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Chapter 3

Social, Economic and Ethical Concepts and Methods

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Chapter 3: Social, Economic, and Ethical Concepts and Methods

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Executive Summary

This *framing* chapter has two primary purposes: first to provide a framework for viewing and understanding human (social) perspectives on climate change, focusing on ethics and economics; and second to define and discuss key concepts and methods that are used in other chapters of this volume.

The significance of the social dimension and the roles of ethics and economics are underscored by the stated objective of the Framework Convention on Climate Change: "to prevent dangerous anthropocentric interference with the climate system."

As this quote suggests, two of the main issues confronting society regarding climate change are: defining what constitutes "dangerous interference" in the climate system, and deciding what to do about it? Fundamentally these are questions for human judgment and decision. The science of climate change has not conclusively defined a sharp threshold that divides safe concentrations of GHG from highly damaging ones. Consequently, determining what is dangerous is a matter of human judgement regarding tolerable levels of risk.

Deciding what to do about climate change has proved very difficult, particularly with the wide range of interests and perspectives that exist in the world. Society may judge in many ways the consequences of different actions we might take, including the consequences of inaction.

An evaluation of these questions is ultimately a matter for ethics, though given the huge complexities of climate change, working it out in practice necessarily involves the quantitative methods of economics.

One of the ethical questions raised by climate change that is widely recognized and much debated is the question of 'burden-sharing' or 'effort-sharing': how action to mitigate climate change and its burden might reasonably be divided among countries and generations?

Another is the question of how much total mitigation to undertake. To answer this question, we must evaluate the effects climate change may have on people and on societies, to judge how bad they might be. These effects will undoubtedly influence the decisions made by individuals, the public, private organizations, governments, and the international community.

Decision-making raises two distinct ethical questions: what decision is made and how is it made? The right decision-making process does not always lead to the right outcome. In a criminal trial, for instance, the right process may be careful deliberation by a jury, but even after careful deliberation a jury may convict an innocent person.

Ethics has the task of assessing both processes and decision outcomes. Its criteria for these assessments can be broadly classified into two sorts: criteria of justice and criteria of value. Justice is concerned with ensuring that people get what is *due* to them. If justice requires that a person be treated in a particular way – not uprooted from her home by climate change, for example – then the person has a *right* to be treated that way. Justice and rights are correlative concepts. On the other hand, criteria of value are concerned with improving the world: making it a better place.

The division between justice and value is contested within moral philosophy, and so is the nature of the interaction between the two. Some authors treat justice as inviolable, so it operates as a 'side-constraint' on our actions: justice sets limits, and we can promote value only within those limits. An opposite view is that the right decision is always determined by the value of the alternatives, so no criterion of justice is separate from value. But despite the complexity of their relationship and the controversies it raises, the concepts of justice and value provide a useful basis for organizing the discussion of ethical concepts and principles in the context of climate change decisions, which is done in this chapter.

Issues of justice are involved in the distribution of costs and benefits between different generations and also among people and nations at a single time. The question of historical responsibility for climate change is important among them.

In grappling with the issue of burden sharing and historic responsibility, it is useful to understand how societies have dealt with actions initially thought harmless and ultimately found to be harmful. Under the two primary legal systems in the world (common law and civil law), responsibility for harmful actions require that the action be considered wrongful conduct at the time of the action. In the context of climate, if some or all past GHG emissions satisfy that standard, the next issue in both common law and civil law countries would be the nature of the causal link with the resulting harm *(high confidence).*

Many different sorts of value are affected by climate change. These include cultural and social values, the wellbeing of animals and, according to many authors, an intrinsic value possessed by nature. Human wellbeing is an important value, but we do not mean to suggest it is the only one. We also consider how the wellbeing of different people may sometimes be aggregated through a 'value function' or 'social welfare function' to determine an overall value for a society.

The methods of economics provide an anthropocentric measure of value to individual human beings. But climate change also affects important cultural and social values, which can be important in decision-making but may not be effectively taken into account in economic analyses. Economics may also be ill-equipped to take into account people's rights or claims of justice. A social welfare function is an aggregate measure of the wellbeing of members of a society. It gives a basis for evaluating the effects of climate change and of mitigation measures, through economic techniques such as cost-benefit analysis. Different social welfare functions reflect different views about the value of equality.

In cost-benefit analysis, the effect of a change in social value at a point in time is found by taking the monetary value of the change to each person, weighted appropriately, and adding up these weighted amounts. The weights – often called 'distributional weights' – are the marginal utility of money to an individual multiplied by the marginal social value of the individual's utility: an empirical factor multiplied by an ethical factor. Nearly all theories of value imply that those who are better off might be reasonably assigned lower weight on their monetary values when determining social value.

Much practical cost-benefit analysis values costs and benefits according to monetary values, added up without any weighting factor. This is to assume implicitly that the distributional weight is the same for each person. This approach could leads to serious error in cost-benefit analysis concerned with climate change mitigation, which often needs to take into account the extremes of wealth between rich and poor countries, as well as within countries *(high confidence).*

Discounting allows economic costs and benefits incurred at different points in time to be compared, assuming that an acceptable social discount rate is known. The relative valuation of economic and environmental assets with respect to time is crucial to decisions on how much cost to incur today, mainly for the benefit of future generations.

The discount rate may be viewed from a normative and from a positive perspective. The normative perspective involves determining what discount rate to use for making long term decisions with regard to climate across generations. The positive perspective focuses on how individuals and markets actually make intertemporal decisions, as revealed by the market interest rate. Both approaches can be relevant in cost benefit analyses, depending on the application.

Using the Ramsey Rule, normatively determining a social discount rate involves making assumptions about the pure rate of time preference, the stability of preferences over long spans of time, the growth rate of consumption, aversion to inequality and risk. Although a significant amount of uncertainty and debate remain, regarding the social discount rate for evaluating mitigation options, a selection of typical analyses in the literature presented in the chapter implies a social discount rate between 1% and 7% per annum *(medium evidence, medium agreement)* or between 0% and 8% per annum *(medium evidence, high agreement)*. Most of the empirical analyses upon which these estimates are based are from the developed world. Discounting in poorer or developing societies is less well understood.

A great variety of policy instruments can be used to address climate change mitigation. Governments can use economic, regulatory and informative instruments to support, affect or prevent social change in the context of climate change. Neither theory nor experience shows 'one-single' best policy choice. In reality, a mix of policy instrument is the norm. Several policy objectives often require a portfolio of policy instruments. But synergies, overlaps, and potentially problematic interactions need careful attention.

Major objectives of mitigation policies are economic efficiency, fair distribution of costs and benefits, environmental sustainability, and institutional or social feasibility. These are similar to the main policy objectives in AR4. Within any given country, formulating carbon policy involves trading off these multiple objectives. But each country may attach different relative weights to those objectives, and so each may legitimately choose a different type of policy and level of ambition, given other countries' mitigation actions.

Climate policies will often affect non-climate societal objectives, resulting in co-benefits or adverse side-effects. As the IPCC uses the term, co-benefit is a physical effect, not an economic or welfare evaluation of that effect. For instance, if SO_2 were regulated in a socially desirable way already, then introducing climate policy may result in a co-benefit of reduced sulphur emissions but no net welfare consequences of that co-benefit due to changes in mitigation costs and other impacts spread through society (*high confidence*). Climate policies that do not raise revenue for the government may have smaller or even negative welfare and economic benefits for society compared to similar policies that raise revenue and offer the chance for welfare-enhancing reductions in distorting existing taxes *(medium confidence)*.

Reducing GHG is not only a technological issue. Behavioural changes in consumption can be a major way to reduce GHG emissions. Whatever their form, these changes will lead to changes in wellbeing. As with other economic measurement, the changes in wellbeing are measured conceptually by the change in income that is equivalent in terms of the impact on individuals' wellbeing.

Specific options to reduce emissions can be ordered in ascending order of their cost per unit of emissions reduced, resulting in a Marginal Abatement Cost (MAC) curve. The area under this curve provides a simplified estimate of total cost of abatement, but it does not capture the economy-wide effects.

Some estimates of mitigation costs involve negative marginal costs, indicating that money can be saved by actions that reduce emissions. The extent of such negative cost opportunities has been debated.

A number of methods have been developed for dealing with trade-offs in mitigating different greenhouse gases (e.g., methane and carbon dioxide). Most methods are simplifications, for very practical reasons; yet such simplifications can lead to biases.

In addition, aggregate measure of the economic damages of climate change, embodied in many integrated assessment models, may have serious flaws due to a lack of empirical foundation, oversimplification and aggregation.

Some evidence suggests that consumers "undervalue" energy costs when they purchase energy-using equipment. Aside from carbon prices, other non-price interventions can reduce energy demand and therefore carbon emissions *(medium confidence).*

Several countries (such as Bhutan and Bolivia) have embodied concepts in their constitutions emphasising an attitude towards nature, where all life is seen as integral.

Achieving strong mitigation will require major technological and behavioural changes. Markets, left to their own devices, will underprovide technological change, even in the presence of a carbon price. Studies suggest that environmental and technology policies work best in tandem.

3.1 Introduction

This *framing* chapter has two primary purposes. One is to provide an overarching framework for viewing and understanding the human (or social) perspective on climate change, focusing on ethics and economics. A second purpose is to define and discuss key concepts that are used in other chapters of this volume. As such, this chapter complements the other two framing chapters, one concerned specifically with risk and uncertainty and one concerned with sustainability.

The significance of the social dimension and the role of ethics and economics is underscored by a key clause in the Framework Convention on Climate Change:

> "The ultimate objective of this convention … is to achieve … stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropocentric interference with the climate system." [Article 2, UN Framework Convention on Climate Change]

As this quote suggests, two of the main issues confronting society regarding climate change are what constitutes "dangerous interference" in the climate system? and what to do about it? Providing information to help answer these two inter-related questions is a primary purpose of the IPCC. Fundamentally these are questions for human judgment and decision. Natural science helps us understand how emissions are transformed into a change in the climate which is in turn generates physical impacts on ecosystems, people and the physical environment; a great deal of progress has been made in our understanding of these matters. But the science of climate change has not discovered a sharp threshold that divides safe concentrations of greenhouse gases (GHG) from highly damaging ones. Instead, it has found that damage and risks increase steadily with increasing concentrations. Consequently, determining what is dangerous is therefore a matter of judging what level of risk humanity desires to tolerate.

