefer studying such issues over as long a period as can be calculated, the author of this paper dismisses this approach out of hand, as the assumptions that would have to be made over the entire time horizon is at best a speculative guess, as well as being absurd on its face. This is especially the case in view of the enormously consequential tail conditions that might evolve over such an ultra-long period of time. It has to be kept in mind that so many other economic and social changes are likely over such a long period that the relevance of applying a utility function such as CRRA over more than a few hundred years is problematic at best.

The time span over which a social cost-benefit analysis is conducted should be sufficient to capture the major welfare effects that result from the policy alternatives being assessed. It also has to be realistic, e.g., demographic, financial, and technological conditions in 500 or 1,000 years are so difficult to predict or even to develop speculative scenarios for (i.e., pure guesswork – for example, this would be similar to projections made at the time of Columbus' discovery of America or at the time of the first Crusades, respectively, of what twenty first century conditions would be like), that it does not seem appropriate for any type of cost-benefit analysis. As a thought experiment, it may be useful to step backward in time to imagine trying to develop an estimate, let alone the relevance of today's emissions of greenhouse gases, during World War I or the American Revolutionary War.

Practically, the selection of a time horizon over which a social cost-benefit analysis is based should be far enough in the future to enable an estimate to be made of a large majority of discounted climate damages, but not too long as to constitute overly speculative guesswork. Possible approaches used for this purpose include:

- The expected life of capital investments required by or expected from the policy being assessed;
- The time when benefits and costs are expected to reach a steady state;
- The extent to which benefits and costs are separated by a given number of generations, such as three or four; and
- Statutory or other requirement applicable for policy or social cost-benefit analyses for long-term activities, such as for nuclear plants and retirement systems.

This contrasts with the expected lifetime of the investment or program (or maximum period dictated by regulatory or legal rules, such as ten years used for U.S. government budgetary purposes). For a cost-benefit analysis of mitigation or permanent ex-ante adaptation projects, a timeframe equal to the period over which the useful expected project life is expected, including that of expected social externalities or co-benefits, could be appropriate. For example, the period analyzed could be that over which ultimate health costs of pollution and climate change resulting from carbon produced from coal power generation would be expected to occur.

If the project or strategy being assessed is short-term, for example, a project being undertaken for adaptation purposes with a relatively short expected return period, the social discount rate might be based on, albeit somewhat less than, the market-based rate for that period. The uncertainty premium is most likely less than and the social externalities and co-benefits may not be as significant as those associated with a longer-term project.

Green bonds (or 'climate bonds') represent a means for financing climate change mitigation, adaptation, or conservation of natural capital. First created by the European Investment Bank and the World Bank, together with the Swedish SEB in 2007/2008, green bonds have been issued by government agencies, multilateral institutions, and private-sector businesses. They enable immediate investment in climate change mitigation and adaptation, being repaid by future generations in such a way that those who benefit from reduced future environmental damage share in financing the mitigation efforts undertaken today.

Best practice would include estimates of the effect of related social externalities and co-benefits. Currently, some governments use exceptionally long periods for climate change cost-benefit analysis. In any event, when comparing alternative proposals or a proposal against a benchmark, a common period should be used. Costs and benefits should also be considered over a common period.

The resulting period used will, in any case, be subjectively based. In theory, more than ninety years ago Ramsey considered utility over a period he estimated that society would be in a state of bliss, satiated with their wants, at a point when additional saving would be pointless. Unfortunately, the author of this paper is unable to estimate such a time period and thus discards such a potential determination.

As an example, two hundred or three hundred years might be a practical time horizon to use in an analysis of a possible climate change-related investment. One justification for the choice of this range of periods is based on a possible scenario: the world exhausts most of the economically recoverable stock of fossil fuels by that time and atmospheric greenhouse gas concentrations have begun to decrease[90]. In Stern (2007), using a 1.4% discount rate, more than half the present value of expected cash flows related to periods after two hundred years. Using something like Stern's social discount rate, the choice of the time horizon became material to the conclusions reached.

Where practical, one approach to take would be to use as a benchmark a selected maximum period of, say, 200 years or through a common year, say 2200, that does not change often. This would be supplemented with an estimate of trends in costs and benefits and sensitivity of using one (or more) alternative periods. In addition, a sensitivity test could be conducted to determine whether the use of different periods would result in a different decision. It should be noted that the lower the discount rate, the effect of this choice becomes more material. For convenience and communication purposes, the end of a century has sometimes been used in climate science projections.

Key take-aways from section 8.2.2 include:

- The initial time period for use in the initial level social discount rate in applying hyperbolic discounting should cover the period of the most significant block of long-term financial instruments of a country, e.g., somewhere between ten and forty years;
- A considerable period of cash flow equivalents and non-monetizable items should be considered; in comparing alternative proposals or a proposal against a benchmark period, a common period should be used; and
- Depending upon the application, possibly two hundred to three hundred years might be used for climate change social cost-benefit analysis, as effects over longer periods may involve too long a period over which to speculate; and

[90] Assuming cost-justifiable carbon capture and storage had only then become economically feasible on a practical scale.

- The effect of using more than one possible time horizon in a social cost-benefit analysis may be useful in comparing possible investments or strategies.

8.2.3: Geographic scope

The purpose of this section is to explore the effects of the choice of the geographic perspective of a social cost-benefit analysis of climate change. Usually, mitigation is addressed at the global level, while adaptation is addressed at a national or local level, although the latter could alternatively be conducted at a regional (cross-border) level as well, depending on the specific adaptation and political arrangements.

Although greenhouse gases are emitted locally, they aggregate in the atmosphere and in the oceans on a global basis, resulting in costs and damages that do not adhere to national borders. All countries are affected, as climate, the atmosphere, and the oceans are all global public goods. It is inappropriate to solely consider national costs and benefits in a social cost-benefit analysis of a climate change mitigation project or strategy, although such information may nevertheless be useful. It is most effective if all levels of government cooperate and share in the effort of planning and implementation of mitigation and adaptation efforts.

In contrast to mitigation that can affect global damages, the goal of adaptation efforts is to reduce the adverse effects of climate change at a local or regional level. As a result, average values or conditions ascertained over a wide area may have to be assessed in a more refined manner in terms of a local area where emissions occur, decarbonization techniques may have to be applied, and losses and damages, especially of the more vulnerable, may be more concentrated. In some cases, the cost to adapt may be less expensive than a country's efforts to mitigate through greenhouse gas emission management. A combination of both mitigation and adaptation efforts can reduce damages from the volatile and long-term effects of climate change more than either one alone.

Certainly, if global mitigation efforts are successful, the need for widespread adaptation, and thus its cost, will be reduced. However, even if the Paris Agreement National Commitments (current and future enhancements) are achieved, adaptation efforts and local capacity building will still be needed to control the adverse effects from climate change and severe weather events.

While an individual country's program to reduce the amount of greenhouse gas emissions may by itself make only a small impact on the planetary climate process, such mitigation efforts by each country are important components of an overall global approach to control climate change – international emission and climate goals are unlikely to be met without near-universal cooperation. In addition, the spirit of a universal social contract requiring sound and sustainable global citizenship can provide mutual support for overall efforts, for if part of the global society does not participate, the entire structure may fall apart.

Unfortunately, because (1) the global scope of the overall problem may seem distant and thus of lower priority and (2) free-riding mitigation actions may seem easier and less expensive in the short-term, intensive mitigation efforts[91] may not be undertaken in some countries. Although a global agreement

[91] Other than those that would occur with the application of market-based discount rates or based on market prices, such as is the case if the price of renewable energy and natural gas is less expensive than fossil fuel driven energy without consideration of social benefits.

with mandates (through some form of coercion, which is not currently possible at the national level) might be more efficient, it is unlikely to be possible at least in the short and medium term. Using enhanced and affordable climate-friendly technological approaches in the power, electricity, transportation, and agricultural sectors, moving toward adoption of agreed-upon best practices, sharing local and national role model efforts, and using of nudges or aspirational goals (persuasion) are in the aggregate likelier to represent the best available courses of action.

Unfortunately, in some cases it can take decades in many cases to meaningfully change practice, such as in aviation where there is currently no substitute source of energy or in steel production where it is massively expensive to replace large plants unless prices increase substantially. This points to the importance of more consistently expressed global metrics and objectives, measured by means of a consistent rulebook (e.g., by the 'Paris Rulebook' adopted at the Katowice COP24 meeting in 2018).

Geographic areas that contain vulnerable groups or individuals tend to bear a relatively large share of climate change-related damages, but have not contributed significantly to the accumulation of global greenhouse gas concentrations. In addition to an overall lack of resources, this may be partly due to what is often relatively weak infrastructure with a heavy reliance on agriculture, where damage is relatively sensitive to the effects of climate change. Overall, damage sensitivity is a function of many factors, including geography, the extent of advanced planning (i.e., ex-ante adaptation) and ability to withstand damages, health care and other infrastructure preparedness, effective and applied land use standards, and building resilience.

Not all stakeholders recognize or value the benefits of mitigation or are willing to help finance such climate-related projects. These stakeholders typically allocate their limited resources to projects with direct short-term benefits, rather than on what can seem to be conceptual benefits spread over the globe and time. Undertaking climate change-related projects that can simultaneously help other problems may help, for example, helping to control local air, water, and land pollution and developing a local green-economy.

As indicated in chapter 3, damages and costs[92] associated with climate change can differ significantly by geographic area, demographic segment, and industry sector, as a result of (1) climate risk itself such as from droughts, severe storms, sea level rise, and temperature variations that are affected by topographical and geographical characteristics and (2) external influences, such as the extent of local adaptation and preparedness efforts. The latter might have been built up in response to law, regulation, taxation, or local priorities.

Values, uncertainties, risk aversion, and threats to growth prospects can also differ significantly by country, region, or locality. Investing with a longer-term view in mind often occurs where a country practices sound governance and manages its fiduciary responsibilities with both a short and long-term perspective.

Practically, adaptation projects and strategies may be best carried out at a level with topographical and geographical features that represent similar exposure and climate risks, such as large river management and drought-responsive infrastructure. Shared information concerning successful approaches can be beneficial, as can a holistic approach implemented by means of a comprehensive social risk

[92] In some areas, direct effects may be beneficial. In addition, industries such as the renewable energy, construction, and electric automobile industries may greatly benefit from mitigation and adaptation efforts.

management process. In any event, local input and involvement is needed to make such a process work effectively. Jurisdictional cooperation between their private and public sectors would in many cases benefit everyone.

It is common for many countries (or even generations) to attempt to (1) avoid the cost of mitigating the build-up of greenhouse gases, by what is in effect free-riding, using what may seem to be cheap energy (e.g., by not considering coal's social externalities or co-costs) or (2) rely on short-sighted planning, relying instead on ex-post adaptation when needed.

Assistance in financing often comes from developed countries, supranational organizations and funds with adequate financial and expert resources. Ex-post adaptation activity is usually a national or local responsibility, although especially when a disaster occurs and arises in a less developed country, supranational organizations, philanthropic foundations, and foreign governments may provide assistance. This underscores the need for risk-pooling and risk-transfer mechanisms such as private or public sector insurance, supported by effective regulatory and organizational oversight. Certain international arrangements, such as the 2015 Paris Agreement, have attempted, with varying degrees of success, to spread these costs globally.

Climate damage in neighboring countries can indirectly hurt the base country. First, adverse climate-related factors, such as pollution, can spread geographically across borders. Extreme damage to one country's vulnerable population or resources, caused by such climate-induced conditions as drought, famine, or vector-borne disease, can cause climate emigration, potentially draining others' scarce resources, especially if both are less developed or developing countries. As in other situations, overall climate change problems can be more effectively addressed by working together, as there is no single country that can by itself solve a majority of the problems involved. It is thus, both with respect to causes and consequences, an international problem.

Depending on its severity and the extent of available resources, international support is often needed and provided to address ex-post adaptation needs (e.g., through disaster recovery efforts), although not all are received in a timely manner. Disaster preparedness demands ex-ante risk-pooling and transfer mechanisms, such as private[93] or public sector insurance from national or supranational organizations, supported by effective regulatory oversight.

It should be remembered that a social discount rate is not necessarily the discount rate applicable to an individual, as personal valuations differ. For example, a person employed as a coal miner whose job is at-risk due to climate change mitigation efforts may have a different personal view than an urban dweller in a developed country with a secure job. Thus, climate change assessments may differ, recognizing that individuals, regions, and countries hold disparate views of their future benefits and costs associated with the effects of or mitigation of or adaptation to climate change.

When damages are quantified on a national or regional basis, two approaches can be taken to social discounting: (1) aggregate estimated damages globally and discount those damages using a global discount rate or (2) estimate damages on a national or regional basis, discount each set of estimated damages using applicable discount rates, and then sum the discounted values. In most mitigation cost-

[93] In many areas and population segments that are especially vulnerable to climate change risk there is inadequate insurance coverage (referred to as an insurance gap), due to high expected losses, which result in affordability problems.

benefit analyses, the former approach is used, while in most adaptation analyses the latter is usually applied. Although in many cases a single global, rather than nation or local-specific, social discount rate is used, scenario-specific discount rates are usually applied. Many countries will compare the social value of alternative uses of their scarce resources for the best bang-for-their-buck, with climate change-related projects representing one of many competing issues they face.

Nominal interest rates are generally higher in less developed and developing countries than in highly credit-rated developed countries, due to such factors as sovereign risk, currency risk, market liquidity, relative lack of financial capacity, and priorities given to satisfying immediate needs. In addition, social discount rates applied in many less developed and developing countries and by regional/global development banks tend to be higher than in developed countries, e.g., in some cases up to 12 percent higher (Harrison 2010), which naturally emphasizes investments with a shorter period of return than do most social discount rates discussed in this paper.

The use of consumption discount rates that reflect uncertainty is likely to make long-term development projects more attractive for a country facing substantial poverty and greater volatility of consumption, being less attractive for either an otherwise similar country whose economy is expanding or for developed countries. Higher discount rates also favor longer-term ex-ante adaptation projects for less developed and developing countries.

The actuarial principle that discount rates should be applied in a manner consistent with the cash flows being discounted, as described in section 8.2, is applicable here as well. As accumulated greenhouse gases affect climate globally, it is appropriate that social discount rates, social externalities, and associated uncertainties be applied in a social cost-benefit analysis at a global level. However, global average values can be challenging to estimate (e.g., global discount rates, uncertainty and risk aversion, as well as social externalities).

Estimated global growth rates estimated for use in the Ramsay formula can be difficult to estimate as well. For example, over the short-term these are dominated by that of developed or fast-growing developing countries, with the large Asian countries becoming more important over the long-term. As these become more mature, global growth rates may decline. As applicable, this type of changing dynamic should be considered.