Addressing the second of these questions, deciding what to do about climate change, has proved to be very difficult, particularly with the wide range of interests and perspectives that exist in the world. Many perspectives can be used to judge the consequences of different actions we might take, including the consequences of inaction.

An evaluation of these questions is ultimately a matter for ethics, but in practice, given the huge complexities of climate change, will require the use of economics. Although economics can quantify many of these consequences, how society interprets and values them is inevitably an ethical question. We are only just beginning to understand the economic, ethical and social dimensions of climate change.

The audience for this chapter (indeed for this entire volume) is decision makers at many different levels, ranging from individuals to firms to NGOs to governments. A consequence of this breadth of constituents is that some of the material in this chapter will be useful to some but not all parties. A firm may find the discussion of costs particularly germane; an environmental NGO may find the discussion of rights-based justice particularly useful.

FAQ 3.1: IPCC is charged with providing the world with a clear scientific view of the current state of knowledge on climate change. Why does it need to consider ethical concepts?

Disagreements over the economic costs of action and inaction are central to the politics of climate change. What ought to be done is the subject matter of ethics. What responses can be considered ethically adequate necessarily relies upon answers to normative questions. A core question is what duties present generations have towards future generations in view of the fact that present emissions affect the quality of life of future generations. This answer to this leaves an intergenerational emissions trajectory which is determined on the basis of the present generation's normative view on duties of present generations towards future generations. A further question is how the responsibility to reduce emissions ought to be allocated among the states, and within each state. A third core issue is how we can view compensatory measures to those who suffer disproportionally from the consequences of climate change against those who are the main causers or beneficiaries. These questions ultimately involve ethical judgments over the distribution of burdens (and benefits) from the consequences of global warming, and the costs of mitigation among individuals living on this planet today and in the future.

The discussion of ethics in this chapter can be divided into two broad categories: questions of justice and questions of value. Justice can be viewed through many lenses. Some view justice through the lens of process – an outcome is just if the process that generated it is just. Others view justice in terms of the actual outcomes enjoyed by different peoples and groups and the values placed on those outcomes by the affected parties. Outcome based justice can take many forms ranging from maximizing economic measures of aggregate welfare to rights-based views of justice (for example, all countries have a right to clean air). Even within an outcome-based perspective, what determines value is subject to broad interpretation. Value may be anthropocentric or it may also recognize non-human values. Under some circumstances, economic analysis in the form of cost-benefit analysis may be appropriate as a guide to policy action. But users of such methods should be aware of the significant ethical assumptions, explained in this chapter, built into the use of cost-benefit analysis for making social decisions.

Rather than provide guidance as to what is the "correct" perspective on justice and value, we seek to illuminate the scholarly literature on different perspectives on value and justice. This can be very helpful in strengthening one's own perspectives on climate related decisions or in understanding the perspectives of others in the climate debate.

The significance of economics to addressing the climate change problem is widely recognized, not only in terms of the contribution economics can make to the debate but also because of the limits of economics. For instance, central to the politics of taking action on climate change are disagreements over the economic costs of action and inaction (i.e., the costs of mitigation and of damage from a changed climate from no mitigation). Within any one country there is great uncertainty regarding (1) the costs of reducing emissions of GHGs, (2) the damage from a change in the climate, and (3) the cost, practicality and effectiveness of adaptation measures, and potentially geoengineering options. Prioritizing action on climate change vs. acting on other significant societal goals is difficult in all countries, but particularly so in developing countries where eradicating poverty and achieving social development are high priorities.

Of course, not all societal concerns and objectives are easily quantified or monetized. Thus economic costs and benefits are not the only input into decision-making about climate change. Many important societal objectives, such as the preservation of traditional values, achieving a just society or providing national security, are not easily examined using economic methods. Furthermore, even if costs and benefits to individuals can be quantified and monetized, using methods of cost-benefit analysis to steer societal action implicitly involves significant ethical assumptions. One goal of this chapter is to make those underlying assumptions clear. In particular, we are explicit about what ethical assumptions must be made in order for cost-benefit analysis to be valid. And conversely, if one is using cost-benefit analysis to support a policy, what ethical assumptions are implicitly being made.

Many readers of this volume will find economic methods including cost-benefit analysis useful and helpful, and we devote space to assessing the practical literature on the economics of climate change. This involves highlighting how climate policy can emerge from a consideration of discounting, mitigation costs, technological change, behaviour and climate damage costs (i.e., costs of impacts from a changed climate). This chapter also provides a framework for categorizing and evaluating climate policies. Many of the issues that are introduced here are taken up in more detail in other chapters of WGIII AR5.

Beyond applications of cost-benefit analysis to climate change, viewing the problem through the lens of economics offers many other insights that can help understand social aspects of climate change. For one, we know that climate system is the global commons. Virtually everyone on earth adds to the load of GHGs, albeit in differing quantifies in different ways. For any individual person or firm, mitigation involves real costs while the benefits of their own mitigation to that person or firm are small and intangible. Thus incentives for individuals or even countries to unilaterally reduce emissions are considerably reduced; free-riding on the actions of others is a dominant strategy. Mitigating GHG emissions is a public good, and thus lack of coordination yields insufficient mitigation. This also explains part of the problem of reaching an agreement among nations to solve the problem.

In contrast, adaptation tends to not suffer from these free-riding problems. Gains from adaptation to climate change (such as changing a crop to one more heat tolerant) tend to be realized to a greater extent by the same parties who are incurring the costs. There may still be externalities involved, but these tend to be more localized and contemporaneous than for GHG mitigation. This is not always the case but it is often suggested that global coordination of adaptation is less crucial than for mitigation from public goods' perspective.

The potential for geoengineering (also known as climate engineering) – for example by injecting soot into the stratosphere to reduce incoming solar radiation – raises its own ethical dilemmas and issues for international cooperation. Although much remains to be learned about geoengineering, it may provide a relatively low-cost backstop option to limit global warming, but with possibly severe environmental side effects. It may be rational for an individual country to undertake climate engineering unilaterally without taking into account the consequences for other countries. The implications for global governance are significant.

There are two types of questions this chapter addresses – normative (what should be done) and positive (how the world works). Questions of ethics are typically normative; questions of economics may be either positive or normative. Positive questions are value-neutral, such as how firms have reacted in the past to cap-and-trade programmes for limiting emissions or how law has, historically, treated responsibility for actions that were not yet known to be harmful. Normative questions involve using economics and ethics to answer questions of what *should* be done, such as what is the appropriate level of mitigation or what is the appropriate burden sharing among countries for current and future mitigation. In making decisions about issues with normative dimensions, it is important to understand the implicit assumptions involved in decision-making. For instance, the notion that maximizing the discounted sum of net aggregate costs and benefits of mitigation provides a non-normative solution to the climate problem is incorrect. Most normative analyses of solutions to the climate problem implicitly involve contestable ethical assumptions.

This chapter does not attempt to answer normative questions, but rather provides policymakers with the tools (concepts, principles, arguments and methods) to make such decisions using their interpretation of their constituents' values. In other words, the chapter is intended as a resource for policymakers and researchers who are grappling with normative questions. The chapter aims to be policy-relevant but not policy-prescriptive.

The next section of the chapter (3.2) provides an introduction to the ethical and socio-economic concepts and principles relevant to climate change that are examined in section 3.3. This section asks how one can value actions that bear on climate change. This includes human values (wellbeing including cultural values) and non-human values. It considers how individual wellbeing can be aggregated to determine social welfare, the overall value of a society. Next, section 3.3 reviews theories of justice, particularly as relevant to climate change. This includes inter-generational and intra-generational justice, the treatment of historical responsibility, and the separate notions of procedural vs. outcome-based justice. Section 3.4 explores the links between ethics and economic analysis, and lays out the role and limits of normative economics in guiding decision-making about climate change. The aggregation of costs and benefits is covered in section 3.5. Section 3.5.1 considers how economic methods can be used to assess costs and benefits to individuals, and how they can be aggregated within a society. Aggregating value across time in particular is further explored in section 3.5.2 with a discussion of discounting future costs and benefits. Section 3.5.3 then introduces the idea of "co-benefits" from climate policy, effects on other economic or social objectives.

In section 3.6 we introduce regulatory mechanisms for achieving mitigation of GHGs. Section 3.7 discusses methods for evaluating regulatory mechanisms for mitigation of GHGs. In section 3.8 we review the measurement of the costs and benefits of mitigation, including developing trade-offs in mitigating different GHGs. Section 3.9 introduces issues of behavioural economics and culture into making decisions about mitigation. In section 3.10 we review what is known about the economics of technological change, including ways of inducing additional change to reduce the costs of mitigating GHG emissions. We conclude (section 3.11) with a discussion of gaps in knowledge and data.

It is no small task to summarize two enormous fields of study (economics and ethics) in relation to climate change in a short chapter. Thus several caveats are in order. We recognize the importance of non-economic societal dimensions of the climate change problem and solutions; however, our mandate is to focus primarily on ethics and economics. Secondly, it should be noted that many of the issues raised here have been addressed in previous IPCC assessments, particularly AR2 (from the mid-1990s). In the past, ethics has received less attention than economics, though parts of both subjects are covered in AR2. The literature reviewed here includes pre-AR4 literature to provide a more comprehensive understanding of the concepts and methods where necessary. However, we highlight what "new" has happened in the field since the last IPCC assessment.

3.2 Ethical and socio-economic concepts and principles

When a country emits GHGs, its emissions cause harm around the globe. The country itself suffers only a part of the harm. Consequently, it is rarely in the interests of a singly country to reduce its own emissions, even though a reduction in global emissions could benefit every country. That is to say, the problem of climate change has elements of a 'prisoner's dilemma' (Gardiner, 2001).[1] A consequence is that effective mitigation of climate change needs to be achieved through some sort of international coordination.

Because of the continuing efforts to reach effective international agreement on mitigation, one of the ethical questions raised by climate change is widely recognized and much debated. This is the question of 'burden-sharing' or 'effort-sharing': how should the burden of mitigating climate change be divided among countries? It raises difficult issues of justice, fairness and rights, all of which lie within the sphere of ethics.

It is only one of the ethical issues that climate change raises.[2] Another is the question of how much overall mitigation there should be. As mentioned in the previous section, what constitutes

[1] A prisoner's dilemma involves strategic interaction among players with cooperation being the best outcome for the players as a group. However when players are making their own decisions without cooperation, it is a dominant strategy for them individually to "defect" from cooperation, resulting in an outcome that is worse than cooperation. Coordination is one way of solving the prisoner's dilemma problem.

[2] A survey of the ethics of climates change is Gardiner (2004), pp. 555-600.

"dangerous anthropogenic interference with the climate system" is a major question for the IPCC. Some natural scientists have suggested limiting the increase in global temperatures to two degrees above the pre-industrial average (Rockstrom et al., 2009; Jaeger and Jaeger, 2010) and this target is commonly adopted in international politics. But natural science cannot by itself answer the question of how much mitigation *should* take place. To answer this question, we must evaluate the effects climate change may have on people and on societies, to judge how bad they might be, and balance these against the costs of emission reduction. This balancing of values, like any other, is ultimately a matter for ethics. Indeed, in one way or another, ethical issues underlie almost every decision that is connected with climate change.

This includes decisions made by individuals in their private lives, by public and private organizations of all sizes, by governments and by groups of governments (the international community). Some of these decisions are deliberately aimed at mitigating climate change or adapting to it. Many others influence the progress of climate change or its impacts, so they need to take climate change into account.

3.2.1 Values and Justice

Decision-making raises two distinct ethical questions: by what process should a decision be made, and what decision should the process arrive at? Both questions need an answer. Even when a process of decision-making is right, those who participate in the process need to judge what outcome is the right one. Moreover, the right decision-making process does not always lead to the right outcome. In a criminal trial, the right process may be careful deliberation by a jury, but even after careful deliberation a jury may convict an innocent person. In its deliberation, the jury needs to judge what would be the right outcome, which in this case is determined by the guilt or innocence of the accused.

Ethics has the task of assessing both processes and decisions. Its criteria for these assessments can be broadly classified into two sorts: criteria of justice and criteria of value. Justice is concerned with ensuring that people get what is *due* to them. If justice requires that a person should be treated in a particular way – not uprooted from her home by climate change, for example – then the person has a *right* to be treated that way. Justice and rights are correlative concepts. On the other hand, criteria of value are concerned with improving the world: making it a better place. Synonyms for 'value' in this context are 'good', 'goodness', and 'benefit'. Antonyms are 'bad', 'harm' and 'cost'.

To see the difference between justice and value, think of a transfer of wealth made by a rich country to a poor one. This may be an act of restitution. For example, it may compensate the poor country for harm that has been done to it by the rich country's emissions of GHG. In this case, the payment is due to the poor country, and it satisfies a right that the poor country possesses. This transfer is justified on grounds of justice. Alternatively, the rich country may make the transfer to support the poor country's mitigation effort, because this is beneficial to people in the poor country and the rich country (and elsewhere). The rich country may not believe the poor country has a right to the support, but make the payment simply because it does *good*. This transfer is justified on grounds of value.

The division between justice and value is contested within moral philosophy, and so is the nature of the interaction between the two. Some authors treat justice as inviolable, so it operates as a 'side-constraint' on our actions (Nozick, 1974): justice sets limits and we can promote value only within those limits. An opposite view – dubbed 'teleological' by John Rawls (Rawls, 1971) –- is that the right decision is always determined by the value of the alternatives, so no criterion of justice is separate from value. But despite the complexity of their relationship and the controversies it raises, the concepts of justice and value provide a useful basis for organizing the discussion of ethical concepts and principles. We have adopted it in this chapter: section 3.2 covers value; section 3.3 covers justice.

Figure 3.2.1 illustrates the connection among many of the issues in justice and value that are considered here.

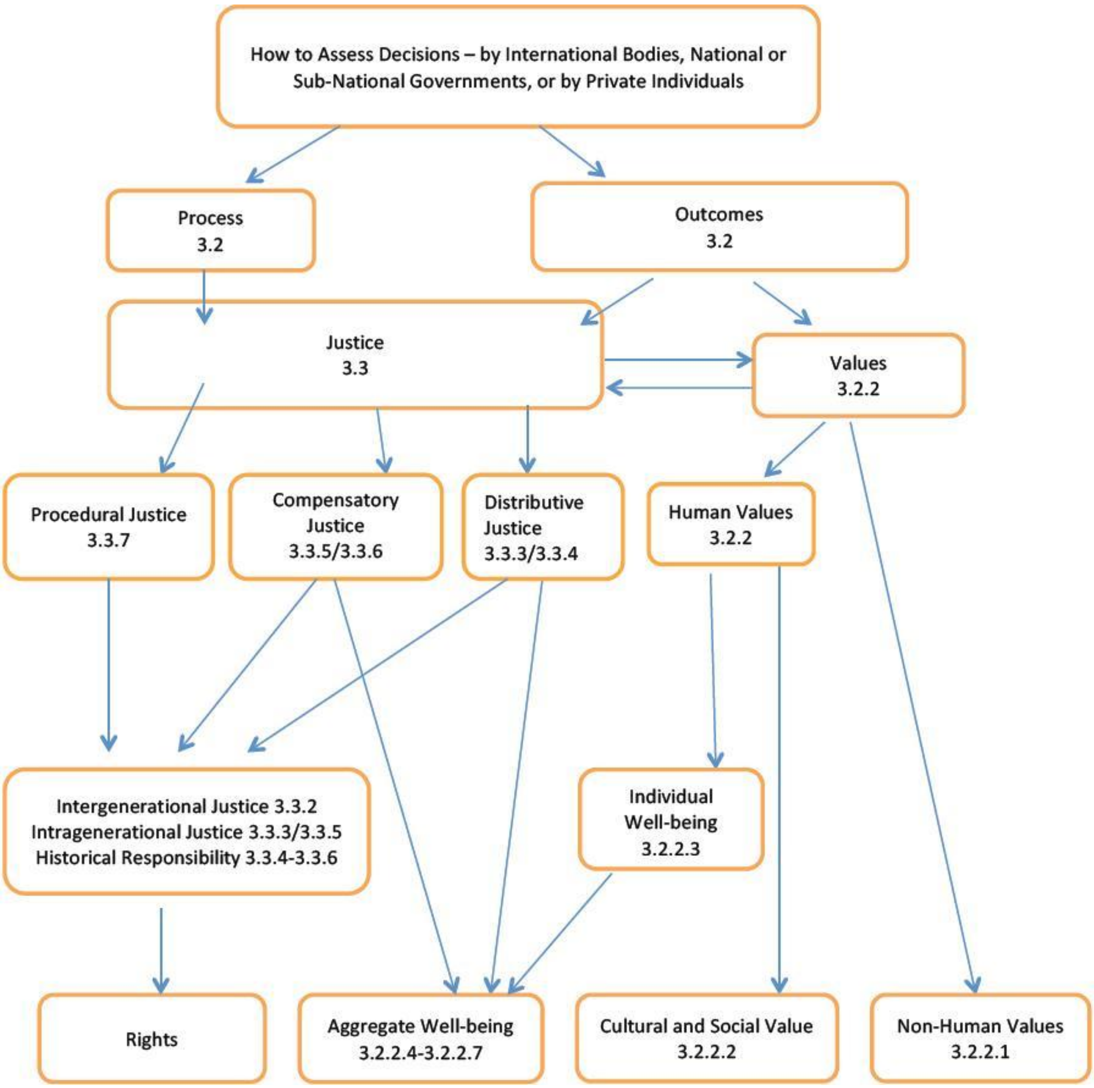

Figure 3.2.1. Justice and Value in Chapter 3

Issues of justice are involved in the distribution of costs and benefits between different generations and also among people and nations at a single time. The question of historical responsibility for climate change is important among them. These issues occupy sections 3.3.1 to 3.3.5. Section 3.3.6 considers how far legal thought can contribute to our understanding of historical responsibility. The ethical assessment of decision-making processes (as opposed to outcomes) is treated in section 3.3.7.

Many different sorts of value are affected by climate change. This section mentions some of them. They include cultural and social values, the wellbeing of animals and, according to many authors, an intrinsic value possessed by nature. Most of section 3.2.2 concentrates on one particular value: human wellbeing. This is an important value, but we do not mean to suggest it is the only one. Those sections outline some accounts of what wellbeing is and how it may be measured. They also consider how the wellbeing of different people may sometimes be aggregated through a 'value function' or 'social welfare function' to determine an overall value for a society.

Section 3.4 is a bridge between the ethical dimensions of the chapter and economic concepts and methods. In particular, the section examines some of the ethical foundations which underlie normative economic analysis, primarily cost-benefit analysis.

Values also enter into the policy-making process. The practical methods for reflecting different values in making decisions about policies are discussed in section 3.7.1.

Box 3.2.1. The private ethics of climate change.

Reports of the IPCC are addressed to governments, and the ethics considered in this chapter is primarily public ethics. However, since private individuals often take climate change into account in their decision-making, this box outlines some issues within the private ethics of climate change.

First, many individuals have a civic duty to influence their governments and support them when they act rightly. Voting is one influence they have, among others (for instance, voluntarily recycling trash). A climate change example would be reducing one's carbon footprint or voluntarily buying carbon offsets. By reducing her carbon footprint, a person can demonstrate that she is willing to make sacrifices in order to reduce emissions, which may induce others to follow suit and may encourage her government to take more effective action (Kutz, 2002; Vanderheiden, 2008).

Second, since emissions of GHG do harm, it seems that an individual does harm to others by her own emissions. Harming others for one's own benefit is unjust except in certain special circumstances. Should such emissions be unjust, then it may be argued that each individual has an ethical duty not to emit GHG (Broome, 2012).

Some philosophers deny that an individual's emissions always do harm (for instance, (Jamieson, 2007); for an opposite view see (Hiller, 2011). Indeed, even after a pollutant has been strictly regulated, typically emissions still occur and most economists would argue that such Pareto-irrelevant externalities are justified.[3] Nevertheless, even if that is so, it may still be argued that each individual has a moral duty to play a part in a collective effort to reduce emissions (Jamieson, 2007; Meyer and Sanklecha, 2011; Sandberg, 2011).

3.2.2 Values and wellbeing

Since values are not the only criteria for assessment, if an action will increase value overall, it by no means follows that it should be done. Many actions benefit some people at the cost of harming others. This raises a question of justice even if the benefits in total exceed the costs. Whereas a cost to a person can be compensated for by a benefit to that same person, a cost to a person cannot be compensated for by a benefit to someone else. To suppose it can is not to 'take seriously the distinction between persons', as John Rawls puts it (Rawls, 1971, p. 27). Harming a person may infringe her rights, or it may be unfair to her. For example, when a nation's economic activities emit GHG, they may benefit the nation itself, but they harm people in other nations. Even if the benefits are greater in value than the harms, the activities may infringe other nations' rights. Other nations may therefore be entitled to object to them on grounds of justice.