Key take-aways from section 8.2.3 include:

- Expected and actual damages from climate change can differ dramatically by region, country, or locality;
- Mitigation efforts, although applied on a local basis, have global effects; as such, global costs, benefits, social externalities, and co-benefits should be considered, although national or local resource constraints can dominate some decision-making;
- Adaptation efforts are primarily national or local in nature, although assistance in financing often comes from developed countries and supranational organizations and funds with adequate financial and expert resources;
- Ex-post adaptation activity is primarily a national or local responsibility, although, especially when a disaster arises in a less developed country, supranational development organizations, philanthropic foundations, and foreign governments can provide assistance, which underscores the need for risk-pooling and risk-transfer mechanisms such as private or public sector insurance, supported by effective regulatory and organizational oversight;

- Global values, e.g., of uncertainty and risk aversion, can be difficult to determine because of a lack of consistent data – as a result, broad estimates or careful averaging may be necessary; and
- Although in many cases a single global, rather than national or local-specific, social discount rates are used, scenario-specific discount rates are usually applied.

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Key take-aways from chapter 8 include:

- It is important to understand the context in which social discount rates are applied, to effectively coordinate the estimation of cash flow equivalents and social discount rates, including social externalities and uncertainties over ultra-long time horizons;
- Uncertainties should be reflected in either cash flow equivalents or the discount rates used, but not in both;
- Although not directly or explicitly included in present value calculations, there are several types of non-monetizable (i.e., not translatable into cash equivalents such as heritage assets, ocean quality, and human mortality and stress) and difficult to quantify areas (e.g., quality of life and health, social externalities, and sustainability) that should be considered, either on a qualitative or other external basis, or as a judgmental reduction in the social discount rates;
- The initial time period for use in hyperbolic discounting prior to reducing social discount rates can cover the period of the most significant block of long-term financial instruments of a country – several European countries use a 30 to 40-year period, although 10 to 20 years may be preferable;
- The time horizon over which a social cost-benefit analysis should be conducted should be far enough into the future to capture a large majority of discounted climate-related damages, but not too long as to represent (almost) totally speculative guesswork; and
- Social cost-benefit analyses of mitigation projects and strategies should usually reflect a global perspective, while adaptation projects and strategies should usually reflect a local or national perspective, as applicable.

Chapter 9: Application of Real Options Analysis

The purpose of this chapter is to explore the application of real options analysis in a social risk management process (section 2.2). This extension of a social cost-benefit analysis in that process can assist decision-making where significant uncertainty exists. Several examples of issues for which real options analysis may be useful are provided.

The basic questions addressed in a social cost-benefit analysis of climate change risk include: what to allocate to or spend resources on, how much to allocate/spend, and when to allocate/spend it. This chapter focuses on the last question – how to assess whether, and to what extent, climate-related programs or investments should be implemented immediately, deferred, or phased in. A real option is the right, but not the obligation, to undertake a specific action[94], including the right to defer the implementation of a project or investment.

[94] These do not include financial options, which are options usually traded in a capital market, providing the right, but not the obligation to perform a financial contract.

The flexibility of a real option can be used in financial planning or by a resource-constrained government. Taking advantage of the extent and type of uncertainty can provide an incentive to include more flexibility in the project or strategy design being assessed. For example, expenditures on climate-relevant projects could be spread over a period of time or be committed to at a later time. A crucial question is whether the entity is willing to tolerate the consequences of a delay. In any event, such an investment should meet the social cost-benefit test of a positive net present value to help ensure that the welfare of society will be enhanced.

A real options analysis can play a key role in a dynamic climate risk management process, especially where flexibility may be needed while significant uncertainty exists. It allows investors or public policy decision-makers, for example, to incorporate new information when and as it becomes available. It can also be used to help design effective regulations and proper timing of required implementation of new requirements. Several design structures can be studied under alternative scenarios (selected on a probabilistic or selected scenario basis, one or more of which could be a stress scenario), together with expected policy responses.

One approach to conduct a real options analysis consists of five stages, involving:

1. *Plan.* Structuring the problem so that the key objectives and decisions-to-be-made can be based on relevant and reliable information and metrics, recognized sources and size of uncertainties, and the extent of possible available flexibilities;
2. *Conduct baseline analysis.* Undertaking a baseline analysis in which a (climate science and economic) model of the problem is specified, as applicable, and estimates of the resulting discounted cash flows (or equivalents) are developed;
3. *Assess scenarios and options.* Evaluating alternative scenarios and options strategies that could be employed using the baseline analysis;
4. *Study sensitivity.* Running sensitivity tests related to the primary areas of uncertainties and of optionalities thought to be inherent in the baseline analysis; and
5. *Monitor.* Implementing a monitoring system that follow the assumptions that underly the delay and whether its design and timing remain appropriate.

Such an analysis can include the following components, as applicable, with feedback loops incorporated where appropriate:

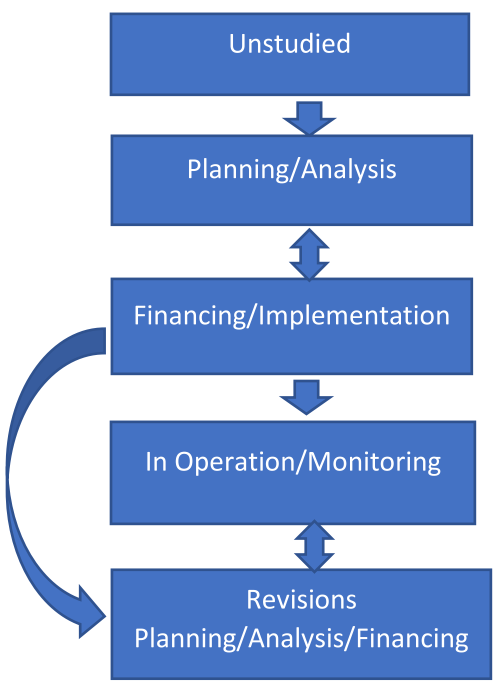
- Identifying relevant information early-on, including relevant pilot studies and a scan of technologies currently available and expected in the future;
- Carrying out preventive/precautionary actions;
- Considering expected flexibility, social externalities, and co-benefits;
- Embedding flexibility from the start when deemed desirable considering the additional costs associated with the flexibility;
- Avoiding irreversible decisions or decisions with irreversible consequences where more desirable alternatives exist or are expected to exist;
- Transferring or sharing risk through contractual arrangements (e.g., using private or public sector insurance), where available;
- Developing less risky options, such as reducing reliance on unproven technology and increasing use of proven technology; and
- Abandoning the project or strategy if it does not add value or becomes too risky.

Real options analysis is most often used to analyze a project in an environment with a great deal of uncertainty and volatility, the project design can be modified over time, or when other factors can change. The other factors might include possible new developments or technologies, new climate-related information, or availability of needed financing that could materially affect the amount or timing of the project's costs or benefits. Although there is always a desire for greater certainty, this desire has to be weighed against the potential costs associated with delay. Flexibility may be needed when there are competing demands on available resources, especially relative to physical assets – hence the term 'real', in contrast to financial options. It can also regularly assess the chance of achieving its objective through use of timing flexibility of its capital investments and of adjustments as the project progresses.

Regarding climate change, disagreements have arisen between (1) those who believe that climate change mitigation investments have to be substantial and immediate and (2) those who favor modest rates of emission reduction in the near term, followed by more dramatic reductions in the medium and long term if they are still needed. Those in the first group believe that the costs associated with irreversible greenhouse gas emissions and atmospheric concentrations will be huge and immediate action is needed to avoid what may become existential risk. Those in the second group feel there is plenty of time to ramp up expenditures, convinced that improved technology will be able to 'solve' the problem in a timely manner at reduced cost. In the meantime, relevant investments would include research and development of no-carbon, low-carbon, and other technologies that will reduce greenhouse gas concentrations and enhance the effectiveness of adaptation processes.

Project management stages are shown in Figure 6. The valuation of a real option can be determined in each stage, with each stage being implemented either immediately or in phases.

Figure 6 – Project stages



The stages involved indicated in Figure 6 for a mitigation or ex-ante adaption project (similar stages are applicable to strategy management) are briefly described in the following:

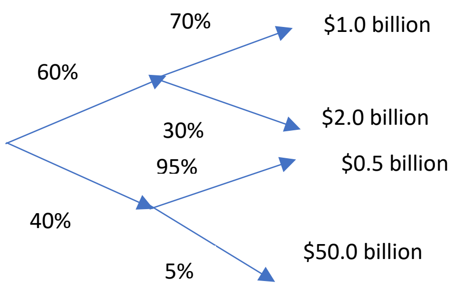
- *Unstudied*. This initial stage is prior to a real options analysis;
- *Planning/Analysis*. This initial project stage includes a real options analysis in the context of a social cost-benefit analysis. Its options are (1) to move to immediately financing and implementation or if an internal project, when it is accepted into the entity's budget, (2) to delay the project, either waiting for further information or for a better time to implement it, or (3) to terminate it from further consideration;
- *Financing/Implementation*. This is the final stage prior to initiation, waiting for external or internal financing/budgeting and includes its development stage;
- *In Operation/Monitoring*. This occurs while the project is in progress; regular monitoring against its objectives is conducted with respect to its efficiency and effectiveness;
- *Revisions: Planning/Analysis/Financing*. After initiation, a project is regularly reviewed for possible revision – if it needs further financing, it may continue to be an operating project at the same time;
- *Delayed*. This could arise prior to implementation or, for example, if financing is not initially successful. It can be planned or unplanned; and
- *Abandoned/Terminated*. This is the terminal stage that can arise any time during initial analysis or assessment in the course of or while a project is being delayed.

Delay in a political setting may in some cases be viewed as 'kicking the can down the road' to future decision-makers. In other cases, delay may prove to be a prudent and possibly pragmatic public policy approach. With regard to climate change mitigation, due to what, in the meantime, may be irreversible increases in atmospheric greenhouse gas concentration, too much of a delay may exacerbate the problem later. Given possible damage of a sudden weather or weather-related disaster and an ever-increasing medium and long-term risk, the relative value of the real option (say, to wait for better information or for new greenhouse gas reduction to emerge) may be small, but may be financially and politically necessary. Nevertheless, in this case a significant delay may be problematic, at best.

The value of a real option is the difference between the expected present value without the real investment and the expected present value with the real investment. The first step in the valuation is to use a probability technique such as a decision-tree (see Figure 7, in which the 60% branch represents starting the project now and the 40% branch represents a delay; the present value of benefits from starting now is $0.78 billion, while for the delay is $1.01 billion, which indicates that it would be financially better to delay). Assuming optimal choices are made at each decision-point[95], this value can be quantified under each option, developed by assessing all relevant branches considering expected time, scale, public and private sector involvement, expected permanent/temporary changes in conditions, and changes in financing method. As indicated elsewhere in this paper, especially in section 8.2.1, qualitative analysis of information and the flexibility option represents crucial supplementary information needed to make a sound decision.

[95] Although this may not occur, for this purpose, the assumption made is that decisions are based on the most reliable and relevant available data and observations.

Figure 7 – Decision-Tree



By addressing the alternatives presented at each branching point based on their probabilities, the expectations under which a decision-tree is made can provide the basis for how a decision-maker assesses choices. The optimal decision is thus evaluated based on a probability-weighting of all possible downstream outcomes of that decision.

The next step is to apply applicable discount rates to the expected costs. The normal approach is to apply scenario-specific (path-dependent scenario) discount rates. Alternatively, a single set of discount rates can be used throughout the decision-tree, in which case artificial probabilities (called risk-neutral probabilities) must be introduced to reproduce the same discounted values as would be produced by the use of the scenario-specific discount rates. In either case, the costs associated with branches with favorable climate outcomes receive less weight in the aggregate present values, while the costs associated with branches with unfavorable climate outcomes receive greater weight (Copeland et al. (2005).

Dixit and Pindyck (1994) demonstrated that the inclusion of the value of real options analysis in a cost-benefit context reflects the effects of uncertainty regarding future costs and benefits. They identified the following characteristics of many investment decisions that could benefit from real options analysis:

- The investment is partially or completely irreversible, i.e., at least part of the initial cost is unrecoverable or sunk, because it cannot be recovered even if the remainder of the investment process does not proceed. If all costs were recoverable, there would be no value in delaying the entire investment[96]; in the case of climate change, once in the atmosphere and ocean, the time it takes greenhouse gases, especially CO_2, to be eliminated naturally is so slow, it is almost as if it is irreversible;
- There is uncertainty regarding the future rewards or payoffs from the investment;
- There is an ability or opportunity to at least partially delay the investment[97]; and
- More information about potential rewards or payoffs (but never complete certainty) become available during any delay period.

The irreversibility of the process between greenhouse gas emissions and environmental damage caused by action (or rather, inaction) over the period until project/investment initiation affects the calculation of social value. This is because costs incurred through the end of the implementation stage contribute to greater uncertainty and can introduce bias to the application of a traditional cost-benefit analysis. The

[96] Assuming that financing cost of the investment continues to be available.
[97] Implementation of certain strategies and investments can take many years to fully implement – partly due to size, complexity, availability of appropriate resources or the political process. The delay referred to here is the delay until applicable decisions taken.

ultimate cost associated with greenhouse gas emissions during the delay period is the present value of the losses and damages attributable to the delay in mitigation over that period compared to that expected if the project was not delayed. The length of the delay depends on unfolding circumstances and the risk tolerance and other views of the decision-maker. The dynamic reassessment means that other factors, such as alternative possible uses of funds, interest rate scenario, time/risk/value preferences, can also change.

Applying real options analysis facilitates an incremental and flexible approach. Three types of approaches that could be used are:

- *Delayed decision / implementation*. This option can increase costs, both in the cost of implementation and during the period of delay, while it can also add values through such factors as new or enhanced technology and information.
- *One-step-at-a-time*. For example, a real option can be created by building a base or low-level wall in an area close to the sea. At a later date, low-lying infrastructure such as a road or railway with a long expected life can be converted to a higher wall or adjoining land can be set aside to form a wider corridor in which greater levee banks can be built to protect against severe flooding or subsidence. This can reduce the initial cost and be upgraded later to provide greater protection when deemed needed, but bears the risk of an earlier-than-expected adverse water surge that might lead to more severe chronic damage.
- *Build in pre-planned stages*. This approach includes adaptation to gradually worsening climate conditions, for example, by building a dyke to protect against rising sea levels (but would not protect against ocean surges or a tsunami). This can be part of a set of preplanned stages or each stage can be contingent on certain conditions being met in the meantime. This could also enable scaling back an investment if additional information indicates that the problem is not as serious as initially thought.

The value of the option to wait to implement climate change mitigation is balanced against the cost and risk of waiting, because during the waiting period, greenhouse gases will continue to be emitted with consequential costs from severe natural disasters (expressed in terms of probabilities and severities of such disasters). Real options analyses can enhance the understanding of how social value evolves over time, reflecting updated estimates of probabilities of possible outcomes and regular reviews to initiate desirable feedback loops. The social cost-effectiveness of the project is greater (smaller) or the duration of the period of waiting before information is gained is shorter (longer).