Any decision is likely to promote some values and damage others, and these values may be of very different sorts. To assess a decision properly, each value must be taken into account. Different values must therefore be weighed or balanced against each other. Some pairs of values differ so radically that they cannot be determinately weighed together. For example, it may be impossible to weigh the value of preserving a traditional culture against the material income of the people whose culture it is, or to weigh the value of biodiversity against human wellbeing. Some economists claim that one person's wellbeing cannot be weighed against another's (Robbins, 1937; Arrow, 1963). When values cannot be determinately weighed, they are said to be 'incommensurable' (Chang,

[3] A Pareto-irrelevant externality is the externality (e.g., GHGs) that still exist after the emissions have been fully and satisfactorily regulated and reduced to a Pareto-optimal level (see, for example, (Baumol and Oates, 1988; Kolstad, 2010).

1997). If a decision among options involves incommensurable values, it may turn out that none of the options is determinately the best. In such a case, the assessment of the decision may have to fall back on an assessment of the merits of the decision-making *process*, which are examined in section 3.3.7 .

An additional distinction we will make is between value for an individual human being vs. value for a group of people (such as a society or nation). For an individual the word 'wellbeing' refers to how well she is. Sections 3.2.2.4 ("Aggregation of Wellbeing") and 3.2.2.6 ("Social Welfare Functions") consider how well off is a society as a whole.

3.2.2.1 Non-human values

Nature provides great benefits to human beings, in ways that range from absorbing our waste − including GHGs − to beautifying the world we inhabit. Beyond this, an increasing number of philosophers have argued in recent years that benefit to human beings is not the only value nature possesses (Leopold, 1949; Palmer, 2011). They have argued that we should recognize animal value (zoocentric ethics), the value of life itself (biocentric ethics) and even the value of natural systems and nature itself (ecocentric ethics).

If animals, plants, species and ecosystems do have value in their own right, then the moral impact of climate change cannot be gauged by its effects on human beings alone. Moreover, its other moral impacts may spread far beyond present and future generations of people. The effects of climate change on species numbers, biodiversity and ecosystems may persist for a very long time, perhaps even longer than the lifetime of the human species (Nolt, 2011).

In moral theory, rational adult humans, who are self-conscious subjects of a life, are often taken (following Kant, 1956)) to have a kind of unconditional moral worth – sometimes called "dignity" – that is not found elsewhere on earth. Others believe that moral worth can be found elsewhere (Dryzek, 1997). For example many human beings themselves lack rationality or subjectivity, yet still have moral worth. The very young and the very old, not to mention people with various kinds of impairment, are among them. If this is accepted, then why deny worth to those animals that are to at least some extent subjects of a life, who show emotional sophistication (Regan, 2004), and who experience pleasure, pain, suffering, and joy (Singer, 1993)?

An argument for recognizing value in plants as well as animals was proposed by Richard Routley (1973). Routley gives the name 'human chauvinism' to the view that humans are the sole possessors of intrinsic value. He asks us to imagine that the last man on earth sets out to destroy every living thing, animal or plant. Most people believe these actions would be wrong, but human chauvinists are unable to explain why. Human chauvinism appears to be simply a prejudice in favour of the human species (Routley and Routley, 1980). By contrast, some philosophers argue that value exists in the lives of all organisms, to the extent that they have the capacity to flourish (Taylor, 1986; Agar, 2001).

Extending this argument, other philosophers have argued that biological communities and holistic ecological entities also have value in their own right. Some have argued that a special has more value than all of its individuals have together, and that an ecosystem has still more value (Rolston, 1988, 1999); compare discussion in (Brennan and Lo, 2010). It has further been proposed that just as domination of one human group by another human group is a moral evil, showing disrespect for the value of others, then so is the domination of nature by humans in general. If nature and its systems have moral worth, then the domination of nature is also a kind of disrespect (Jamieson, 2010).

If these claims about the value of nature are correct, and if climate change leads to the loss of environmental diversity, the extinction of plant and animal species, and the suffering of animal populations, then it will cause large harms beyond those it does to human beings.

It is very difficult to measure these harms in a way that makes them commensurate with human values. They cannot be measured by economic techniques, which are designed to measure costs and benefits to human beings (see Section 3.5.1). True, people are willing to pay for preserving features of nature even if they expect no benefit to themselves from them (Aldred, 1994). But when a good is not a benefit to people, we have no reason to think that an aggregate of people's willingnesses to pay for it is a measure of its value (Broome, 2009).

3.2.2.2 Cultural and social values

It is a great benefit to a person to live in a flourishing culture and society. Some authors claim that cultures and societies may also have value in their own right, over and above the benefits they bring to people (Taylor, 1995).

The degree of equality in a society may be treated as a value that belongs to a society as a whole, rather than to any of the individuals that make it up. Various measures of this value are available, including the Gini coefficient and the Atkinson measure (Gini, 1912; Atkinson, 1970); for an assessment see (Sen, 1973). Section 3.2.2.6 explains that the value of equality can alternatively be treated, not as a separate social value, but as a feature of the aggregation of individual people's wellbeing.

Climate change threatens damage to cultural artefacts and to cultures themselves. Evidence suggests that it is already damaging the culture of Arctic indigenous peoples (Ford et al., 2006, 2008; Crate, 2008). Cultural values and indigenous peoples are discussed in section 3.9.2.

3.2.2.3 Wellbeing

Human wellbeing is one important value that needs to be taken into account in decision-making. We mean 'wellbeing' to include everything that is good or bad for a person, and makes her life go well or badly. But what things are those? — what constitutes a person's wellbeing? This question has been the subject of an extensive literature since ancient times.[4] One view is that a person's wellbeing is the satisfaction of her preferences. Another is that it consists in good feelings such as pleasure. A third view is that wellbeing consists in possessing the ordinary goods things of life such as health, wealth, a long life, participating well in a good community, and so on. The 'capabilities approach' in economics Sen (1999) embodies this last view. It treats the good things of life as 'functionings' and 'capabilities' – things that a person does and things that she has a real opportunity of doing, such as living to old age, having a good job, having freedom of choice, and so on.

A person's wellbeing will be affected by many of the other values that are mentioned above, and by many of the considerations of justice mentioned in section 3.3. It is bad for a person to have her rights infringed or to be treated unfairly, and it is good for a person to live within a healthy culture and society, surrounded by flourishing nature.

Box 3.2.2. Wellbeing, Utility and Economics

The term wellbeing – or utility – has two meanings in economics. In one meaning, as used in the text here, it connotes the condition of an individual, whether assessed by the individual himself or by others. The other meaning is associated with the term "utility function," which relates preferences to behaviour. If a person prefers A to B, this is equivalent to saying that A has a higher utility for him than B, which in turn is equivalent to saying that (other things being equal) he would choose A over B. In this connotation, preferences are a disposition to take particular actions. They are a building block in the economic theory of choice.[5]

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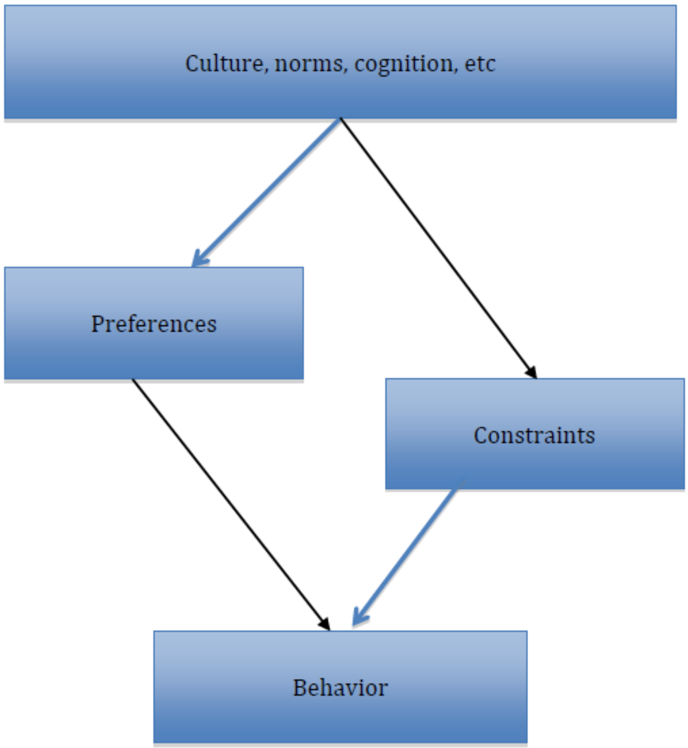
[4] For example: Aristotle, *Nicomachean Ethics*. Recent work includes: (Griffin, 1986; Sumner, 1996; Kraut, 2007)

[5] The two meanings may conflict; thus, an individual may concede that some of things he prefers are bad for him and reduce his wellbeing.

In this theory, a decision maker faces a choice among some alternatives (the choice set). He evaluates the alternatives based on certain considerations (attributes), which are compared, weighted and aggregated through the utility function. The decision may also be constrained by a limited budget or other restrictions. The evaluation in the utility function and/or the constraints may be influenced by norms, expectations, culture, and social context, as well as by the availability of information and by cognitive factors such as salience etc. The decision maker chooses the alternative which maximizes his utility subject to whatever constraints apply. This choice process is illustrated in the following diagram.



As noted in section 3.9, neoclassical economic theory adopts a somewhat narrow view of preferences, assumes those do not change over time, and de-emphasizes culture and cognition. Behavioural economics employs richer formulations of preferences, acknowledges cognitive factors, and allows for purposive behaviour short of utility maximization.

Various concrete measures of wellbeing are in use (Fleurbaey, 2009; Stiglitz et al., 2009). Each reflects a particular view about what wellbeing consists in. For example, many measures of 'subjective wellbeing' (Oswald and Wu, 2010; Kahneman and Deaton, 2010) assume that wellbeing consists in good feelings. Monetary measures of wellbeing, which are considered in section 3.5, assume that wellbeing consists in the satisfaction of preferences.

Other measures assume wellbeing consists in possessing a number of specific good things. The Human Development Index (HDI) is intended to be an approximate measure of wellbeing understood as capabilities and functionings (UNDP, 2010). It is based on three components: life expectancy, education, and income. The capabilities approach has inspired other measure of wellbeing too (Dervis and Klugman, 2011). In the context of climate change, many different metrics of value are intended to measure particular components of wellbeing: among them are the number of people at risk from hunger, infectious disease, coastal flooding, or water scarcity. They may be combined to create a more general measure. Schneider et al. (2000) advocates the use of a suite of five metrics: (1) monetary loss, (2) loss of life, (3) quality of life (including coercion to migrate, conflict over resources, cultural diversity, loss of cultural heritage sites, etc.), (4) species or biodiversity loss, and (5) distribution and equity.

3.2.2.4 Aggregation of wellbeing

Whatever wellbeing consists in, we may ask how it may be aggregated. How does the wellbeing of different individuals combine to make up an overall value for a society as a whole?

Assume that each person has a level of wellbeing at each time she is alive, and call this her *temporal wellbeing* at that time. Taking a society together, temporal wellbeing is distributed across times and across the people in the population. When a choice is to be made, each of the options leads to a particular distribution of temporal wellbeing. A stylized choice between two options is shown in Figure 3.2.2.

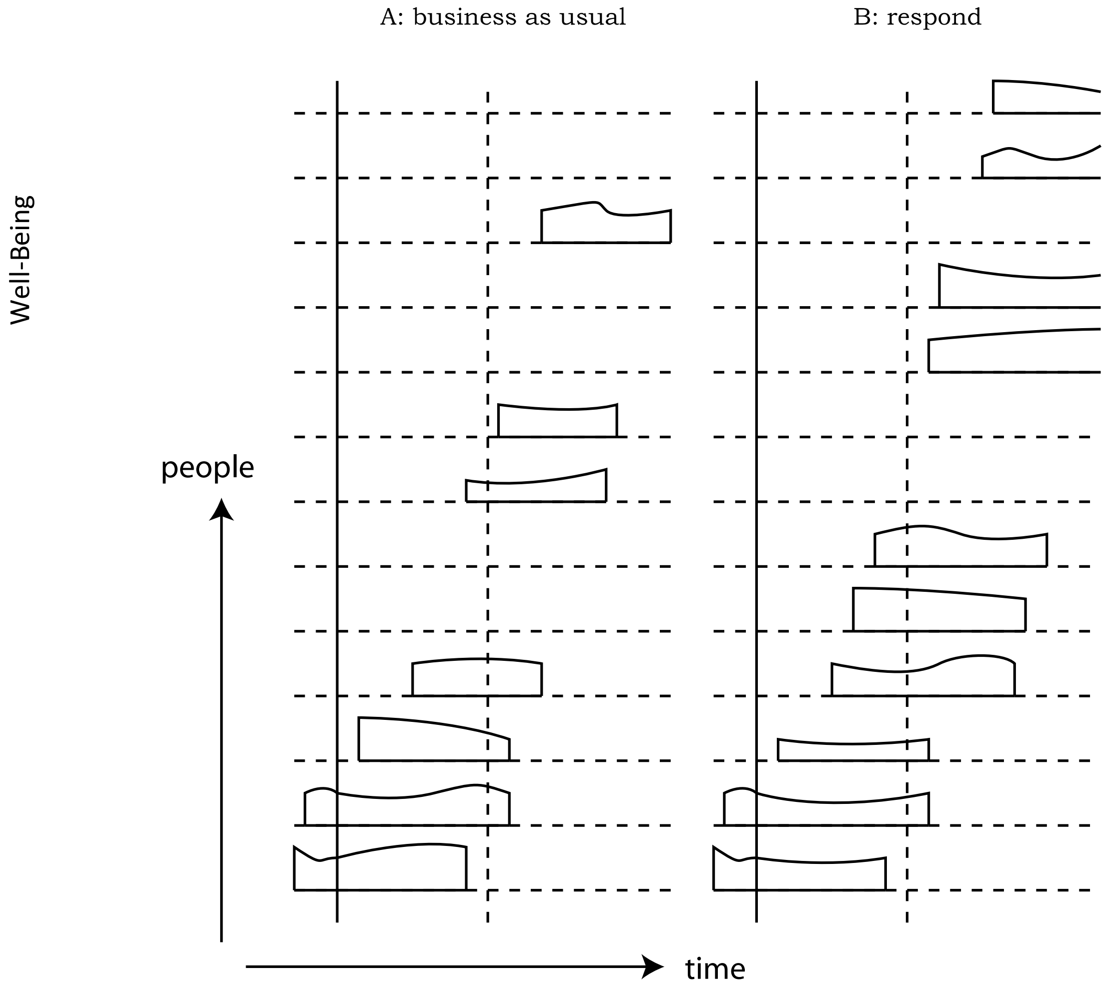


Figure 3.2.2. Comparing two distributions of wellbeing: The diagram illustrates in stylized fashion the choice between business as usual and responding to climate change. Each half of the diagram shows the distribution that will result from one of these two options. Time is measured horizontally. A vertical solid line in each half of the diagram marks the present and a vertical dotted line marks some future time. Each horizontal pair of dotted lines displays the life and wellbeing of one particular person. The little graph on the person's line within one of the options shows the time when her life begins and when it ends, and the height of the graph shows her temporal wellbeing at each time she is alive. If the person does not live at all in one of the options, then she has no graph on her line there. The distributions are arbitrarily drawn for the purpose of illustrating some typical features of decisions about climate change. They illustrate the non-identity effect: the people who live in the further future under the option of business as usual are different individuals from those who live under the option of respond.

The diagram makes the implicit assumption that each person's temporal wellbeing, at every time she is alive, is measurable by a number. It assumes moreover that the measurement is on a ratio scale (a cardinal scale in which significance is attached to the zero of wellbeing), which is intertemporally comparable. These are strong assumptions. Accounts are available of how in principle they may be satisfied (e.g., see Drèze and Stern, 1987; Broome, 2004, pp. 78–103; Oswald and Wu, 2010), but nevertheless serious objections remain. In particular, different components of a person's wellbeing – social relationships versus the pleasure of eating, for example – seem plausibly to be incommensurable in value.

We need to assess the value of distributions of wellbeing like this. Doing so involves aggregating temporal wellbeings across each distribution to arrive at an overall, social value for the distribution. The diagram illustrates some of the special problems of aggregation that are raised by climate change. In the option *respond,* people living in the further future have greater temporal wellbeing and live longer lives than they do in *business as usual*, but *respond* involves some sacrifices of temporal wellbeing in the near future. Another feature is that the choice between the options affects the population of people who live in the future.

3.2.2.5 Lifetime wellbeing functions

Let us assume that each person's temporal wellbeings can be aggregated to determine a *lifetime wellbeing* for the person, and that the social value of the distribution depends only on these lifetime wellbeings. This is the assumption that each person's wellbeing is *separable*, to use a technical term. It allows us to split aggregation into two steps. First, we aggregate each person's temporal wellbeings across the times in her life to determine her lifetime wellbeing. For this we need to specify *lifetime wellbeing functions*, which express each person's lifetime wellbeing as a function of her temporal wellbeings. Second, we aggregate lifetime wellbeings across people to determine the social value of the distribution. For this we need to specify a social value function – often known as a *social welfare function* – which expresses the social value of a distribution as a function of the people's lifetime wellbeings.

It seems reasonable to assume that each person's lifetime wellbeing function has the same form. This form is not much constrained by theory, and in the literature it has generally been left to intuition. Many different forms have been proposed. [6]

The most straightforward makes a person's lifetime wellbeing simply the total of her temporal wellbeings at each time she is alive. If a person's wellbeing depended only on the state of her health, this formula would be equivalent to *qalys* or *dalys* (quality-adjusted life years or disability-adjusted life years), which are commonly used in the analysis of public health (Murray, 1994; Sassi, 2006). They take a person's lifetime wellbeing to be the total number of years she lives, adjusted for her health in each year. Since wellbeing actually does not depend on health only, qalys or dalys provide at best a rough approximation to a lifetime wellbeing function. If they are aggregated across people by simple addition, this is to assume implicitly that a year of healthy life is equally as valuable to one person as it is to every other. That may or may not be an acceptable approximation for the broad evaluation of climate-change impacts and policies, especially for evaluating their effects on health (Nord et al., 1999); but also see (Currie et al., 2008).

Other authors take lifetime wellbeing to depend on the 'shape' of a life. It is sometimes said that, for a given total of temporal wellbeing, a life that improves over time is better than one that declines (Velleman, 1991). This view is supported by the idea of consumption habit formation (see for example (Campbell and Cochrane, 1999). An opposite view discounts later times, which means that, for a given total of temporal wellbeing, a life that declines over time is better than one that improves (Kaplow et al., 2010).

[6] For two practical examples, Fullerton and Rogers (1993) and Altig et al. (2001) use computer models to calculate lifetime wellbeing for twelve different groups ranging from low lifetime income to high lifetime income. They measure effects of taxes on each lifetime income group.

3.2.2.6 Social welfare functions

Up to this point we primarily have been discussing the wellbeing of individuals. But policy decisions typically involve an appreciation of the welfare of society as a whole. This is the classic problem of social choice: if we know how a policy affects the wellbeing of individuals, do we have a way of determining of the policy affects the welfare of society? (see Sen, 1970).

Some (perhaps most) economists have claimed that interpersonal comparisons of wellbeing are impossible.[7] If they are right, the wellbeings of different people are incommensurable and cannot be aggregated. This sceptical view leads to the Paretian approach to valuation, which is considered in section 3.5.1.3 .

In this section we set it aside, and assume that temporal wellbeings are measured in a way that is comparable across people.[8] This allows us to proceed to the second step of aggregation, which is to aggregate different people's lifetime wellbeings through a social welfare function, to arrive at social value or 'social welfare'.[9]

We shall first consider social welfare functions under the simplifying but unrealistic assumption that the decisions that are to be made do not affect how many people exist or which people exist: all the options contain the same people.

A theorem of Harsanyi's (1955) gives some grounds for thinking that, given this assumption, the social welfare function is *additively separable* between people. This means it has the form:

Equation 3.2.1. $$V = v_1(w_1) + v_2(w_2) + \ldots + v_I(w_I).$$

Here w_i is person *i*'s lifetime wellbeing. This formula says that each person's wellbeing can be assigned a value $v_i(w_i)$, and all these values – one for each person – are added up to determine the social value of the distribution.