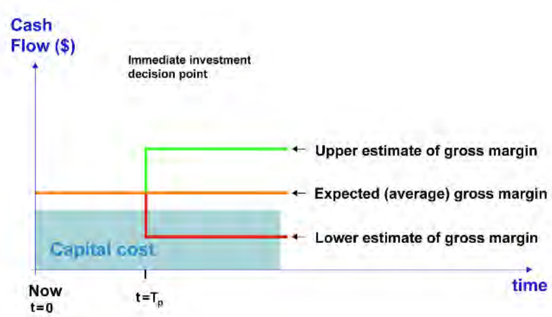
Figure 8 is an example (from Watkiss et al. 2013) of a real options analysis used in an assessment of an investment decision. It shows the expected gross margin over time, with annuitized capital costs represented by the shaded area. Uncertainty arises from a possible shock that occurs at time T_P, which could affect the project's cash flows either adversely (the red line) or favorably (the green line). Case A ('now or never') does not include any flexibility to wait, so the normal net present value criterion (must be greater than zero) is applied at time t=0 to decide whether to make this investment. The best estimate (the central orange line) for A is the average of the high and low estimates (symmetrical here) of the offsetting likelihood of the shock, such that the expected value of the investment remains profitable. In this case, the decision-maker should proceed with the investment.

Case B ('flexibility') provides an opportunity to wait until time T_P before making the investment commitment. This delay avoids the potential loss resulting from conditions worse than expected (the red dashed area). However, this loss avoidance should be weighed against the opportunity cost of waiting (the orange dashed area).

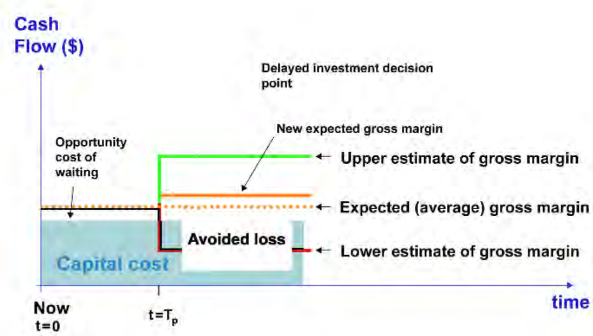
To directly compare the A and B options, the decision-maker compares the relative value of the two options at t=0 measured by their expected net return (probability weighted mean) in present value terms. In the A branch, the expected net present value return is $25m, since revenue begins to flow immediately. In the B branch, the expected net return of $37.5m needs to be discounted. If the duration of the wait, T_P, was 3 years and a discount rate of 7% is used, the net present value would be $30.6m. In this case, the decision-maker would be better off waiting. In contrast, if the duration of the wait was 8 years at a 7% discount rate, the present value of the investment option would be $22m, so the decision-maker would be better off to invest immediately and take the future downside risk.

Figure 8 – Effects of optionality

A – Now or never at t = 0



B – Possibly wait until t = T_p



Based on Watkiss et al. (2013)

Policymakers may ask and wait for more or better scientific knowledge about the risks associated with climate change before deciding on the amount of resources to allocate or spend, say, to reduce greenhouse gas emissions. The analysis enables a balancing of the costs associated with the amount and timing of specified actions with the costs and benefits of inaction. In this case, there will be a positive real option value associated with waiting for more information prior to the adoption of a policy that may impose large sunk costs.

But practically, they may not be willing to wait for the resolution of all scientific and technological uncertainties, especially for projects that may involve a considerable expenditure or if a significant amount of damage may be incurred. Those with a high tolerance for risk can push for waiting for better information before making a decision to, say, drastically limit emissions. Nevertheless, the Rio Conference (1992) favored the following precautionary principle: "the absence of certainty, given our current scientific knowledge, should not delay the use of measures, at an acceptable cost, that prevent the risk of large and irreversible damages to the environment."

In addition, Dixit and Pindyck (1994) demonstrated that it may be appropriate to delay an investment with a positive marginal net present value if the probability distribution of future cash flows is quite skewed (large or long tail). To determine the value of this information, consideration should be given to the amount and type of uncertainties involved and the risk aversion of the policymaker.

An example of a possible scientific development is scalable greenhouse gas removal from the atmosphere, for which some hope will be used to reduce the amount of accumulated greenhouse gases. An example includes carbon capture and storage (see section 3.4). Unfortunately, no approach has proven sufficiently effective to reduce significant amounts of greenhouse gases at an affordable price. Despite this, many climate change models and policies assume that such a technique will be developed within the next several decades.

However, since flexibility (holding open options) can also be costly, there can be a limit to its use. Although investment in new technologies that can substitute for fossil fuels is a primary mitigation strategy, as Libecap (2014) indicated, "If investment is delayed until more is known, catastrophic climate change may occur. Alternatively, if preemptive technology investments are revealed to be the wrong ones and irreversibly change the capital stock, society may be less able to address subsequent climate change."

Arrow and Fischer (1974) considered such a problem in assessment of a proposed environmental project with irreversible costs, such as the construction of a dam in a remote valley. In this case, the previously unexploited valley could also be used by future generations for an alternative purpose, whose added value was then unrecognized. In this case, building a dam in the valley becomes an irreversible phenomenon: once built, there would be limited viable alternative uses for the valley. In contrast, not building the dam would be a strategy that leaves options open for the future (thus, a possible co-benefit). The challenge was how to estimate the value of the option associated with the conservation strategy and to consider it in the cost-benefit analysis of the dam project. A similar methodology can be applied to mitigating the effect of greenhouse gases.

As indicated above, both costs and benefits are usually associated with flexibility or a voluntary delay. Costs include more emissions than if an immediate action is undertaken, as more greenhouse gases are irreversibly added to that already accumulated. Benefits include the possible use of improved carbon capture and storage technology in a new plant than if a less efficient plant was prematurely built or more effective renewable energy sources could be obtained that would lower ultimate costs.

Dobes (2010) discussed some of the timing challenges involved through an example of an ex-ante adaptation program, building sea walls or dikes today in the Netherlands or Vietnam to anticipate a future intensification of storm surges, representing a commitment of resources sooner than previously anticipated. An opportunity cost will be incurred, especially where the resources could have been used for other socially beneficial purposes such as education or health care. At the same time, postponing this adaptation measure too long might inflict additional costs, pain and damage on people and property if a storm surge occurs earlier than anticipated. Although much of the analysis could be conducted quantitatively, potentially huge non-quantifiable economic, psychological and political damages also need to be considered in the decision-making process.

As an example of an issue for which real options analysis can address is an analysis of three possible alternative approaches that could be taken regarding the desirability of temporary carbon storage:

- Buying time (a real option) for learning and technical advancement, which also may increase the incentives for future research and development;
- Ensuring that temporary storage could be converted to become permanent, if and when enhanced or new technologies come online that lower the cost of carbon capture and storage; and
- Slowing the rise of global temperature by mitigation, delaying the effects of climate change.

The cost of acting rapidly (although possibly prematurely) to increase the use of energy based on non-fossil fuel sources, such as solar, wind, geothermal, or biomass, might be viewed as sunk cost. Massive premature investment in unproven technologies[98] may prove quite expensive, both in terms of inefficient use of financial resources and possible crowding-out actions that address other worthwhile problems. Although not as satisfactory to stakeholders who wish to move ahead immediately because of possible massive irreversible costs, in some cases a delay may be worthwhile. As the practicality of technologies evolve, costs and benefits should be regularly reassessed, particularly if they can decrease costs and increase effectiveness.

An example of an improved energy source is solar power. Initially, its cost was uncompetitive with other sources of energy, but because of its promise, public subsidies were provided that encouraged increased research and development, which have proven successful. The resulting increased scale (volume) has enabled enhanced technology with lower unit costs and more efficient energy production, distribution, and storage. Already in some parts of the world the cost of this source of energy, even without subsidies, is competitive with fossil fuels.

A bad-news principle (some refer to it as the 'precautionary principle'), described by Bernanke (1983) and Dixin and Pindyck (1994), may be applicable. If the future concentration of greenhouse gas (or a pollutant) becomes less than expected (good news) or if the economic and health effects of greenhouse gas (pollution) turns out to be less adverse than expected (more good news), environmental rules can then be relaxed. In contrast, if future concentrations or the economic and health effects become greater than expected (bad news), there is little that can be done to correct the situation. Unfortunately, we do not (yet) know when or where the tipping point is that will result in catastrophic damage. Even if rules become much more stringent, it will take many years, decades, or even centuries for concentrations of greenhouse gases to fall. It is the possible bad news that should direct current policy. The greater the uncertainty about when the tipping point will be reached, the greater the overall uncertainty, and thus the lower the social discount rate.

Strengths of real options analysis include:

- Its results can provide important insight when confronting and managing major investment decisions and can be used to assess in quantitative and economic terms the relative benefits of alternative timing of action by directly reflecting uncertainty into the analysis;
- It can be used to identify and value the net economic benefits of flexibility in an adaptive risk management process; it can produce an economic appraisal of whether the additional marginal cost associated with flexibility is offset by real option values for future learnings or advances;
- It explicitly reflects the possibilities involved and forces the modeler to make probabilistic assessments of possible alternatives and communicate the underlying assumptions and methodologies followed; and
- Compared to textbook cost-benefit analysis, it is probabilistic rather than deterministic, can consider delays, reflects uncertainty and flexibility, and can include analysis of optional investment timing, especially useful for adaptation decisions.

Weaknesses include:

[98] Includes those that have not yet been demonstrated as being capable of scaling up to a substantial size at an affordable cost.

- It can be difficult to implement. This may be due to inadequate data and resource intensity, the need to quantify not-easy-to-estimate[99] probabilities, costs, and benefits using a decision-tree methodology. The weaker the basis for the probability estimates may result in less accurate analysis;
- It is more complicated than alternative approaches that do not consider uncertainty. As a result can be more challenging to communicate clearly;
- The well-being of society depends on several key considerations, not just the quantification of the amelioration of adverse climatic events; and
- Feedback loops and a monitoring regime also need to be implemented and managed.
- This type of analysis cannot be applied to most ex-post adaptation projects due to their need for immediate action.

Key take-aways from chapter 9 include:

- A cost-benefit analysis involves not only how much to spend and what to spend it on, but also when to spend it, especially in an environment subject to uncertainty and choices;
- A real option is the right, but not the obligation, to undertake a specific action;
- Real options analysis determines the value of real options that can provide insight into timing decisions, whether by choice or necessity;
- A relevant application is whether to immediately implement or mitigate or adapt in stages.
- The use of decision-trees and probability distributions to analyze the cost and desirability by taking into account the costs (e.g., increased accumulation of greenhouse gases in the atmosphere and oceans) and benefits of delays (e.g., possible enhanced technology, better information, and planning), as well as availability of financing or other resources; and
- Three approaches that can be taken are delayed decision / implementation, one-step-at-a-time, and building in pre-planned stages.

Chapter 10: Social Cost of Carbon

The purpose of this chapter is to provide an understanding of the social cost of carbon and carbon pricing. Two means of this pricing is provided by carbon taxes and cap-and-trade schemes. Considerations underlying the social cost of carbon and its calculation are also covered. It is a metric commonly used in assessing the net effect of costs and benefits of greenhouse gas emissions that include the social externalities and co-benefits involved. It is an estimate of the cost of future damages caused by currently releasing a unit of carbon into the atmosphere. This chapter does not develop an independent estimate of the social cost of carbon, as the derivation of an estimate of the underlying costs is outside the scope of this paper; nonetheless, some interesting things can be said about it and the role of carbon pricing.

An important application of the social discounting process is the estimation of the social cost of carbon dioxide (SCC, usually referred to as the 'social cost of carbon'). The social cost of CO_2 is the marginal cost of damages resulting from the emission of a unit (one metric ton of CO_2 emissions). It is often used to represent the social value of global damages due to man-made (anthropomorphic) climate change, in excess of underlying direct costs. Its size can serve as a wake-up call indicating the urgency for needed mitigation and ex-ante adaptation action. The concepts underlying the SCC can also be applied to other

[99] Due to future unknowns, lack of non-market price information, and political constraints or opportunities.

greenhouse gases on a global, rather than a domestic level. The differences between methane and carbon dioxide is discussed in section 3.2 and Table 1, which can be analyzed separately or on a combined basis. The calculation of the social cost of methane differs, partly because of differences in intensity and period they stay in the atmosphere before dissipating compared with those characteristics of CO_2.

The objective of social discounting is to quantify a single aggregate net present value (or a range of net present values), considering factors including the value of social externalities and co-benefits associated with climate change. The resulting net present value can be quite sensitive to the underlying assumptions, especially the social discount rate. It can also serve as input into the development and management of numerous national and international policies, including those involving regulation (i.e., guidelines or mandatory rules) and taxation.

An increasing number of companies are using an internal carbon price in their business planning, investment decisions, and risk management with respect to climate change. Here too, a major factor that has differentiated estimates of the SCC is the discount rate used.

The price of carbon is not the same as the SCC. The price is what is charged, for instance through a tax, possibly modified by a subsidy regarding its application to a particular population or industry segment. The price is usually a rounded number set for practical reasons, in contrast to the SCC that is directly a result of a detailed cost calculation.

In response to an abuse of a public good (in this case greenhouse gases in the atmosphere), economists often suggest putting a price on the contributing activity causing harm, which in this case is represented by a carbon price, and encouraging the development of a more benign alternative. According to Gerlagh and Liski (2012), a goal of a public environmental agency assessing climate policy should be to place a price for a unit of carbon at a level so that each unit of carbon emissions increases the welfare of current and future generations at a rate at least as great as the present value of marginal damages caused by that unit.

SCC estimates can be used as a base from which to determine an appropriate carbon price based on the design of the pricing system. The SCC can also be used as a basis for setting up or updating a cap-and-trade set of tradable emission allowances, to determine emission or gas/petrol taxes, as a basis for determining green-technology/renewable energy mandates, or other regulatory incentives (e.g., automobile performance standards). Its use can assist in making the operation of certain markets more effective and efficient to enhance the mitigation and adaptation processes.

A carbon price can also serve as an important global price signal (Stern 2007) to governments, businesses and households to encourage sound greenhouse gas management and to stimulate research and development in alternative energy sources. Its ultimate objectives include encouragement to use environmentally cleaner technology and shrink or eliminate industry segments that cannot clean themselves up promptly. The SCC that can be used in determining the price of carbon is the cost associated with the atmosphere's capacity to absorb greenhouse gases that could be used to charge the full social cost of each metric ton of CO_2[100] to those who are responsible for CO_2 emissions, or conversely the benefits that accrue to society by a reduction in one ton of emissions.