The proof of Harsanyi's Theorem assumes that the social welfare function is defined, not just on distributions of wellbeing like the ones illustrated in Figure 3.2.2, but on uncertain prospects of these distributions. It assumes that the function satisfies the axioms of expected utility theory (see Chapter 2). It also assumes that it is Paretian: if one prospect is better for someone than another, and worse for no one, then it is has greater social welfare. These assumptions are plausible, but they can be challenged (Diamond, 1967; Broome, 2004 ch. 6-11; Fleurbaey, 2010). So, although the additively separable form is commonly assumed in cost-benefit analysis, it is not entirely secure. In particular, this form makes it impossible to give any value to equality except indirectly through prioritarianism, which is introduced in section 3.3.2 and is defined below. The value of inequality cannot be given by the Gini coefficient, for example, since this measure is not additively separable (Sen, 1973).

It is often assumed that the functions $v_i()$ all have the same form, which means that each person's wellbeing is valued in the same way. Alternatively, the wellbeing of people who live later is sometimes discounted relative to the wellbeing of people who live earlier; this implies that the functional form of $v_i()$ varies according to the date when people live. Discounting of later wellbeing is often called *pure* discounting. It is discussed in section 3.5.2 .

[7] Examples are: Robbins (1937), Archibald (1959), Arrow (1963, p. 9). A survey and discussion of this sceptical view appears in Hammond (1993).

[8] Potential bases of interpersonal comparisons are examined in: Fleurbaey and Hammond, (2004); Sen,(1982, pp. 264–281); Elster and Roemer,(1993); Broome, (2004 section 5.3); Arrow, (1977), Adler (2011), pp. 185-201).

[9] A recent major study is Adler (2011).

Even if we take for granted an additively separable form, different ethical theories imply different social welfare functions. *Utilitarianism* values only the total of people's wellbeing. Its social welfare function is

Equation 3.2.2. $V = w_1 + w_2 + \ldots + w_I$

Utilitarianism gives no value to equality in the distribution of wellbeing: a given total of wellbeing has the same value however unequally it is distributed among the people.

But the idea of distributive justice mentioned in section 3.3.3 suggests that equality does have value. That view can be incorporated into a social welfare function. One way is through *Prioritarianism*, which has the social welfare function

Equation 3.2.3. $V = v(w_1) + v(w_2) + \ldots + v(w_I)$

where the function *v*() is *increasing* and *strictly concave*. This means that the graph of *v*() has an upward slope but a downward curvature. (Section 3.5.1.2 explains that a person's wellbeing w_i is commonly assumed to be a strictly concave function of her consumption, but this is a different point.) A prioritarian function values each person's wellbeing in the same way. However, improving a person's wellbeing contributes more to social welfare if the person is badly off than if she is well off. The slogan of prioritarianism is 'priority to the worse off'. It indirectly gives value to equality in the distribution of wellbeing: it implies that a given total of wellbeing is more valuable the more equally it is distributed (Sen, 1973; Weirich, 1983; Parfit, 1997). In judgements about climate change, a prioritarian function will give relatively more importance to the interests of poorer countries. This is illustrated in Figure 3.2.3 with two people, one rich and one poor. An equal increase in personal wellbeing is shown to have dramatically different implications for social value.

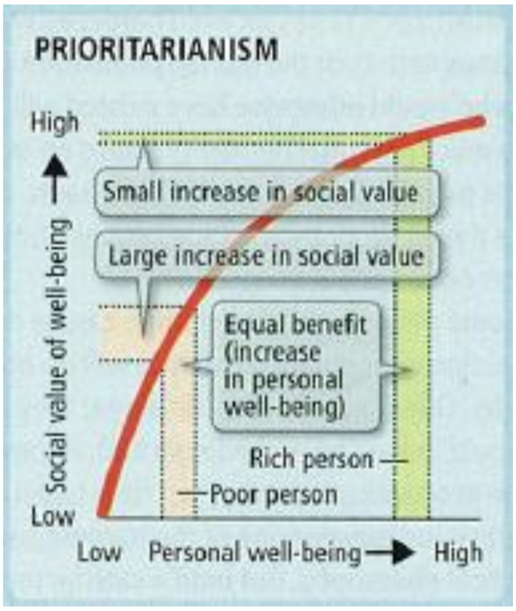


Figure 3.2.3. The Prioritarian View of Social Welfare. The figure compares the social implications of similar increases in well-being for a rich person and a poor person. (Source: Broome, 2008)

3.2.2.7 Valuing population

We next need to evaluate changes in population. Climate change can be expected to have a major impact on the world's human population. With a small probability, severe climate change might lead to a catastrophic collapse of the population (Weitzman, 2009), and even to the extinction of human beings. Valuations of the impact of climate change and of policies to mitigate climate change therefore need to take changes in population into account.

The utilitarian and prioritarian social welfare functions for a fixed population may be extended in a variety of ways to a variable population. For example, the utilitarian function may be extended to *average utilitarianism* (Hurka, 1982), whose social welfare function is the average of people's wellbeing. It gives no value to increasing numbers of people. The implicit or explicit goal of a great deal of policy-making is to promote per capita wellbeing (Hardin, 1968). This is to adopt average utilitarianism. This goal tends to favour anti-natalist policies, aimed at limiting population. It would strongly favour population control as a means of mitigating climate change, and it would not take a collapse of population to be, in itself, a bad thing.

The utilitarian function may alternatively be extended to *critical-level utilitarianism*, whose social welfare function is the total of the amount by which each person's wellbeing exceeds some fixed critical level. It is

Equation 3.2.4. $$V = (w_1 - c) + (w_2 - c) + \ldots + (w_J - c)$$

where *c* is the critical level (Broome, 2004; Blackorby et al., 2005 ch. 10). Other things being equal, critical-level utilitarianism favours adding people to the population if their wellbeing is above the critical level.

Total utilitarianism (Sidgwick, 1907, pp. 414–416) is critical-level utilitarianism with the critical level set to zero. Its social welfare function is the total of people's wellbeing. Total utilitarianism is implicit in many integrated assessment models of climate change (e.g., Nordhaus, 2008). Its meaning is indeterminate until it is settled which level of lifetime wellbeing is counted as zero. Many total utilitarians set this zero at the level of a life that has no good or bad experiences – that is lived in a coma throughout, for instance (Arrhenius, 2011 section 2.2.3 and 2.2.4). Since people on average lead better lives than this, total utilitarianism with this zero tends to be less anti-natalist than average utilitarianism.

However, it does not necessarily favour increasing population. Each new person damages the wellbeing of many existing people, through her emissions of GHG (and the demands she makes on Earth's other limited resources) and the emissions of her progeny. If the damage an average person does to others in total exceeds her own wellbeing, total utilitarianism, like average utilitarianism, favours population control as a means of mitigating climate change.[10]

Each of the existing ethical theories about the value of population has intuitively unattractive implications (Parfit, 1986 part 4). Average utilitarianism is subject to particularly severe objections. Arrhenius (2011) crystallizes the problems of population ethics in the form of impossibility theorems. So far no consensus has emerged about the value of population. Yet climate-change policies are very likely to affect the size of the world's population, and different theories of value imply very different conclusions about the value of these policies. This is a serious difficulty for evaluating policies aimed at mitigating climate change, which has largely been ignored in the literature.

3.3 Justice, equity and responsibility

Justice and fairness are important issues in international climate negotiations, as well as in climate-related political decision-making within countries and even for individuals.

In this section we review and assess what the literature has to say regarding justice, equity and responsibility. We consider distributive justice, which for the purpose of this review is taken to be concerned with outcomes, and procedural justice, which is concerned with the way in which outcomes are brought about. We also discuss compensation for damages and historic responsibility for harms. In the context of climate change, considerations of justice, equity and responsibility concern the relations between individuals as well as groups of individuals (e.g., countries), both at a

[10] Harford (1998) shows that an additional person causes damage from her own emissions and the emissions of her children (and of their children, etc.). Kelly and Kolstad (2001) examine this issue in the specific context of climate change.

single point in time and across time. Accordingly we distinguish intra- and inter- as well as transgenerational justice.

An important caveat to this discussion is that the literature reflects no agreement on a correct answer as to what is just. We try to indicate where opinions differ in the literature. As with everything in the IPCC, the review of the literature in this section is intended to be policy relevant but not policy prescriptive.

3.3.1 Causal and moral responsibility

People gain numerous benefits from engaging in activities that have emissions as their side-effect. Much of the climate change that is caused by these emissions materializes long after the gas is emitted. Even though industrialization in the developed world is causally responsible for a large part of the build-up in GHGs (Den Elzen et al., 2005; Lamarque et al., 2010; Höhne et al., 2011), developing countries will likely suffer disproportionally more from climate change (IPCC, 2007 WG II AR4 SPM). Though some developed countries will have high or very high monetary damages as a result of climate change there is a significant asymmetry: on the one hand, the highly industrialized countries have the main causal responsibility – in part owing to their past emissions – for climate change, and relatively modest physical damages and even some benefits from future climate change. On the other hand, many developing countries have comparatively little causal responsibility, but are expected to suffer significant physical damages from climate change and partly owing to this are at greater risk of violations of their basic rights. This asymmetry suggests that we distinguish between the following questions of justice and moral responsibility: Do considerations of justice provide guidance in determining the appropriate (1) level of present emissions on a global scale, (2) distribution of emissions among those presently living, and (3) role of historical emissions in distributing global obligations? A further question is: who might be considered morally responsible for achieving justice, and thus could be considered a bearer of duties towards others? The question of moral responsibility is also of central importance in answering the question of who owes compensation for damages that are caused by emissions.

A separate issue is how decisions should be taken in the political realm. This is the subject of procedural justice (sec. 3.3.7).

3.3.2 Inter- and trans-generational justice and rights of future people

Intergenerational justice involves what currently living people owe to future people and what past people owed to us.[11] (Rawls, 1971, 1999, sec. 44, 2001, sec. 49.2 and 3; Barry, 1977; Sikora and Barry, 1978; Partridge, 1981; Parfit, 1984, pt. IV; Birnbacher, 1988; Heyd, 1992). This reflects a broad understanding of justice, according to which justice considerations apply to intergenerational relations if future or past generations can be viewed as holding legitimate claims or rights against present generations, who in turn have corresponding duties to future or past generations. It has been observed that considerations based on the rights of future people cannot or cannot fully account for all the concerns we might have for future or past people (Baier, 1981; De-Shalit, 1995, chap. 1; Meyer, 2005, chap. 4 and 5).