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[100] One metric ton of CO_2 produces 0.2727 tons of carbon, so US$100/tons of carbon is equivalent to about 3⅔ tons of CO_2. According to joint EPA/Department of Transportation rulemaking on May 7, 2010 ("Clean Energy:

There have been several approaches taken internationally to the design of a carbon pricing program. Carbon pricing is viewed by many to be a cornerstone in the effort to mitigate emissions, although politicians are rarely enthusiastic about raising taxes, even when referred to as fees, contributions, or levies. But they may not be of sufficient size to significantly modify behavior. When implementing such a system, it is common to use a step-up design (a relatively low price initially, gradually increasing to an ultimate level), so that ultimately the price is supposed to begin to change behavior, that is, to provide a sufficient incentive to reduce the use of carbon, pollution, and greenhouse gas emissions. This design theoretically allows those affected to get used to the system of carbon pricing, as it can take a considerable time to modify behavior or sources of energy. Unfortunately, due to political pressure or participation if voluntary, this level may not be easily achievable.

Using carbon prices (through a carbon tax) as a price mechanism is one approach to mitigation. An example of another[101] is to provide a fixed number of emission permits (which regulates through setting a total maximum quantity of emissions) in a cap-and-trade scheme using a market-mechanism. This is generally more effective for larger emitters, such as power or energy companies.

The approach that should be used partly depends on the relative cost of mistakes in setting the price or quantity, because the need to buy expensive permits could put many firms out of business whose missions could have been fixed in other ways. Coordinating carbon prices, either through taxes, a market, or other vehicles, and their effect on individual, business, and government behavior, may prove to be a better policy approach than focusing on a 'targets and timetables' approach independent of cost.

Although the use of such a price provides a price-signaling function, it has proven to be politically sensitive and a political failure in several recent cases around the world, for example in France in late 2018. Such a price (tax) has received significant push-back, partly because any tax is unpopular to some if not many, even though the prices used so far have generally been at a level that may be too low to spur sufficient human behavior to result in a significant reduction in emissions, yet may be too high to avoid push-back from those who have to pay for it. So far, a modest tax often receives a modest response, with push-back occurring when it gets close to the level that may have a significant effect on behavior, which is a primary conceptual reason for imposing the price in the first place.

Opposition inevitably arises from several types of stakeholders, including fossil fuel companies that believe that they will be competitively harmed and working-class groups that believe they cannot afford it and will be taken advantage of as a result of the regressive nature of the price/tax. Those who desire fewer disruptions in carbon-based industries also tend to use a relatively high social discount rate, with its resultant lower SCC. The SCC can be viewed as a Pigouvian tax.

A crucial issue with carbon taxes, especially a new one, can be how its tax proceeds are to be used, as it can be quite regressive to consumers, with those of lower income paying a much higher percentage of their income than those of higher income. Although there are about fifty countries, primarily developed ones, that use some form of carbon pricing, there is also a wide range of designs, taxation, and methods of distribution of the proceeds, which can have a direct or indirect effect on income and inequality.

Calculations and References"), assuming all the carbon in the gasoline is converted to CO_2, US$40 per ton is equivalent to 35.55₵ per gallon (U.S.). Each gallon of gas produces, on average, 0.00887 metric tons of CO_2.

[101] According to Parry et al. (2018), taxes raise about twice as much revenue as today's cap-and-trade schemes, although this conclusion differs significantly by country and level of taxation.

Determining the optimal level and design of taxation involves many factors of a cultural, climatic, economic, and behavioral nature.

Certainly, putting a tax on gasoline/petrol for cars is rarely sufficient to make people stop driving, although there will be some who seek alternative approaches to travel or energy use because of the additional cost. Another approach to mitigating greenhouse gas emissions in transportation is for individuals and businesses to communicate digitally or set minimum gas/petrol efficiency requirements for new cars and other vehicles. However, the latter approach can take a long time to reduce emissions, as it takes many years to change the stock of automobiles.

Carbon pricing cannot achieve its objectives in every industry sector. For example, in the absence of consumer demand, it may not provide a sufficient incentive[102] to make buildings more energy-efficient, primarily because builders want to hold their building costs to a minimum. Targeted taxation aimed at a specific behavioral modification tends to be more effective than the use of general taxes. Builders or owners therefore may not be sufficiently motivated to construct energy-efficient buildings, with a tendency to skimp on such building features, such as insulation or a renewable energy system, which could have long-run favorable environmental returns.

There have been instances where ultimate cost savings have enhanced consumer and business sensitivity and demand for greener buildings. This can be observed by the increase in installations of solar energy systems as they have become more affordable and accepted. Other areas in which carbon pricing may not be as successful as desired is its relatively limited role in enabling or incentivizing climate-effective agricultural or airline transportation practices.

Heine et al. (2019) found strong synergies by combining green bonds with carbon pricing to achieve favorable sustainability outcomes, investor returns, and debt sustainability. These synergies were stronger when carbon is priced through taxes rather than by emissions trading. The issuance of green bonds also can help enhance intergenerational equity by enabling immediate investments in climate mitigation, with bonds being repaid by future generations who, as a result, will suffer reduced climate damage and, given continued economic growth, will be better able to afford it.

One methodology used to calculate the SCC involves the following steps: (1) select an emissions scenario, possibly an IPCC scenario or one based on the output of one or more IAMs, as a baseline emission trajectory, with inputs regarding future economic growth, population, and technological changes, or alternatively a given increase in greenhouse gas concentration in the atmosphere, (2) develop a climate model to project the likely future changes in the climate based on the emissions scenario, possibly by region, (3) develop a damage model to estimate the consequential impacts on society, (4) estimate the total associated economic costs[103] by year, (5) discount the cost estimate to the present using social discount rates, and (6) apportion the net present value of climate damages to the volume of greenhouse gases emitted or for another metric to estimated GDP. Note that this calculation

[102] Stiglitz (2019) indicated that a carbon tax, for practical reasons, cannot solve the entire incentive problem, as there may be multiple market failures and public policy constraints, including distributive issues and vertical inequalities (by income) and horizonal inequities (between those with the same income who differ in their consumption preferences). Further, a larger carbon tax may have an adverse impact on the relative demand for, say, unskilled labor.

[103] Both monetizable and other damages, including changes in market damages (e.g., effects on net agricultural productivity, energy use, and property damage from increased flood or subsidence risk) and other damages (e.g., to human health and services that ecosystems provide to society) that can continue for centuries.

may not consider important non-monetizable items (see section 8.2.1), nor evaluate qualitative considerations.

Social value is represented by the aggregate streams of monetized damages that are converted into present value terms in step (5) by social discounting. This reflects the effect of society's willingness to exchange value in the future (since much of the damage will be occur in years subsequent to the emission of carbon) for value today. The optimal carbon price (tax) is the price assigned to carbon emissions that balances the incremental cost of reducing carbon emissions with the incremental benefits of reducing climate damages.

In sum, the formulation of the SCC is based on forecasts of climate, technology, damages, and preferences. It can utilize multiple models with numerous parameters. As with any model used for social value purposes, the choice of parameters, including the social discount rate applied, can be very important, as the SCC is quite sensitive to these choices, as well as covering social externalities and associated uncertainties. Sound model governance needs to be applied, including an appropriate level of peer or independent review, as applicable.

For example, regarding the effect of the social discount rate, Nordhaus (2016), using his DICE-2016R model, estimated the SCC to be US$128.50 using a 2.5% discount rate, US$79.10 using 3.0%, US$40.90 using 4.0% and US$19.70 using 5.0%, all as of 2015 (as of 2030, corresponding values were, for example, US$164.60 at 3.0% and US$104.90 at 4.0%). Since any such estimate involves significant uncertainty, it should be recognized that the SCC is a crude, but still important measure. It needs both supplementary estimates of its sensitivity to alternative parameter values and an indication of non-monetizable items not directly considered in the calculations.

According to Nordhaus (2016), the effect of the asymmetric probability of costs on the SCC might be about 15% of its expected value. He indicated that its uncertainty, measured by the coefficient of variation associated with economic variables (e.g., amount of emissions and damages) was greater than for geophysical variables (e.g., atmospheric carbon concentration or temperature).

The SCC increases with climate sensitivity and slower atmospheric carbon depreciation and decreases with slower temperature adjustment and larger social discount rates. Greater economic growth may increase emissions, as well as increase the capacity to allocate resources to attempt to develop cost-effective carbon capture and storage or other new technology to reduce accumulated carbon in the atmosphere and oceans. This could in turn ultimately lead to a larger social discount rate and lower SCC, which will in turn increase the value of the real option to delay mitigation action if such technologies are on the horizon.

The Interagency Working Group on the Social Cost of Greenhouse Gases (IWG, U.S. 2016) combined tens of thousands of SCC estimates obtained from: (1) three IAMs, (2) five different socioeconomic and emissions projections, (3) a common distribution of equilibrium climate sensitivity, and (4) distributions for other parameters. This resulted in three probability distributions of SCC values for three different constant social discount rates (2.5%, 3.0%, and 5.0%), from which the IWG calculated an average value for each social discount rate. The choice of these rates was based on a pragmatic assessment: 3.0% was based on an approximate post-tax risk-free rate over a long period of time assuming no correlation between economic growth and climate change damages, 5.0% was selected assuming there was a positive correlation, and 2.5% reflected both the uncertainty associated with the social discount rate and a possible negative correlation between economic growth and climate change damages (e.g., through increased climate risk resilience in a scenario with higher incomes or economic deterioration because of climate change).

The IWG's estimate of the SCC in 2020 at a 3.0% social discount rate was $42 per metric ton of CO_2 emissions[104] in 2007 U.S. dollars (US$12 at a 5.0% social discount rate and US$62 for a 2.5% social discount rate). At a 3.0% social discount rate and a 95th percentile of the SCC estimates (a lower-probability but higher impact climate scenario), the SCC was expected to be US$123). This means that (using a 3.0% social discount rate) an estimate of the benefits from a new regulation projected to reduce CO_2 emissions by 1 million metric tons as of 2020 (in 2007US$) would have an expected present value of US$42 million. These estimated costs increase over time[105]. The IWG noted the importance of using consistent internal assumptions across models used.

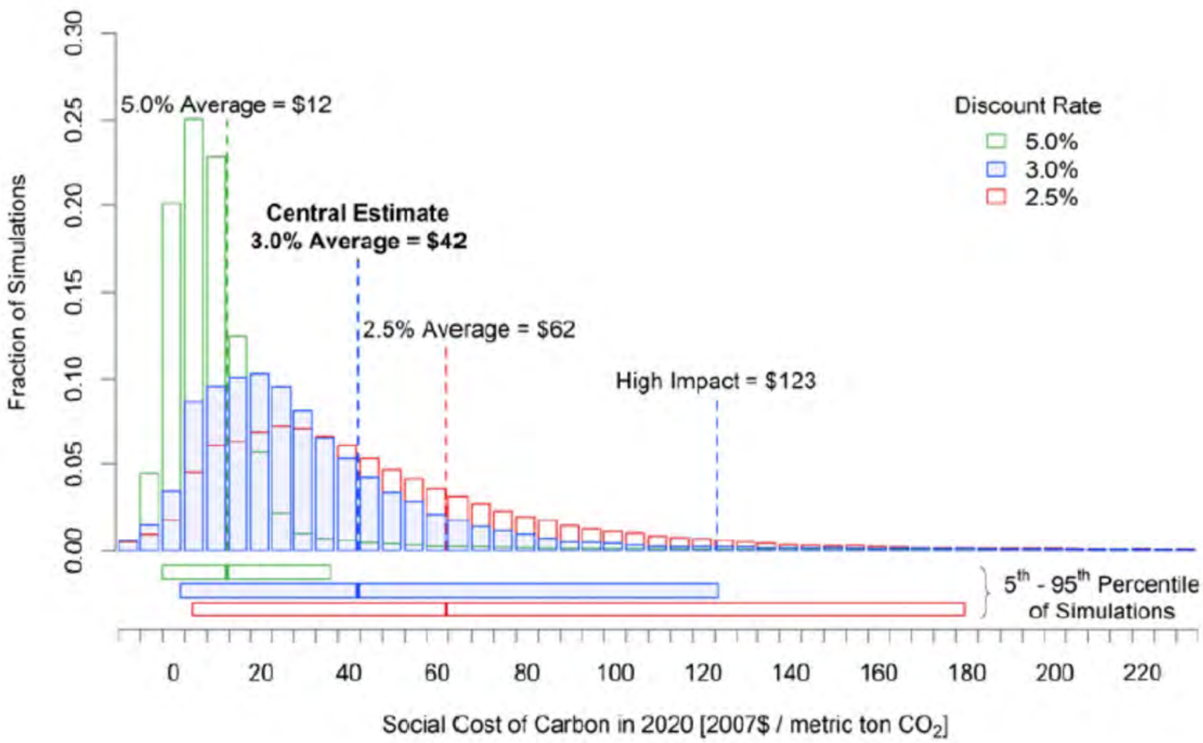
In an IMF blog, Gaspar et al. (2019) indicated that "To limit global warming to 2°C or less—the level deemed safe by science—large emitting countries need to take ambitious action. For example, they should introduce a carbon tax set to rise quickly to US$75 a ton in 2030." In addition, most stakeholders prefer to have a predictable environment in which there is a set of prices, rather than have government regulations dictating the technologies to apply.

Figure 9 is a graphical representation of the probability distribution of the SCC, as indicated in the Technical Appendix to the IWG report (2016), illustrating the significant effect of social discount rates.

[104] The corresponding estimated social cost of methane, CH_4, in 2020 in 2007 U.S. dollars at a 3.0% social discount rate was US$1,200 and of nitrous oxide, N_2O, was US$15,000. These are much higher than that of CO_2 because their effect is far more intense.

[105] The social cost of greenhouse gases increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change and because GDP is growing over time (many damage categories are modeled as proportional to GDP). For example, the IWP (2016) indicated that, using a 3.0% social discount rate, the SCC at 2040 was estimated to be US$60.

Figure 9 – Social Cost of Carbon – possible distribution for selected discount rates



Source: Interagency Working Group on Social Cost of Greenhouse Gases (2016), developed using assumptions derived from estimates of the SSC from the U.S. Environmental Protection Agency.

In March 2017, a Presidential Order (U.S.) was issued indicating that several assessments made by the IWG "shall be withdrawn as no longer representative of governmental policy". It also mandated that "any such estimates are consistent with the guidance contained in OMB Circular A-4 of September 17, 2003 (Regulatory Analysis)". Although this circular did not put a price on carbon, the discount rate it suggests using is 7%, which is significantly higher than the 3% used and recommended by the IWG in 2010 and 2016. The use of a 7% social discount rate dramatically decreases the estimated SCC.

An alternative approach to estimating the SCC using expert opinion was presented by Pindyck (2016), due to his skepticism concerning the use of heroic assumptions regarding tail risk damages and the accuracy of IAMs. Pindyck indicated that this approach was especially useful with respect to the probabilities of the range of damages and that of emissions, possibly the two areas with the greatest amount of uncertainty. He surveyed economists and climate scientists who have written cited articles, papers, or reports on this subject within the past ten years. Out of about 600 responses, 534 expressed a high degree of confidence in their views. In each respondent category there was a wide dispersion of views, especially striking because most of the respondents are either an expert or close to being an expert. Pindyck developed a simplified model based on these views that focused on tail risks over the next 50 and 134 years. The responses regarding SCC estimates ranged from US$10 to more than US$200[106] per metric ton and an average of about US$81 per metric ton for those expressing a high

[106] Pindyck focused on averages (aggregate mean), rather than using a marginal approach (see section 2.4) that indicated that it is more appropriate to use an aggregate average, rather than marginal values. Interestingly, economic expert respondents estimated a much lower SCC than did the climate scientists. The average respondent

degree of confidence in their response. Regarding sensitivity to social discount rate variations, US$81 was derived using a 4.0% social discount rate, US$121 if 2.5% had been used, and US$65 when 6.0% was applied.

Anthoff et al. (2009) discussed how the SCC reacts to changes in critical terms of the Ramsey formula (formula (4) in section 5.2.1):

- The higher the ρ, the *pure rate of time preference*, the less weight is given to costs and benefits in the future. Since damages from climate change are expected to increase over time, the present values would be reduced, thus decreasing the size of the SCC. Some argue that, because of concern for intergenerational equity, ρ should be zero for ethical reasons (see section 7.2), while others believe that ρ should be treated the same as other independent policy parameters.
- In a growing world economy, the social discount rate resulting from a larger g, the *per capita growth rate of consumption*, would be larger, resulting in a smaller SCC.
- A larger η, the *elasticity of marginal utility,* that is in part a measure of risk aversion, results in a higher social discount rate, which leads to a smaller SCC. However, a larger aversion to risk implies a greater concern with uncertainty and adverse surprises. As a result of the extended Ramsey formula (formula (6) in section 6.1), the SCC may increase with higher values of η. Its role may also be complicated, since the direction of influence depends on the relative size of η. Since climate change disproportionally affects the vulnerable, a relatively large proportion who is poor, concerns relating to income inequality may increase the SCC.

While expected cash flow equivalents depend on the amount of climate-induced damages rather than society's preferences, social discount rates are affected at least in part by risk preferences. For example, in a country in which seemingly distant risks (in terms of at least time, if not geographic distance) such as climate change are not given a high priority, the effect of social discount rates, and therefore the SCC, might be small. In contrast, in a country more concerned with long-term future risks, the social discount rate effect of adverse climatic factors on potential investments might be quite significant and carbon emissions might carry a sizable risk premium. Thus, in contrast to the discussion in section 5.3 that indicated that market-based interest rates should not be used directly, discount rates from capital markets may provide useful information regarding the risk preference component of the SCC and the relative economic importance of climate-related risks.

Estimates of the marginal damage due to carbon emissions require an aggregation of estimated monetized damages due to global climate change to people with a wide range of incomes and in different countries. Implicitly or explicitly, such estimates assume a social welfare function that considers a particular attitude towards equity. Therefore, national decision-makers' assignment of social value may differ depending on the relative importance assigned to such factors as current consumption and long-term sustainability.

Daniel et al. (2016) indicated that the pricing of risk in the usual calculation of a SCC calculation uses estimates of benefits resulting from mitigation of climate emissions that follow a CRRA/constant-elasticity of substitution/power utility preference assumption that is inconsistent with evidence from financial economics. They showed that, when the variation in historical asset returns are incorporated, the risk premium embedded in the SCC uncertainty is likely to be a large and important factor. In

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provided an estimated average social discount rate of about 2.9%, with those expressing high confidence in their estimates a social discount rate of about 2.6% and those from developing countries of about 4.1%.

addition, they pointed out that the inclusion of the effect of expected catastrophic damages decreases the discount rate used and raises the SCC.

Key take-aways from chapter 10 include:

- The social cost of carbon is an important application of social discount rates – it is the marginal (in present value terms) cost of expected damages resulting from the emission of one metric ton of CO_2;
- A lower social discount will lead to a larger SCC;
- The social cost of methane and the social cost of nitrous oxide are greater than that of carbon;
- The SCC can be used to quantify social externalities, at least to the extent they are monetizable or can be quantified;
- Carbon pricing can be used as a global price signal or internal company benchmark, as well as the basis for a carbon tax or prices in a cap-and-trade market;
- Realistic carbon prices can provide the incentive to change behavior with regards to the amount of carbon emissions, although to do so it has to be larger than most carbon prices (taxes) currently used, which has attracted political resistance;
- The quantification of the SCC utilizes the output of several models (addressing emissions, climate, damage, and economic valuation), whose assumptions should be internally consistent, set and maintained using sound model governance processes;
- A wide range of SCC estimates have been developed, to a large extent the result of the use of different social discount rates;
- The SCC should not be used alone in a social cost-benefit calculation, as it does not incorporate non-monetizable items and other factors; and
- A possible alternative to a quantitative calculation of the SCC is to base its components on an expert opinion survey, although that could produce as large a range in value as that from a modeling process.

D. Practical Issues and Conclusion

Chapter 11: Alternatives to social discounting

The purpose of this chapter is to explore alternatives to social discounting. These include the use of non-discounted values. Supplementary information, including scenario testing, is also covered.

Although the focus of this paper is on social discounting and the considerations involved in the discounting process, it is important to remember that the value of discounting is to provide useful information for use in social and other policy decision-making. This includes serving as an important input to social cost-benefit analysis of climate change-related projects and strategies of the public sector. Relevant stakeholders use this process to compare the desirability of adopting projects and strategies that affect the public interest, based on the results from stochastic (Monte Carlo) modeling[107] or the use of a range of deterministic scenarios. In addition, many aspects of the social discounting process can used in a variety of social risk management endeavors in both the public and private sectors.

Although policymakers may desire a single answer, analysts need to accompany their reports, which include an average or best-estimate finding, with a range of results based on specified alternative assumptions, methods, or probability confidence levels add valuable insights, as well as shining light on the uncertainties involved.

Alternative approaches and supplementary or complementary analysis include the following:

1. *Scenario analysis*
   A scenario (or ensemble) analysis is based on an assessment of the effects of a given set of internally consistent conditions (a scenario) in a single time trajectory. The analysis or comparison of the results of multiple scenarios is particularly useful to study a range of conditions or strategies, as the future will always be uncertain. It can include both net present values over the time horizon of the analysis and the undiscounted values at selected points in time measured relative to a benchmark or competing proposals, such as or corresponding values of a baseline scenario or GDP. It is important to use a set of consistently developed scenarios[108] in comparing alternative courses of action.

   The advantage of scenario analysis is that it can be performed without a quantification of the extent of uncertainty in the underlying parameters that underlie the scenario, for example, assigning a specific probability that alternative temperatures (e.g., a 2°C ultimate level) will be experienced over the coming decades and centuries[109]. Developing a reasonable probability distribution of mitigation actions, which may dependent on the extent or intensity of political intervention, can be problematic. The way in which the likelihood of a particular scenario is assigned may nevertheless be important.

[107] The basis of the entire SCC process can be viewed as a stochastic process.
[108] Such as those in the IPCC's Fifth Assessment Report (2013).
[109] In contrast, a stochastic model incorporates expected probability distributions of the underlying drivers or conditions, such as the amount of emissions, temperature values, or damages to an area.

It can be easy to read more into each scenario than is justified, particularly if it provides an impression of over-precision that may not be warranted. A scenario only represents one illustrative possible future along a continuum of possibilities. It is common to compare expected costs and damages associated with a given level of greenhouse gases (or corresponding global mean temperature change) with conditions that would arise in a business-as-usual scenario as a baseline without mitigation or adaptation projects or strategies. Alternatively, the scenario analysis can consist of a comparison between competing investments or strategies, all else being equal. It can be particularly useful when studying the effect of possible future discontinuities, such as a meteorological tipping point or government interference. When social externalities and co-benefits are included, it can be referred to as a social scenario analysis.

2. *Sensitivity analysis*
   A sensitivity analysis is similar to a scenario analysis, in that alternative projections are performed for each scenario. The difference is a focus on the effect of a specified change in a particular variable, e.g., overall temperature values. It is similar because other associated factors are consistently modified, i.e., each sensitivity scenario is internally consistent. Related is *stress test analysis*, when the scenario being studied is an extreme case (possibly an outlier or in the tail).

3. *The tail*
   Although current risk-adjusted expected (mean, best-estimate, or median) present values under specified or a range of possible scenarios can represent a baseline finding, illustration of net present values for a project in a tail scenario (similar to stress testing) can be valuable to review and communicate as part of any findings or recommendations. Although such a scenario may seem extreme, they may not be a worst-case scenario, as those may be too scary to be given much credibility. Analysis of a range of tail scenarios can be particularly relevant in climate change analysis in which sustainability of global standards of living, property values, and human health are at risk. In addition, because some of the probability distributions involved are asymmetric (and non-linear) and the net present value of damages within the tail might be viewed as being arbitrary, scenario analysis might be appropriate because of the heavy weight given these values in deriving an expected value.

4. *Internal rate of return*
   Although based on a cost-benefit analysis utilizing a time value of money, this approach reverses the problem by solving for an internal rate of return (equivalent to a discount rate) that balances the applicable costs and benefits, considering the opportunity cost of the capital involved. In a social cost-benefit analysis, it is not necessarily clear what this capital is or how to take into account the non-monetizable factors involved. Alternatively, if a sustainable steady-state scenario can be identified, it could serve as the point at which a sustainable internal rate of return could be solved for.

5. *Payback rule*
   Sometimes used in corporate finance, this metric compares the cost of an investment to the time needed to recoup it.

6. *Undiscounted values*
   Providing undiscounted expected costs and benefits by year or decade, as applicable, expressed in either monetary terms or as a percentage of a benchmark, such as expected GDP or baseline values. The use of GDP as a benchmark (denominator) is especially useful when making cross-country comparisons, as reliable global consumption data may not be available Just as in other approaches, a range of undiscounted values by period can provide useful perspectives. If shown in monetary terms, it is important to be clear regarding whether the monetary amounts are expressed in current values or values as of a future year (i.e., nominal or real). This information is useful in any case as a useful supplement to a social cost-benefit analysis or a social valuation.

7. *Qualitative information and non-monetizable items*
   Not everything affected by climate change can be quantified or monetized (as indicated in sections 7.1 and 8.2.1). For example, consideration of expected or likely trends or considerations beyond the next century or two that would be discounted so heavily no matter what the social discount rate is may be best illustrated qualitatively or at the end of the time horizon whether the future cash flow-equivalents are increasing, decreasing, or stable. A qualitative assessment of the investment, program, or strategy being studied needs to accompany the quantitative analysis, including covering its expected likely success or failure in achieving its objectives and its implications. This qualitative analysis section can include an assessment of effects on identified non-monetizable items (e.g., number of lives saved or premature deaths caused).

8. Early warning indicators and methods
   Identification and quantification of factors that drive climate change and its consequential damages can serve as valuable early warning indicators, especially as they relate to possible tipping points that may increase consequential damages. Although the timeframes involved can lead to short-term volatility and false positives (relative to long-term trends and future scenarios), early warning indicators can serve to speed-up mitigation and ex-ante adaptation efforts, spurring preventive international, national, or local actions. The application of real options (see chapter 9) using probabilistic or scenario analysis can provide insight to the risks involved, especially relating to tail scenarios and the desired need for timely action.

   It may be more applicable for analysis of ex-ante adaptation, rather than mitigation options that may prove to have too long a needed timeframe to make a significant short or medium-term impact due to the cumulative and irreversible nature of climate change. Nevertheless, since science has ascertained many cause-and-affect trajectories (e.g., from greenhouse gas emissions to changes in climatic factors to damage), any step in the process can serve as an early indicator of future adverse events or conditions to come. The introduction of early warning mobile phone warnings of tropic cyclones in Bangladesh (even if measured in terms of minutes or hours) to lead large populations to safety shelters have reduced mortality and morbidity substantially where otherwise hundreds of thousands of people would otherwise had died. Although the development of these

   Even slow-onset conditions such as sea level rise and desertification have early warning indicators, e.g., de-glaciation and periodic famines and increasing local temperatures. Although changes in these indicators may be too late to begin mitigation activities, they can point to the need for ex-ante adaptation efforts to be accelerated.

9. *Expert opinion*

    Structured expert judgment can bring significant added value to the development of modelling assumptions regarding future conditions and their uncertainties (see Drupp 2018 and Pindyck 2016). Using a group expert opinion generally proves better than that of a single expert (that is, if a single individual is responsible for all assumptions and modeling). Nevertheless, Stern (2015) argued that, because social value and investment decisions can be quite sensitive to the choice of discount rates, it is better to use a more objectively-based value, rather than one based solely on judgment.

It is important to continue to conduct rigorous research and transparently document the basis for the variables that make up the (IAM) models and the parameters used in these models used in social cost-benefit analyses, as well as the discount rate(s) used. Periodic and dynamic reviews (based on updated assumptions) are needed, possibly every three or five years. The choices made constitute are integrally important in maintaining sound model and decision-making governance process regarding preparedness for climate change-related risks and damages.

Key take-aways from chapter 11 include:

- In addition to expected values or a range based on stochastically generated results, key insights into a reasonable range of future conditions can be provided by conducting scenario analysis (based on an internally consistent set of conditions) and sensitivity analyses (focused on the effect of a specified change(s) in particular variables);
- It is important to use consistently developed scenarios in comparing alternative courses of action under conditions of uncertainty;
- Undiscounted values (the mean, confidence range, or a selected scenario) at various future years can provide insight, especially expressed relative to an emission or economic benchmark such as GDP, as applicable;
- A qualitative analysis, including the effects on non-monetizable factors clearly communicated recognizing expert knowledge and the involvement of stakeholders, and documentation of the basis for key assumptions made and sensitivities needed to be included in any report on a social cost-benefit analysis; and
- Preset early warning indicators of potential changes in conditions or non-linearities need to be reviewed on a regular basis, although care is needed to distinguish random short-term weather volatility from long-term climate trends.

Chapter 12: Practical Considerations

The purpose of this chapter is to present some of the practical aspects of and considerations involved in the social discounting process.

Communication of results. Effective communication of valuation results involves convincing others of the recommendations made. Although a complete report is needed to support its recommendations, one or more summaries containing key aspects of the analysis that relate to the audience(s) of the report is also valuable. In a public sector analysis, one summary might be provided to policymakers, while a shorter one might be addressed to the general public – both should be tailored to the intended audience, as applicable.

Recent extreme weather events and conditions have significantly contributed to the effectiveness of a climate change advocacy message. Translation of climate change messages to key aggregate metrics facilitates the communication of objectives, such as the goal of 1.5^{o}C or 2.0^{o} C global temperature rise from pre-industrial conditions, reduction in automobile gasoline/petrol use of miles per gallon/litre, or emissions expressed as a proportion of total electricity generation.

Key elements of such a report documenting the findings of a social cost-benefit analysis might include the following sections. Although most have been discussed elsewhere in this paper, the following provides some additional observations regarding these report elements.