One question of intergenerational justice concerns the duties of present generations towards future generations in view of the fact that present emissions affect the quality of life of future generations. Some justice theorists have offered the following argument for a cap on emissions (Shue, 1993, 1999; Caney, 2006a; Meyer and Roser, 2009; Wolf, 2009): (1) future people's basic rights include

[11] In the philosophical literature, "justice between generations" typically refers to the relations between people whose lifetimes do not overlap (Barry, 1977, pp. 243–244). In contrast, "justice between age groups" refers to the relations of people whose lifetimes do overlap (Laslett and Fishkin, 1992). See also Gardiner (2011), 145-48.

rights to survival, health, and subsistence; (2) these basic rights – often understood as a subset of the general and universal moral rights whose protection is owed to all by all, i.e. as a subset of human rights – are very likely to be violated when temperatures rise above a certain level; (3) currently living people can slow the rise in temperature by limiting their emissions, and they can do so at reasonable costs to themselves; thus, (4) a reduction in emissions is required for currently living people to fulfil their minimal duties of justice to future generations. In imposing a global emission reduction, currently living people will help to ensure that future people will be able to realize their basic rights. What sort of life is sufficiently good is a matter of dispute among normative theorists (Page, 2007; Huseby, 2010). It is also a matter of dispute when an imposition of harm on future people is wrongful. For instance, it has been said that currently living people wrongfully harm future people if they cause future people to realize a much lower level of well-being than they enjoy themselves (Barry, 1999). However, future generations might not be worse-off than current generations, even with climate change. They may be better-off, due to improvements in technology and investments in capital.

This line of reasoning is open to objection, since it presupposes both that present people can violate the rights of future people, and that the protection of future persons' rights is practically relevant for how present people ought to act.

Some theorists claim that future people cannot hold rights against present people owing to special features of intergenerational relations, among them that future people cannot have rights because they cannot exercise them today (Steiner, 1983), and that mutual interaction between non-contemporaries is impossible. However, some justice theorists argue that the duty of justice not to violate other people's basic rights exists even if the bearer of the right is able neither to exercise it nor to interact mutually with the bearer of the duty (Barry, 1989, p. 189; Buchanan, 2004 Part one) since rights are being attributed to beings who have interests whose protection or realization is important enough to justify imposing duties on others.

The main source of skepticism concerning the very possibility of future people having rights vis-à-vis those currently living rests upon currently living people making choices that affect the identity and number of future people. On the genetic identity view of personal identity, any action that affects people's reproductive choices, directly or indirectly, will have an effect on the genetic identity of future people. Many of our actions in fact have an indirect effect on when future people will be conceived. If we decide between two long-term policies regarding how to respond to climate change, for example, we know that depending on which we choose, different (and most likely also a different number of) future people will come into existence. In these choices people are created who would not have existed had we taken an alternative choice. The so-called non-identity problem (Parfit, 1984, 2011; Heyd, 1992) raised by these cases is whether an action can be said to harm (or benefit) any particular person, and consequently whether a particular person can complain of having been harmed (for example, of his or her rights being violated), when the actions do not make him or her worse off than he or she otherwise would have been because he or she would never have come into existence had currently living people chosen to do something other than conceive him or her.

Four main responses can be made to the 'Non-Identity-Problem' so understood: First, some philosophers hold the view that future people whose existence depends upon currently living people's actions cannot have rights vis-à-vis the current people's actions (see Schwartz, 1978; Heyd, 1992). Accordingly, possible future people have no rights claims against currently living people and currently living people's actions are not constrained by considerations of intergenerational justice. Second, others argue that currently living people can violate the rights of future people even if the former cannot harm the latter (Kumar, 2003). Thus intergenerational justice could not concern the distribution of claims to welfare over generations. Third, some theorists attempt to limit the practical significance of the non-identity-problem by limiting the relevant actions to those that are not only likely but indeed necessary conditions of the existence of the concerned person (Roberts, 1998), secs. 3.4 and 3.5). Finally, some have sought to circumvent the non-identity problem by claiming that people are harmed by any action that causes their quality of life to be below a certain threshold, with this threshold often being defined in terms of a set of basic or human rights (McMahan, 1998; Shiffrin, 1999; Meyer, 2003; Harman, 2004; Reiman, 2007; Shue, 2010).

Assuming that currently living people stand under the duty to protect future people's basic rights, the uncertainty of the consequences of currently living people's actions on future people raises a complication for the specification of their duties. Currently living people's actions or omissions do not violate future people's rights for certain, but rather impose on them the risk of their rights being violated (either with known or unknown probabilities) (Bell, 2011). For the specification of what currently living people owe future people one has to weigh such uncertain or probabilistic consequences against other certain or very likely consequences of these actions, in particular but not exclusively the violations of rights of currently living people (Oberdiek, 2012; Temkin, 2012). This is an important issue for the assessment of many long-term policies and is a central concern with geoengineering measures (Crutzen, 2006; Schneider, 2008a; Victor et al., 2009; Baer, 2010; Ott, 2012) (see section 3.3.8).

3.3.3 Intragenerational justice: distributive justice

As one example, suppose an intergenerationally just global emissions ceiling has been determined. Then the question arises of how the ceiling ought to be divided among states (and, ultimately, their individual members) (Jamieson, 2001; Singer, 2002; Meyer and Roser, 2006; Caney, 2006a). Distributing emission permits is one means for arriving at a globally just distribution of benefits from emission-generating activities. Another is the idea of distributing sacrifices in reducing emissions justly (Miller, 2008). Among the widely discussed views of distributive justice are strictly egalitarian views (Temkin, 1993), indirectly egalitarian views such as prioritarianism (Parfit, 1997), and sufficientarian views (Frankfurt, 1999). (For a discussion of utilitarianism and its implications see sec. 3.2.2). A strictly egalitarian position holds that equality is of intrinsic value, implying that we have a reason to worsen the state of better off persons for the sake of equality even though it is better for no one. Many find such levelling down objectionable (Holtug, 1998). According to prioritarianism, equality as such does not matter, but we ought to give some priority or greater weight to benefiting people who are not well off: If X is worse off than Y, we have at least a *prima facie* reason for prioritizing the promotion of the wellbeing of X over that of Y. Prioritarianism does not necessarily prescribe an equal distribution of goods, since some people may be able to draw more benefit from goods than others can. Prioritarianism has been criticized for not giving enough weight to improving the situation of the worst off people and for not distinguishing between the fulfilment of people's needs and the satisfaction of their mere wishes (Crisp, 2003; Benbaji, 2006). Sufficientarianism prescribes that all persons should have the opportunity to enjoy a particular level of wellbeing. Some commentators have objected that we cannot avoid an arbitrary specification of such thresholds (Arneson, 2000; Roemer, 2004). For the sake of illustrating the problems of applying a principle of distributive justice to the subject matter under consideration this section considers the implications of prioritarianism, which is among the most common perspectives on distributional justice.

We can distinguish two options for applying a principle of justice such as prioritarianism to the distribution of obligations for emission reductions or, alternatively, rights to emit. According to the first option, we ignore the distribution of other goods for pragmatic reasons when determining the fair distribution of emission rights. With the background distribution regarded as irrelevant, people can be considered neither worse off than others nor in a position to extract more benefits out of emission rights than others. Thus prioritarianism might demand a distribution of equal per capita emission rights, or, if other regulatory approaches are used, demand greater sacrifices in reducing emissions from the better-off agents. According to the second option, we distribute emission rights in light of the currently highly unequal distribution of other assets. If we assume tradability of emission rights in an effective and fair global market, the scope for unequal benefiting from emissions is reduced (depending on how they are initially distributed), because those who would benefit little from emission rights can sell them. However, people in the developing world are so much less well off than the developed world that we could give many more, or all, emission rights to them, and they might still be worse off than many people in the industrialized countries. However, owing to the interdependent ways in which the distributions of goods affect the well-being of people, aiming at bringing the overall distribution of goods closer to the prioritarian ideal by adjusting the distribution of only one particular good seems questionable (Wolff and de-Shalit, 2007, pt. 2; Caney, 2009, 2012).

FAQ 3.2: What factors are relevant in considering responsibility for future measures that would mitigate climate change?

It is difficult to unambiguously indicate what responsibility should be taken by different parties in mitigating future emissions. Income and capacity are certainly relevant, as are ethical perceptions of rights and justice. It may also be instructive to examine how similar issues have been dealt with in the past in non-climate contexts. Under the two primary legal systems in the world (common law and civil law), responsibility for harmful actions is generally a basis for liability only if the actions are contrary to some legal standard such as negligence or nuisance. Negligence is based on the standard of the reasonable person. On the other hand, liability for causing a nuisance does not exist if the actor did not know or have reason to know the effects of its conduct. Both legal systems would require inquiry into whether emission of GHGs falls into a defined category of wrongful conduct. If some or all past emissions satisfy that standard, the next issue in both common law and civil law countries would be the nature of the causal link with the resulting harm.

3.3.4 Historical responsibility and distributive justice

Historical responsibility with respect to climate change concerns the past contributions made by various countries to the stock of GHGs in the atmosphere. The Framework Convention on Climate Change (UNFCCC) refers to “common but differentiated responsibilities” among countries of the world. This is usually interpreted to imply that current and historical differences of causal responsibility for climate change among countries as well as differences in wealth should play a role in determining emission reduction obligations as well as obligations to pay for adaptation measures globally (Rajamani, 2000; Rive et al., 2006; Friman, 2007).[12]

While some ethical theorists have argued that the distribution of emission reduction obligations and other burdens and benefits among the present generation must take into account the differing levels of past emissions and their effects on the wellbeing of currently living and future people, a number of objections have been raised against this view (see, e.g., Gosseries, 2004; Caney, 2005a; Meyer and Roser, 2006; Posner and Weisbach, 2010, chap. 5). First, as currently living people cannot possibly influence what previously living non-contemporaries did, they cannot be held causally responsible for the actions of their ancestors. Second, previously living people could not reasonably have been expected to know of, the harmful consequences of their emissions on (more remote) future people; thus they can be excused because of their justifiable ignorance of the consequences of their actions. Third, and owing to the non-identity problem, people would not exist as the individuals they are had previously living people not engaged in the emission-generating activities as they did, and thus nobody is better or worse off owing to the emissions of previously living people; thus, according to some interpretations, no normative link exists between the welfare level of currently living people and previously living people’s emission-generating activities (see section 3.3.3).

[12] Additionally, under the UNFCCC Articles 4.3 and 4.5, developed countries committed to provide financial resources and to transfer technology to support developing countries in taking their climate-related actions; while Article 4.7 links the extent to which developing countries meet their Convention commitments to the implementation of the finance and technology commitments of developed countries (United Nations, 1992).