1. *Background and objectives*. A description of the context and agreed-upon-in-advance objectives of what is being analyzed is especially important where the stakeholders have diverse perspectives and interests and the analysis identifies possible effects on long-term societal welfare and sustainability. If the objectives are to compare alternative courses of action, their analyses should use the same baseline for comparative purposes and a predetermined basis for selection. This section also covers the process used and the parties involved in the development of the analysis.

2. *Basis for the methods used and corresponding assumptions*, including that for social discount rates. As indicated in chapter 2, a comprehensive social cost-benefit analysis incorporates climate, damage, and economic segments. Because of its scope, this paper has focused its attention on the third segment. Nevertheless, it is important to link and ensure internal consistency of the assumptions underlying the segments. The source of data used and the correlation between assumptions under alternative circumstances should also be considered. Importantly, the basis for the selection of the social discount rates used, the discounting process, and what is (or is not) discounted needs to be compatible and that uncertainty is neither double-counted nor ignored in the analysis. The approach taken, for instance, whether a marginal or aggregate approach was taken (see section 2.4) and how uncertainty is shown. Sources and bases for the assumptions, including areas where expert judgment was used need to be appropriately disclosed, although these could be included in an attached technical supplement.

3. *Quantification and other support for the recommendations*.
    a. Quantification. An appropriate level of technical detail included should be tailored to the audience, especially when the report (or rather, its summary) is aimed at the general public. Since climate change-related issues can involve complicated processes, it is important to be clear and straight-forward. This includes the quantification of the underlying conditions and the effects of the investment, program or strategy being analyzed. Where practical, charts and other data-visualization tools should be used, especially for long-term trends and to illustrate areas of uncertainty.
    b. Social externalities and co-benefits. As discussed in section 2.3, the consequential social externalities and co-benefits associated with the proposed approach should be included. It is important to indicate why they should be considered in making a decision and the methods and assumptions used for this purpose.

c. Qualitative assessment and non-monetizable items. In some cases, these items are as important as the quantitative portion of the analysis. As such, they should be given due consideration in reaching the recommendations and be given appropriate prominence in the report's recommendations/conclusions. Because the qualitative discussion might be viewed as being developed on a subjective basis, it is especially important to discuss what might be viewed as potentially biased views on these items.

4. *Uncertainties* and how they are dealt with. A description of the degree of confidence in the analysis and the estimates in it should be described. One suggested set of descriptors consists of being 'certain', 'highly likely', 'unlikely', 'reversible', 'suggestive', or 'highly correlated with other risks'. An alternative set is 'possible', 'suggestive', 'likely', 'persuasive', 'probable' and 'compelling'. Alternatively, a range of probable outcomes and values could be developed and used for comparison purposes. Examples include the use of intervals (e.g., confidence envelopes, scenario results), probability density maps, fan charts, icon arrays, and multiple samples in space or time. An over-emphasis on best estimates may lull a policymaker to sleep in believing that the estimates made are precise. The nature and possible effects of likely asymmetric ranges are important to emphasize. As the stakes involved may be quite large, possible tail conditions and early warning indicators should be given due emphasis.

   As discussed in chapter 11, it is desirable to have a common set of scenarios for comparative purposes (e.g., certain scenarios described in IPCC reports (see The Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (2013) for examples[110]) have been used for this purpose, or the baseline climate factors could be adjusted by, say, 20% in both directions, as appropriate, as well as a consistent basis for significant assumptions.

5. *Balance*. As indicated throughout this paper, the choice of social discount rates needs to balance several quantitative and qualitative factors, some of which may be offsetting to some extent. They should be based on objective facts and considerations to the greatest extent practical. In the case of climate change, concerns regarding the physical, economic, and human consequences need to be given weights according to social preferences.

6. *Other considerations*. Political, economic, financial, and ethical concerns and constraints can arise with respect to climate change and climate change-related projects and strategies. Where applicable, the extent to which they are effectively addressed by the design of the investment, program or strategy being assessed should be included.

   Due to the complexity of many social cost-benefit analyses involved, it is important to consider the possibility of streamlining the process involved. This might include the use of templates and guidelines developed for this purpose. Nevertheless, because of the importance and complexity

[110] One of the four most commonly used scenarios is known as RCP 8.5, often referred to as 'business-as-usual' (with a high population growth rate, low technical progress and large-scale use of coal) that shows emissions increasing at a high rate – scary, but often helpful. Three others (RCP 6.0, 4.5 and 2.6), produce a more reasonable range (3^{o}, 2.5^{o} and 1.5^{o}C) by 2100, given in AR5. AR6, expected in 2021 to include revised scenarios that will show separate scenarios by region.

of the issues that may be involved, it remains important to involve key stakeholders and to expose the analysis to other experts.

Limitations of any such analysis need to be pointed out. They can be illustrated in the ranges provided, e.g., in the degree of confidence and identification of major areas of risk in the scenarios presented. In developing a social cost-benefit analysis there is a need for analysts and modelers to remain humble.

7. *Recommendations and basis for conclusions*. Because of what may be controversial recommendations and conclusions made in a social cost-benefit analysis and because of the sensitivity of the social discount rates used, it is particularly important to effectively and clearly communicate in a transparent manner (balanced against in some cases privacy concerns) and make their basis publicly available (for public entities).

   In assessing many climate change-related efforts, recommended actions should represent a win-win situation for all stakeholders wherever possible, as it is in everyone's self-interest to take appropriate action. Nevertheless, when it comes to making a potentially large financial commitment, decisions are inevitably made in the context of competing priorities and objectives – a challenge in the best of situations.

Social considerations. Most human endeavors are affected every-day by the weather, which has generally been out of humanity's control. At the same time, we have seen that human activities have contributed to climate change. Human actions can also be used to help mitigate some of these changes, as well as how to reduce some of their adverse impacts. However, the affordability of the resources needed for this purpose can be a significant issue. The high cost of financing for some countries underlines the potential severity of these long-term damage issues. In many cases, those who are the most vulnerable[111] to the short and long-term effects of climate change and would benefit most from long-term planning and risk management, are also among those whose resources may not permit it to make needed changes.

Governments and non-governmental organizations (NGOs), including philanthropic and community organizations, provide or greatly assist in planning for disaster recovery (ex-post adaptation). Although their emphasis is normally on ex-ante adaptation (as well as, inevitably, ex-post adaptation needs) rather than mitigation, the need for external financing for these purposes (e.g., from international aid or loans, or the insurance sector for sudden-onset damages) can be great. In preparation for possible ex-post adaptation needs, practical and effective dissemination of disaster preparedness plans, emergency infrastructure development, or recovery require special care. The integration into these plans of modern communication technologies, such as text-based disaster alerts, may be desirable. Neither the world, nor any country can afford to ignore the possibility of tail scenarios.

Regular review. Because knowledge of the dynamic nature of the climate damage process will continue to increase and, in any event, conditions will inevitably change, a dynamic set of climate and damage-related metrics, including results of present value calculations, will be needed. The inevitability of feedback loops, non-linearities, and discontinuities in these processes, as well as human behavior and advancements, also point to the need for continual improvement and updates in analysis.

[111] Including those who are homebound or disabled, in isolated areas, and those of extreme ages.

Assumptions and other inputs to climate change analysis (as well as social cost-benefit analysis of other social policy issues) need to be reviewed on a regular basis, say every three or five years, and updated as appropriate, reflecting current information, experience to date and reasonably expected policy decision-making and implementation. This is an example of a continuous learning process. As it is always difficult to project anything for decades, let alone centuries, it may prove more practical and revealing to project several decades at a time, possibly in 25- or 50-year period segments. Taking such an approach might be a surrogate for studying a generation at a time, possibly with different social discount rates within a time segment or from the current date to each time segment.

Financial reporting and corporate responsibility. There has been a recent increase in corporate financial reporting concerning the external effects of climate change of a company's actions on and its impacts on the company. Typically, this has addressed ESG factors to help its investors assess key sustainability risks and ethical performance. A multi-disciplinary effort is needed to conduct a comprehensive social cost-benefit analysis supporting this type of financial disclosure.

In the future (if not already), investment and financial institutions will likely demand further disclosure regarding what companies are doing in response to environmental risks, particularly focusing on the actions large emitters are taking. In part this will be due to pressures on these institutions by their regulators and rating agencies. The development of this information may make the social discounting process just as important to the private sector as it is to the public sector in its environmental policy-making. As time goes on, the author expects enhancements and guidance to improve consistency, relevance, and quality of the information provided for such disclosure. Similar disclosure is also appropriate for public sector entities.

It has only been since climate change has been 'moved forward' by becoming more visible as a result of global temperature increases and severe storms, that significantly greater concern been raised. At the same time, regulatory attention been given a much high priority and numerous companies have been setting climate-related goals and expanding disclosures that would have been unheard of five or ten years earlier. This suggests that either social discount rates used were too high, cash flow equivalent damages were underestimated, or the extent and type of uncertainty was under-appreciated.

Asset and pension fund managers, insurers, other financial institutions and their regulators have been increasingly pushing companies in certain business segments to take more rapid and sizable action, as well as more extensive disclosures. It is being rapidly recognized that current private and public sector business-as-usual practices may lead to a global temperature increase of at least 3°C over pre-industrial times, which could prove catastrophic in some parts of the world. The continued push by governments to cut emissions to meet or exceed their Paris commitments may trigger a transformation of the energy and other industry segments that could make, for example, a large number of fossil fuel projects uneconomic or stranded, and collateral damage to other industries such as agribusiness. Collective action can avoid being viewed as being victims, scapegoats, or passive risk carriers by instead becoming active instruments of change.

Model governance. This covers the process followed to derive social discount rates and amounts discounted, including the management of the methodology used in the development of the models and accompanying assumptions used. The governance process addresses all aspects of the social risk management process (in sections 2.1 and 2.2). This includes controls over the process followed, input and output validation and security, calibration to known information, testing, avoidance of conflicts of interest, review by another professional(s), mitigating misuse and misinterpretation, and effective communication and appropriate documentation regarding the basis for its estimates and use.

Role of judgment and potential bias. In assessing any approach, areas of bias needs to be identified. Possible areas of concern include: overreliance on judgmental/subjective assumption or parameters, selective use of facts or studies, embedded political viewpoints, overemphasis on the short-term, overreliance on biased experts, unsupported estimates falling in extreme ends of ranges, an extreme degree of risk aversion/tolerance, analysis paralysis or waiting for the perfect answer/scientific certitude that is unlikely to emerge in a timely manner, ignoring secondary/tertiary effects such as co-benefits, following inertia or a herd-mentality, and an overly strong personality in the analytic team. The sooner these or other possible sources of bias are recognized, the more likely an objectively-based strategy can be developed and resources can be better allocated among projects or areas of focus.

Independent review. To help ensure a minimization of unintended bias, incompleteness or errors, an independent review may be appropriate. The extent of such a review, whether conducted in an informal basis by colleagues or by other members of a team or a formal peer review process[112] can depend upon the significance of the item being assessed and external requirements imposed. Exposure to public review may be appropriate in some cases. The integrity of a social cost/benefit analysis is important to maintain in any case.

Verifiability. Ideally, the data, assumptions and results used should be verifiable. The data should be transparent, with the quality confirmed. However, in some cases this may not be practical, due to privacy or proprietary reasons. Nevertheless, to the extent possible they need to be transparent and available.

Multi-disciplinary approaches. The types of social cost-benefit analysis discussed in this paper usually benefit from the involvement of those with a broad range of expertise and experience, using a multi-disciplinary approach. These include climate scientists, engineers, economists, actuaries, and ethicists. Although such an effort can complicate the process, at the same time it can increase the overall quality of the results and usefulness of its findings and recommendations.

Although actuaries have historically not been active in discussions of this application of discount rates, their experience with discounting cash flows over long periods in a broad range of applications and financial risk management of long-term risks indicate they can provide valuable insight to this issue. Their experience with the design of approaches to address this type of risk and its underlying uncertainties can provide added value. Actuaries have played crucial roles in the assessment of environmental risks as they affect human lives and property – dealing with the risks associated with climate change should be no exception, where a wide range of approaches and specialized knowledge developed by other professionals can be applied.

Because of their experience in applying comprehensive risk management principles in both insurance and non-insurance areas, they can provide valuable perspectives in the assessment of specific techniques. The profession has a rich history of addressing complex problems and developing forward-looking insights and solutions in the public interest. They follow an approach of dynamic learning and applications to changing conditions, both over short- and long-term periods.

[112] Conducted in an objective and possibly independent manner (for instance, in a manner consistent with a code of professional conduct that involved actuaries would be subject)

Risks and uncertainties are involved in any projection involving human behavior, including the effects of intended and unintended incentives, especially over the longer term. As described in this paper, contributing factors include the low frequency of many of the effects of climate and weather, the inclusion of both direct and indirect damages with immediate, delayed, and second-order effects, multiple causes, and effectiveness of resilience and other adaptation measures. Incorporating plausible future human and political actions into social cost benefit-analyses are particularly difficult, in many cases best analyzed through scenario analysis.

Research needed. Further research is needed, especially in areas where there is currently a high degree uncertainty. Indeed, it is appropriate to pursue every possible alternative approach, given the potentially catastrophic severe tail event if nothing is done. These areas are embedded in the entire climate change process, especially in estimating damages. New and enhanced techniques are needed to achieve effective and cost-efficient scalable technologies to achieve or exceed carbon neutrality are needed in the coming decades. In addition, cost-effective methods of providing incentives for adoption of low-technology approaches are also needed. Continuing to develop and implement consistent and high-quality data and metrics[113] regarding climate change, mitigation, and adaptation are also of crucial importance.

Improved modeling is also needed. This includes enhanced integration of climatic/environmental, damage, and economic models. A multi-disciplinary framework integrating perspectives from the physical, natural and social sciences is needed.

The achievement of greater consensus regarding climate change and social discounting methodologies, models, and assumptions, is also needed. Despite the large volume of papers written on these and related subjects, further science and dialogue is needed, both regarding climate science and economic models applied, as well as the application of some of the key concepts covered in this paper.

Nevertheless, perfect estimates coving the long-term, including the effects of climate change, will not be achievable. This is simply too complex an issue. However, we need to keep in mind that social discount rates that are excessive can result in a trivialization of damages to future generations, while if too low, social discount rates may overweight the far-distant future. In spite of this, we will have to live with estimates that contain, in most cases, a considerable room for error. The findings need to be rigorously challenged on a regular basis to ensure the best practical, timely, and useful information for decision-makers.

Key take-aways from chapter 12 include:

- Effective communication of a social cost-benefit analysis, including its quantitative and qualitative components, has to keep in mind the expected users, including particular focus on areas of known differences of opinion;
- Rigorous documentation of the basis of findings is needed, indicating where judgement was applied and how areas of significant uncertainty were dealt with;
- The social aspects and implications of alternative program design, including affordability and motivations to mitigate and ex-ante adapt to climate change and its adverse effects, should be considered in a program or strategy's social cost-benefit analysis;
- The level of analysts' degree of confidence in the cost-benefit results needs to be incorporated in a cost-benefit analysis;

[113] One example is how to address emissions created by products consumed within a national border but produced outside. These can be enormous due to cross-border trade, possibly a quarter of the global total.

- Climate policy is all about managing its uncertainties through risk management principles, whether at a global, national, or local level for the private and public sectors; and
- A comprehensive multi-disciplinary effort should support a comprehensive social cost-benefit analysis that contributes to ESG disclosures in relevant reports and financial statements of private sector companies and public sector entities. Actuaries can play a role in these efforts.

Chapter 13: Conclusion

> *the choice of an appropriate discount rate is one of the most critical problems in all of economics … The most critical single problem with discounting future benefits and costs is that no consensus now exists, or for that matter has ever existed, about what actual rate of interest to use.*
>
> Martin Weitzman (*2001), p 160*

A social cost-benefit analysis is one component of a comprehensive social risk management process conducted primarily by the public sector, which includes both quantitative and qualitative components. A key element in this analysis is the determination of social value of various long-term strategies and proposed investments or programs using the most appropriate discount rate, referred to as a social discount rate.

Unfortunately, "There is no correct single discount rate, or approach to discounting, appropriate to climate policy. Nor is there a single appropriate approach for *how* to determine the discount rate. In part because one confronts here fundamental disagreement about where the market appropriately ends as a social construct to deal with questions of allocation and distribution." (Kane 2012).

This paper not only addresses the fundamentals of the social discounting process, but also addresses some of the most contentious related issues that have been raised, including the role of market rates, the treatment of social externalities and co-benefits, and the scope and methods used in its application.

A social cost-benefit analysis is an appropriate approach to assess the acceptability and cost-benefit analysis of climate-related strategies and investments, considering both mitigation and ex-ante adaptation. It has been pointed out that, looked at overall, climate change-related issues are unique, although many of their characteristics are shared with other social issues. The range of potential social discount rates currently used for assessment of investment in climate change mitigation and adaptation is wide, conceptually covering: the social rate of time preference, the consumers' rate of time preference (the consumption rate of interest), the risk-free rate, and the government's cost of funds.

Developing estimates of the value of methods that address the expected costs associated with climate change can be challenging, to say the least. Integrating the latest available information regarding climate science applied to local conditions to develop effective mitigation and adaptation solutions is crucial in developing sound and affordable private and public sector mechanisms to spread and manage the risks involved.

Actuarial principles indicate that the discount rate(s) should be compatible with the cash flows or their equivalent that are being discounted. Therefore, it is important that the significant uncertainty involved in climate risk and its projections neither be double-counted nor ignored. Assuming that the expected cash flows do not incorporate undue prudence, uncertainty should reduce the social discount rate, preferably in a decreasing (hyperbolic) fashion. An initial period of ten to forty years could be used before discount rates decrease; this approach has the advantage of reducing a potential bias toward climate change programs or investments that might occur if a shorter initial period was used.

Other key factors that in many cases can reduce the discount rate used include:

- Social externalities, co-benefits, and sustainability considerations;
- Many significant items that cannot be monetized or be included in a discounted cash flow framework;
- In cases in which the possible massive size of its costs and benefits, aggregate rather than marginal concepts that are used in most cost-benefit analyses may be appropriate;
- Uncertainties, especially those involving tail risks resulting from asymmetric damage potential and the long-term increasing nature of climate change uncertainties;
- Whenever future generations are involved, ethical considerations involving the implied social contract between generations;
- Other ethical issues, such as free-riding that can arise by countries and industry segments not contributing their fair share of expected costs; and
- As society cannot allocate all of its funds toward climate risk projects, the irreversible nature of the risks involved and the net cost of real options of delayed action need to be considered.

Principal conclusions reached in this paper include:

1. The social discount rate is an extremely important factor in many social cost-benefit analyses and social cost of carbon calculations, as results can be sensitive to the discount rate chosen;
2. An unadjusted market-based discount rate is not appropriate as a basis for social discounting;
3. Although an extended (for uncertainty) Ramsey formula is a commonly used economic formulation for analysis of social discount rates involving inter-generational equity issues, other methods should be further explored, addressing the considerations described in this paper;
4. A hybrid hyperbolic discount rate methodology should be used, with an initial rate over a short-term period being somewhat close to a market-rate to avoid undue bias among competing risks;
5. A global perspective is appropriate for analysis of mitigation over a fixed, albeit long time horizon, while a regional, national, or local perspective may be more appropriate for analysis of ex-ante adaptation, as the effect of climate change differs by region of the world, although the greenhouse gas accumulation in the atmosphere and the oceans that constitute a primary driver of climate change are global in nature.
6. A reduction in social discount rates from those based on the market should reflect factors including the effect of social externalities and uncertainties, as well as the other factors indicated in the immediately preceding list;
7. Scenario-specific discount rates should be applied in both stochastic modeling and scenario analysis, both important quantitative tools used for this purpose;
8. Carbon pricing can be used as a price signal and internal company benchmark, as well as the basis for a carbon tax or prices in a cap-and-trade market;
9. Effective and transparent communication of findings in social cost-benefit analyses, including appropriate disclosure of the methodologies, models, assumptions and scenarios used; and
10. Despite the large volume of papers written on this and related subjects, further research is needed to encourage greater consensus, ensure compatibility of assumptions across climate and economic science models, and the application of some of the concepts addressed in this paper.

You cannot escape the responsibility of tomorrow by evading it today.

-- Abraham Lincoln

Appendices

Appendix 1: Numerical Discount Rates

Table 8 shows the net present value today of 100 at a range of periods using a selected set of discount rates. For example, the present value using 2.5% today of a cash flow for $500 million in 200 years is $3,585,000 ($500,000,000 x 0.717 / 100) and using 4.0%, $195,000 ($500,000,000 x 0.039 / 100).

Table 8. Discounted value of 100 using a given interest of a given number of years

year	2.0%	2.5%	3.0%	3.5%	4.0%	UK*	France#	2.0%	2.5%	3.0%	3.5%	4.0%	UK*	France#
5	90.573	88.385	86.261	84.197	82.193	84.197	82.193	102.475	100.0	97.596	95.262	92.994	95.262	92.994%
10	82.035	78.120	74.409	70.892	67.556	70.892	67.556	105.012	100.0	95.250	90.748	86.478	90.748	86.478%
25	60.953	53.939	47.761	42.315	37.512	42.315	37.512	113.004	100.0	88.545	78.449	69.545	78.449	69.545%
50	37.153	29.094	22.811	17.905	14.071	19.726	20.749	127.698	100.0	78.403	61.543	48.364	67.801	71.316%
75	22.646	15.693	10.895	7.577	5.278	9.421	12.647	144.304	100.0	69.422	48.280	33.635	60.035	80.590%
85	18.577	12.259	8.107	5.371	3.566	7.360	10.375	151.535	100.0	66.125	43.813	29.087	60.035	84.629%
100	13.803	8.465	5.203	3.206	1.980	5.082	7.709	163.068	100.0	61.470	37.875	23.391	60.035	91.070%
150	5.128	2.463	1.180	0.574	0.279	1.671	2.864	208.235	100.0	48.194	23.309	11.313	67.842	116.294%
200	1.905	0.717	0.271	0.103	0.039	0.621	1.064	265.912	100.0	37.786	14.345	5.471	86.633	148.506%
250	0.708	0.208	0.062	0.018	0.006	0.295	0.395	339.565	100.0	29.625	8.828	2.646	141.440	189.639%
300	0.263	0.061	0.014	0.003	0.001	0.140	0.147	433.619	100.0	23.227	5.433	1.280	230.921	242.166%
400	0.0363	0.0051	0.0007	0.00011	0.00002	0.0518	0.0203	707.094	100.0	14.278	2.058	0.299	1,008.586	394.896%

* Using discount rates from HM Treasury (2011): 3.5% years 1-30, 3.0% years 31-75, 2.5% years 76-125, 2.0% years 126-200, 1.5% years 201-300, 1.0% years 300+; rates are reduced where 'pure STP' = 0: 3.0% years 1-30, 2.57% years 31-75, 2.14% years 76-125, 1.71% years 126-200, 1.29% years 201-300, 0.86% years 300+.

\# 4% for 30 years, 2% thereafter.

For perspective, Weitzman (2001) derived the following set of approximate recommended discount rates from a large survey of economists: 4% for years 1-5, 3% for years 6-25, 2% years 26-75, 1% for years 76-300, and close to zero for years greater than 300.

Selected current governmental policy with respect to discount rates to be used in social cost-benefit analysis (Scandinavian countries based on Mouter 2010) include:

- Denmark. 4% (3% risk-free + 1% risk premium) for years 1-35; 3% for years >35 and <70 years (2.5% risk-free + 0.5% risk premium); 2% for years >70 (2.0% risk-free).
- France. 4% for 30 years; 2% thereafter.
- Netherlands. 4.0%. Incorporate macro-economic risk in the discount rate and two independent scenarios. Based on risk-free rate of 3.0%.
- Norway. 2.5% for 40 years, 2.0% thereafter. Based on return in international markets.
- Sweden. 3.5%. Derived from Ramsey, level for practical reasons.
- United Kingdom. See * above. No specific risk premium.
- United States. Three alternative discount rates: 3%, 3.5%, and 5.0%.

Appendix 2: Shadow Price of Capital Approach

Shadow pricing is often used in cost-benefit analyses. It uses a monetary value assigned to currently unknown or difficult-to-calculate costs in the absence of observable market prices.

An example of the use of a consumption-based discount rate can be seen in the application of a shadow price of capital approach, as discussed in U.S. Environmental Protection Agency (2000). Under this approach, expected costs are increased to reflect the higher social costs resulting from the displacement of private investments. It can be particularly useful where market prices are distorted and do not reflect the full direct and indirect costs and where no market prices are available. Discount rates used in the determination of shadow prices reflect the time value of money to consumers in a manner consistent with how individuals value and trade consumption. The U.S. EPA recommended that a shadow adjustment should not be made, as long as private investment is not crowded out.

A hypothetical example follows. Suppose the expected pre-tax rate of return from an investment is 5% and the post-tax rate of return is 3%, with the difference attributable to taxation of capital income. Assume that increases in government debt displace private investments dollar-for-dollar and that increased taxes reduce individuals' current consumption on a one-for-one basis. Finally, assume that the current cost of a public project of $100 is three-quarters financed with government debt and one-quarter with current taxes. Also, this project produces benefits estimated to be worth $500 forty years from now.

Using the consumption rate of interest shadow price of capital approach, start with, say, 75% of the $100 current cost (the amount of displaced private investment) by the shadow price of capital. $167 is the social price of capital. This is determined by taking a $1 private investment with similar characteristics that produces a stream of private consumption of $3 per year and tax revenues of $2 per year. Discounting the private post-tax stream of consumption at the 3% consumption rate yields a present value of about $100. Discounting the stream of tax revenues at the same rate yields a present value of about $67. The social value of this $100 private investment (the shadow price of capital) is thus $167, substantially greater than the $100 private value that individuals would assign. This yields $125.25, to which is added the $25 by which the project's costs displace current consumption. The total social cost is therefore $150.25. This results in a net social present value of about $3, which is the present value of the future $500 benefit discounted at the 3% consumption rate (about $153.28), minus the $150.25 social cost.

Variations of this approach exist. For example, the Kolb-Scheraga (1988) approach annualizes capital expenditures using a pre-tax rate and then discounts all costs and benefits using the consumption rate of interest.

If the government obtains financing for a project through taxation that displaces only private consumption, then, relative to consuming the resources today, overall welfare is increased as long as the project generates future benefits that exceed those costs when discounted at the consumption rate of interest.

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Glossary

Adaptation. A deliberate effort or adjustment in an ecological, social, or economic system(s) to increase the capacity to cope with, obviate or ameliorate the bio-physical effects of a changing climate. It can take the form of a changes in processes, practices, or structures to moderate or offset potential loss or damages, or to take advantage of opportunities associated with changes in climate. Examples include: dykes, flood control reservoirs, embankments, forestry protection, building structure updates, emigration, and retrofitted telecommunication systems.

Adverse outcome. A result that damages a person or a person's resources or property.

Aggregate. The total amount, including both sunk, fixed, and variable components.

Ambiguity. Unclear, indefinite, or of doubtful interpretation. *Ambiguity risk* can arise from unknown causes or an unknown mix of risks. *Ambiguity aversion* is a preference for known risks compared with unknown risks.

Assumption. An expectation regarding one or multiple aspects of the future. Also, a component of a model that may be based upon objective or subjective factors. A *parameter* is the quantity of the factor that represents the assumption.

Behavior. The way in which a person acts in response to a particular situation or stimulus. A field in which the effect of behavior is the primary focus is referred to as *behavioral economics*.

Carbon dioxide. A naturally occurring greenhouse gas, CO_2, is also a by-product of burning fossil fuels (such as oil, gas, and coal), burning biomass, certain land use changes, and industrial processes. It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance in the atmosphere.

Carbon price. The price for avoided or released carbon dioxide (CO_2) or CO_2-equivalent emissions.

Carbon pricing. Determining the price of carbon dioxide (CO_2) or CO_2-equivalent emissions.

Catastrophic risk. A possible situation where the outcome is an extremely damaging loss or damage, possibly even existential in nature.

Certainty-equivalent (risk-adjusted). The guaranteed amount of money (cash) that an individual would view as equally desirable to a risky asset. It can be applied to the discount rate used or the amount being discounted.

Climate. Weather conditions, including such factors as temperature, precipitation, and humidity, prevailing in an area in general or over a long period.

Climate change. A change in global or regional climate patterns, primarily caused by human activity through natural processes that may involve air, land or sea.

Climate change process. The aggregation of a series of cause-and-related trajectories that range from the underlying drivers of climate change, that is, primarily greenhouse gas emissions, to consequential damages. It can include one or a multiple number of feedback loops.

Climate risk. Exposure to climatic conditions that can result in damaging effects.

Climate sensitivity. The effect on global climatic factors to a change in greenhouse gas concentration in the atmosphere, especially affected by feedback loops.

Climatic factors. Elements of climate, including temperature, precipitation, humidity, barometric pressure and wind.

Co-benefits. In the climate change context, the favorable (or avoidance of unfavorable) side-effects associated with mitigation or adaptation efforts to reduce climate change or its effects that are not directly related to the climate hazard. Also, the indirect (secondary or tertiary) benefits of a mitigation action, such as air pollution or reduced premature morbidity and mortality. A *co-cost* is the corresponding adverse side-effect; in this paper, such costs are incorporated into references to co-benefits on a net basis.

Constant relative risk aversion (CRRA). A commonly used utility function under which a consumer keeps constant the extent exposed to risk, that is, if there is an increase in real income, the consumption of total goods will change in a proportional manner.

Consumption. The use, decay, or destruction of a resource, such as a good or service.

Consumption rate of interest. The consumers' marginal annual rate of time preference. It is usually measured by the after-tax real rate of return on savings. It determines the consumer's valuation of current consumption relative to future consumption (the consumer's marginal rate of time preference).

Cost-benefit analysis. In a risk management process, a structured approach applied in an analytical manner that weighs the costs and benefits (advantages and disadvantages) of a strategy, policy, or investment (depending on what is being assessed) according to specified criteria, defined by the stakeholder(s) for which the analysis is being conducted. It often compares alternative courses of action or recommends the top-ranked projects (with the most beneficial outcomes at the lowest cost) until the amount of available or designated financing runs out. It is usually primarily quantitative in nature, although it often includes qualitative aspects.

Cost of capital. The cost of a company (or entity)'s funds (whether from debt or equity) or, from an investor's point of view, the required rate of return on a portfolio of existing securities.

Damages. Financial or physical losses. In the context of climate change, the adverse effects that result from a climate change-related event or condition. These can consist of monetizable and non-monetizable items, and can include real and opportunity costs.

Decarbonization. The process of moving from a high-carbon based economy to a lower one, the objective of which is to reduce greenhouse gas emissions. Depending upon the current condition of the economy, this can represent a costly undertaking.

Disaster risk management. Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of disaster risk, to foster disaster risk reduction and transfer, and to promote continuous improvement in disaster preparedness, response, and recovery practices. It has the explicit purpose of increasing human security, well-being, quality of life, and sustainable development.

Development. This refers to the stage of economic development of a country or to the process of increasing its wellbeing. Countries are often categorized according to whether they are *less developed*, *developing* or *developed*.

Discounting. A mathematical process or operation that aims to make monetary (or other) amounts received or expended at different times (years) comparable across time.

Discount rate. The percentage reduction, generally expressed as an annual rate, in the value of an item(s) at a certain point in time compared to the corresponding value at an earlier time. A discount rate is often based upon a market-based concept that measures the change in the relative price of a good or financial instrument between different points of time. It can be based on prices of observed transactions, usually of financial instruments in a marketplace, with the actual rate based upon the risk and other characteristics of the item. Variations include a *real return on capital*, an *opportunity cost of capital*, a *real rate of interest*, a *social discount rate,* and a *real rate of return*, depending on its application.

Economic efficiency. An economic state in which every resource is optimally allocated to serve each individual or entity in the most efficient manner, while minimizing waste and maximizing return. An economy is efficient when any change made in a given economy to assist one entity would harm another.

Elasticity of marginal utility. The speed that the marginal utility of consumption is expected to decline as the utility of consumption increases. η in the Ramsey formula.

Environmental, social, and governance (ESG). Factors used to categorize an entity's concerns and exposures to environmental and social issues. These criteria can help to better assess or measure the future financial performance of a company. An example of an application is the set of voluntary disclosures that address how an entity is affected by relevant issues, recommended by the Task Force on Climate-related Financial Disclosures (TCFD).

Ethics. Ethics involves questions of social justice and social value. *Justice* is concerned with right and wrong, equity and fairness, and, in general, with the rights to which people and living beings are entitled.

Ex-ante adaptation. Adaptation efforts implemented in anticipation of harm from a future risk or adverse outcome, e.g., before a famine or sea level rise causes damages.

Ex-post adaptation. Adaptation efforts after an event or harm occurs that has or is anticipated to result in harm, e.g., after a flood or drought. Also referred to as *disaster recovery*. The results or costs are sometimes referred to as *losses and damages*.

Existential risk. A *risk* that poses permanent and severe adverse consequences to humanity or a segment of humanity that can never be undone.

Exponential discount rate. A specific form of discount rate, the rate of which is constant over time. The discount percent is a future reward expressed as a fixed percentage for each unit of elapsed time.

Externality. An externality arises when one party's action(s) results in uncompensated benefits received or costs incurred by another party. These costs or benefits are usually, but not necessarily, an indirect consequence of an associated product, service, or activity not reflected in prices that would be charged for the product, service, or activity. The user of a cost-benefit analysis in the product, service, or activity assessed does not usually include or consider anything outside its direct costs and direct benefits. Such costs, benefits, or activities may arise in the distant future or may be primarily experienced by one or more third parties.

Free-riding. A situation in which those who benefit from certain resources, goods, or services do not pay for them. A form of moral hazard, arises when a country does not participate in its fair share of mitigation costs related to climate change, even though it receives benefits from others' actions.

Governance. A comprehensive and inclusive concept of the full range of means for deciding, managing, Implementing, and monitoring policies and measures of an entity. Governance issues are disclosed in ESG disclosure reporting.

Greenhouse gases. Gas in the atmosphere that absorb and emit radiation within the thermal infrared range, trap heat in the atmosphere and contribute to the greenhouse effect. Their accumulation tends to increase the global temperature and to have other effects on the Earth's climate. Examples are carbon dioxide and methane.

Hyperbolic discount rates. The discount rate for a given length of time decreases as the time horizon increases. Although technically they incorporate a decrease following a hyperbolic curve, they have more generally been used to describe any set of discount rates that decrease over time.

Integrated assessment model (IAM). This type of model is used in the study of the effects of climate change. It usually consists of multiple equations and simulation features consisting of three major components: (1) a sub-model that estimates future climatic factors by means of demographic, economic, meteorological, and geophysical factors, as well as their interactions, (2) a sub-model that estimates losses/damages based on the results of the climatic factors estimates derived in the first sub-model, and (3) a valuation model that estimates the value of the losses/damages derived in the second sub-model. It thus values the effect of the links between greenhouse gas emissions, greenhouse gas concentrations, changes in climatic factors such as temperature or precipitation, to resultant damages.

Interest rate. The annual rate payable by the issuer to the owner of a financial instrument as a result of that ownership.

Intergenerational equity. Social justice in the distribution of economic and non-economic costs and benefits across generations.

Internality. Similar in some respects to an externality. However, the costs or benefits included are incurred by the person or entity involved rather than a third party, often in the long-term but not necessarily recognized at the current time.

Intragenerational equity. Social justice in the distribution of economic and non-economic costs and benefits across population segments within the same time period.

Investment rate of interest. The rate at which it is expected that a given investment will return. It emphasizes opportunity cost, also referred to as the *opportunity cost of capital* or *producer rate of interest*.

Irreversible. Cannot be changed back to a previous condition or state.

Marginal. The analysis of the effect of an additional cost or resource associated with an additional volume of an item, that is, it varies directly with the additional volume. This excludes sunk or fixed costs or benefits.

Market-based discount rate. The equivalent annual discount rate based on the interest rate derived from prices of transactions of applicable financial instruments in a market, which as a result reflects the preferences of market participants.

Methane. A greenhouse gas, a major component of natural gas, is associated with all hydrocarbon fuels. Significant methane emissions also occur as a result of animal husbandry and agriculture, solid and organic waste, and biomass burning.

Mitigation. An action or technique that reduces costs or risks. In the case of climate change, a reduction in or elimination of one (or more) driver of changes in climatic factor(s) and consequential damages, including emissions of greenhouse gases, for example, through reduction in the use of fossil fuel generated energy, green-agricultural practices, and effective thermal insulation of buildings.

Model. A simplified representation of reality using statistical, mathematical, scientific, actuarial, or financial concepts and equations. It is used to study the effects of a system or one or more of its components.

Non-monetizable. An item whose value cannot practically be converted to a financial asset or liability, e.g., heritage assets and human life and health.

Options analysis. (see *real option*)

Per capita growth rate of consumption. Economic rate of growth of, for example, a country, per person. *g* in the Ramsey formula.

Pigouvian tax. A tax on an economic or market activity or item that generates negative externalities. It is usually intended to correct an inefficient market outcome by incorporating the social cost of the negative externalities.

Prudence (conservatism). Cautiousness or acting in a safe manner. For instance, in evidence when an individual's inclination to save more when uncertainty about future consumption increases.

Public good. An item that is consumed by or be of benefit to all in society as a whole or available to all individuals. An individual can consume such a good without reducing its availability to another individual(s). Public goods available everywhere, such as the atmosphere and oceans, are sometimes referred to as a global public good.

Pure rate of time preference. The annual rate of decline in the weight placed on a unit of utility in the future compared with an equal unit of utility the year before. ρ in the Ramsey formula.

Ramsey formula. A growth-related economic model that has been used since Ramsey (1928) to derive social discount rates over the long-term, particularly in conjunction with the analysis of intergenerational issues. It originally focused on how to compare values related to current consumption and savings.

Real option. The right, but not the obligation, to undertake a specific action, such as deferring, abandoning, expanding, staging, or contracting-out a capital investment project. An ability that can be exercised profitably under some, but not all, possible situations. *Real options analysis* refers to a cost-benefit analysis that incorporates the value of real options. *Real option value* refers to the opportunity cost or benefit resulting from irreversibility and uncertainty.

Real rate of interest. The nominal interest rate (usually obtained through observation of prices of financial instruments in a financial market) less the corresponding overall price level.

Real return. A measure of the yield on one or a portfolio of investments, adjusted by the corresponding change in the overall price level.

Resilience. The ability to resist the effects of an extreme event with minimal damages and functionality. Often used in assessing the quality of building construction to withstand damage, although it can also refer to the general adaptability of a building, community, or household.

Risk. A possible situation where the outcomes are unknown but governed by estimated probability distributions. In some cases, risk refers to exposure to an event with an adverse outcome or loss.

Risk aversion. The preference to avoid or mitigate the effects of outcomes with unfavorable results. Similar preferences apply to *ambiguity aversion*, *uncertainty aversion*, *loss aversion* and *tail aversion*.

Risk-free rate. The rate at which a minimum amount of risk for a specified term is involved; usually the rate implied by prices for the sovereign country's fixed income securities for the applicable duration.

Risk management. The process of identifying, assessing, and controlling threats and opportunities. The threats or risks could stem from a wide range of sources, including climate change, financial uncertainties, legal liabilities, strategic management errors, accidents, and natural disasters.

Risk tolerance. The maximum amount that society (or an individual, as applicable) is willing to lose, or the level of control needed, to eliminate or mitigate risk to an acceptable level.

Scenario. An internally consistent set of conditions assumed to exist. It is used in modeling or projecting the future. *Scenario analysis* is an assessment of the implications or effects of one or more often a multiple number of scenarios, each of which can include a single trajectory of conditions over time. A *stressed scenario* is such a set of conditions under specified extreme conditions in a *stress test*.

Shadow price. A monetary value assigned to currently unknown or difficult-to-calculate costs in the absence of correct market prices. It is estimated on the willingness to pay, often calculated based on a given set of assumptions, which makes it a proxy value.

Slow-onset. A hazard, like sea level rise or desertification, that takes years, decades, or centuries to develop.

Social costs. The full costs of an action in terms of social welfare losses, including costs of social externalities associated with the impacts of the action on the environment, the economy, and on society.

Social cost-benefit analysis. A cost-benefit analysis that includes consideration of social externalities, co-benefits, or context.

Social cost of carbon (SCC). The estimated marginal cost of damages resulting from the emission of a unit (one metric ton of CO_2 emissions). Analogously, the value or benefit associated with preventing a unit of carbon dioxide emissions. The change in the discounted value of the utility of consumption denominated in terms of current consumption per unit of additional emissions.

Social discount rate. A parameter that measures the importance of social externalities and the welfare of future generations with respect to the present. It is calculated as a rate per year, like an interest rate, but can also refer to the discount in future utility or social welfare. Although usually applied to utility units (utils) or cash flow equivalents, it can also be applied in a similar manner to non-monetizable items, although usually separately. It can be applied in a social cost-benefit analysis of social strategies, programs, or investments in mitigation or ex-ante adaptation actions. It can be applied to a wide range of issues that include social externalities, such as economic growth, climate change, energy policy, disposition of nuclear waste, major infrastructure programs, and reparations for slavery.

Social discounting. The process of applying a social discount rate to the social value of a set of costs and benefits (usually, in the form of cash flow equivalents).

Social externality. An externality that involves or affects a broad segment, if not all, of a population, usually as viewed from the vantage point of society, rather than of an individual. Its cost is the difference between costs to society and private costs. For example, the costs or benefits due to climate change or pollution resulting from greenhouse gas emissions are usually not considered in the price of the activity or the result of that activity.

Social justice. Concerned with ensuring that everyone gets what is due to them in terms of opportunities and setting forth the moral or legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society. It encompasses economic, political, and social rights and opportunities.

Social risk management. The risk management process relating to risks associated with a given population or society.

Social value. The aggregation of the quantitative and qualitative effects of a social program or strategy applied to individuals, communities, or populations. The quantitative aspect of social value can be determined as: (1) the difference between the application of the social discount rate and the corresponding discount rate not considering social externalities or (2) the discount rate at applicable time intervals multiplied by the expected social externalities at those times.

Social welfare function. A process for aggregating individual preferences into social preferences, with the level of welfare in an economy or society expressed as a function of economic variables and preferences.

Stranded assets. Assets exposed to reductions in value because of unanticipated changes in their initially expected revenues due to innovations and/or evolutions of the business context, including changes in public regulations. An example is when there is a significant decline in value of fossil fuels or a fossil fuel company where the fossil fuels owned can no longer be sold.

Sustainability. Activity that meets the needs of the present without compromising the ability to meet future needs at a certain level over a long period of time, even under adverse conditions. Although its application differs by type of situation, in the context of climate change it can be applied to the ability of the Earth to re-absorb greenhouse gas emissions.

Tail condition or *tail event*. The occurrence of a low probability / high severity situation. The extreme (usually most adverse) part of a probability distribution. *Tail risk* is associated with the likelihood and severity of an outcome in the tail of the distribution. In most cases, the result is a *catastrophe* with economic or physical damages greater than an arbitrarily large amount of effects.

Tipping point. A point at which a series of relatively minor changes causes a large, more significant change or disruption.

Tragedy of the commons. A situation where individuals or private economic agents exploit scarce or rival common environmental resources for their own rational, self-interested aims. It can possibly lead to severe adverse consequences such as by means of over-production or over-exposure, with possible permanent depletion of the resources for all. This could arise because of action or inaction.

Uncertainty. In contrast with risk, it arises when the outcomes, although random in nature, are governed by an unspecified or unknown probability distribution or model. Also, the lack of certainty with regards to an outcome.

Utility. The satisfaction (value) that a person or people receive from the consumption of a good or service, or to the change in their welfare or well-being. A *util* is a unit measure of this satisfaction.

Value of a statistical life. The financial amount attributable to a premature death, corresponding to the amount society is willing to spend to reduce risk enough to save one life.

Vulnerable. That population segment or area that is most exposed or *at-risk* to losses or damages.

Weather. The state of the atmosphere at a place and time as regards, for example, temperature, precipitation, humidity, wind, and sunshine.

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With roots dating back to 1889, the Society of Actuaries (SOA) is the world's largest actuarial professional organizations with more than 31,000 members. Through research and education, the SOA's mission is to advance actuarial knowledge and to enhance the ability of actuaries to provide expert advice and relevant solutions for financial, business and societal challenges. The SOA's vision is for actuaries to be the leading professionals in the measurement and management of risk.

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