From the perspective of distributive justice, however, these objections should not stand in the way of taking into account past emissions and their consequences. If we are only concerned with the distribution of benefits from emission-generating activities during the lifespans of individual persons, then we could take into account present persons' benefits from their own emission-generating activities since their birth. Also, present people have benefited since birth or conception from past people's actions that have emissions as a side-effect. These two ways of taking into account the consequences of (some of the) past emissions are not open to the first and the second objection as described in the previous paragraph (see Shue, 2010). Also, the non-identity problem, on which the third objection is based, is not relevant as the two ways of taking past emissions into account concern the distributive effects of emission-generating activities only after the identities of people have been determined, namely since their conception. Thus, if in distributing emission permits we aim at distributing benefits from emission-generating activities, then according to prioritarian standards those who have inherited a disproportionally large share of benefits from their predecessors – e.g., a well-functioning infrastructure and tertiary education system established before those presently alive were born – should receive a smaller share of emission permits relative to some unspecified baseline.

Associated with the historical responsibility concept are related concepts, including historical inequity (Agarwal and Narain, 1991) equal rights to environmental space (Simms, 2001; Hayward, 2007; Vanderheiden, 2009), greenhouse development rights (Baer, 2010) and ecological debt (Jernelöv, 1992; Hayes and Smith, 1993; Azar and Holmberg, 1995).

3.3.5 Intra-generational justice: compensatory justice and historical responsibility

A further basic issue is whether those who suffer disproportionally from the consequences of climate change (or will die prematurely owing to these consequences) have just claims to compensatory measures against those who are the main causers or beneficiaries of climate change (see, e.g., Neumayer, 2000; Gosseries, 2004; Caney, 2006b). One way to distinguish compensatory from distributive claims is to rely on the idea of a just baseline distribution that is determined by a criterion of distributive justice. Not all deviations from this baseline call for compensatory measures; rather, only deviations from this baseline owing to wrongful actions call for compensatory measures. Other deviations (e.g., owing to luck or other non-wrongful actions) call for re-distributive measures in the sense of a levelling out of undeserved benefits or harms (and some deviations, such as those which occur as a result of a person's free choices, may not call for any redistribution at all). Under this approach, compensatory duties to pay for climate damages and adaptation costs would have to rely on the wrongfulness of what was done. Defining "wrongful" is a matter of normative theory and not easy (Feinberg, 1984; Coleman, 1992; McKinnon, 2011).

We can distinguish three versions of compensatory payments depending on who has the duty to make payment (Gosseries, 2004; Caney, 2006b): the emitter of wrongful emissions, or the beneficiary of wrongful emissions, or some individuals due to their membership in a community of which (they or) some other (previous) members caused the wrongful emissions. Accordingly we can distinguish three principles of compensatory justice: the Polluter Pays Principle (PPP), the Beneficiary Pays Principle (BPP), and the Community Pays Principle (CPP).

According to the Polluter Pays Principle (PPP), the duty bearer for compensatory payments is the emitter. In this context, an agent emits wrongfully if (1) the agent exceeded his or her fair share (determined along the lines as outlined in section 3.3.2), and (2) the agent knew or was liable to know about the harmfulness of his or her emissions. Someone is wrongfully harmed by emissions if he or she either (1) is worse off due to wrongful emissions than he or she would otherwise be, or (2) falls below a specified threshold of harm due to wrongful emissions, or both. The PPP is widely discussed but is not universally accepted. As a general principle of compensatory justice – disregarding whether it can be usefully applied in climate change context – the principle that the emitter of wrongful emissions has the duty to provide compensatory payments (PPP) is more widely accepted than both BPP and CPP.

The justification for compensatory payments in the context of climate damages encounters at least four basic difficulties. These have implications for what duties of compensation and what rights to receive compensation can and cannot be justified for currently living and future people. The first two problems were already introduced in section 3.3.4 on historical responsibility and distributive justice:

First, potential duty bearers might have been (blamelessly) ignorant. It is unclear at what point people could have been reasonably expected to have knowledge of the harmful effect of GHG emissions (Gosseries, 2004, pp. 360–361). Thus, for all or for some period of their lives, previously as well as currently living people might have been (blamelessly) ignorant of the harmful consequences of their emissions on future people (see also section 3.3.6 , below).

Second, due to the non-identity problem (see section 3.3.2), potential recipients might only be said to be harmed according to a threshold conception of harm. Thus, currently living people can only claim to be wrongfully harmed if they fall below the threshold of wellbeing owing to the consequences of historical emissions. They cannot be said to be harmed simply because climate quality is worse than if less had been emitted in the past. However, as has been argued in section 3.3.3 , we have no agreement on how best to specify the relevant thresholds for wellbeing.

Third, again due to the non-identity problem, potential payers might not be said to have benefited. Without past emissions, they would not be worse off but rather not exist at all.

Fourth, potential duty bearers might be dead, and thus cannot have a duty to provide measures of compensation.

The Polluter Pays Principle therefore has difficulties in completely ascribing compensatory duties and identifying wronged persons. Owing to the first and fourth problems just mentioned, the principle will be able to ascribe duties of compensation only to currently living people for their more recent emissions, even though many more people are causally responsible for current and future harmful effects of climate change. With respect to the damages caused by past emissions, compensation payments are only justifiable for some part of the problem. The third problem does not arise for PPP, as the question of whether or not the polluter benefited from the emissions is not obviously relevant to her compensatory duty under PPP. Establishing a climate change compensation fund – into which agents have to pay levies for imposing the risk of harm on future people by causing emissions (McKinnon, 2011) – would provide an institutional solution of the fourth problem for the harmful consequences of current and future emissions only.

The Beneficiary Pays Principle (BPP) might be justified on the basis of weightier reason to even out undeserved deviations from a just baseline that are due to a wrong than to even out deviations that are due to more general causes. Some currently living people can be seen as currently benefiting from past emissions that impose costs on other currently living people. Accepting benefits from wrongful emissions can possibly be seen as transferring (some of) the wrongdoer's duty of compensation to the beneficiary (Gosseries, 2004). Also condemnation of injustice can be thought to imply not being willing to benefit from it while others suffer from it (Butt, 2007, p. 143). However, BPP is open to at least two objections. Owing to the non-identity problem and according to the radical interpretation of its practical significance (see section 3.3.4), currently living people can only be said to have benefited since birth or conception from the emissions of past people. Their duties of compensation based on BPP only concern past emissions that have had beneficial consequences for them; all other past emissions – namely those with harmful consequences and those that had beneficial consequences for past people only – remain uncovered. Second, if voluntary acceptance of benefits is a condition of their giving rise to compensatory duties, the potential bearers of the duties must be able to forego the benefits in question and at costs that are not unreasonably high. Otherwise the acceptance cannot be considered voluntary.

The Community Pays Principle (CPP) claims that members of a community – and many countries will count as such – can have collective outcome or remedial responsibility (Thompson, 2001; Miller, 2004; Meyer, 2005) for wrongful actions of other members of the community, including past members. Due to their membership in the transgenerational community, currently living members can have a duty to shoulder the burdens, which go along with the wrongful actions of past members without being in any way morally or causally responsible for these actions. It is a matter of debate whether and, if so, under what conditions currently living people can be said to have inherited compensatory duties. While reliance on CPP solves the fourth of the problems listed (that is, potential polluters might be dead), compensatory payments along the lines of CPP still only cover wrongful emissions (see first problem as introduced above) that can be shown to be harmful (see second problem as introduced above). Thus, emissions made under ignorance of their harmful nature remain uncovered.

The practical relevance of these reasons for believing in the applicability of principles of compensatory justice is limited in at least two ways. First, given that many effects of climate change can be seen as undeserved harms – and harms that go along with undeserved benefits for other persons – levelling off such effects on the basis of a concern for distributive justice is an equally plausible response. Attributing duties of distributive justice to agents does not presuppose any wrongdoing of these agents (see section 3.3.4). Principles of distributive justice can also be applied (at least to some degree) to the distribution of duties to pay for adaptation measures to those who suffer from climate damages. It has been suggested that these duties should be allocated mainly to the highly industrialized and rich countries according to their ability-to-pay, which ability reflects the correlation between their current level of wealth and the level of (past) emissions they have caused (Jamieson, 1997; Shue, 1999; Caney, 2010; Gardiner, 2011). Secondly, currently living people stand under intergenerational duties of justice with respect to climate justice (see section 3.3.2 above) if, first they can be said to know about both the seriously harmful consequences of their emission-generating activities for future people and effective measures to prevent those consequences, and if, second, they can implement these measures at reasonable costs to themselves to protect future people's basic rights (see, e.g., Birnbacher, 2009; Gardiner, 2011). Failing to fulfil their duties vis-à-vis future people would then constitute harmful wrongdoing.

3.3.6 Legal concepts of historical responsibility

Legal concepts are relevant as reflections of how societies have actually dealt with problems of responsibility for environmental harms initially thought to be benign. Legal systems in many nations have long struggled to define the boundaries of responsibility for harmful actions and are now beginning to do so regarding climate change. It remains unclear whether national courts will accept lawsuits against GHG emitters as a basis for liability and legal scholars vigorously debate whether liability exists under existing law (Mank, 2007; Burns and Osofsky, 2009; Faure and Peeters, 2011; Haritz, 2011; Kosolapova, 2011; Kysar, 2011; Gerrard and Wannier, 2012).

Torts law in modern legal systems generally follows either the common law or civil law model, a division extending through both developed and developing countries. Common law and civil law differ, but both would require inquiry into whether emission of GHGs falls into a defined category of tortious conduct (Hunter and Salzman, 2007; Faure and Peeters, 2011; Brunée et al., 2012). If some or all past emissions satisfy that standard, the next issue in both common law and civil law countries would be the nature of the causal link with the resulting harm (Faure and Peeters, 2011; Haritz, 2011; Brunée et al., 2012).

Across national legal systems, harmful conduct is generally a basis for liability only if it breaches some legal norm (Tunc, 1983) such as negligence, or an unreasonable interference with the rights of the public or of property owners (Mank, 2007; Grossman, 2009; Kysar, 2011; Brunée et al., 2012;

Goldberg and Lord, 2012; Koch et al., 2012). Negligence is based on the standard of the reasonable person or the *bone pére de famille* (Wagner, 2007). Similarly, nuisance liability does not exist if the actor did not know or have reason to know the effects of its conduct (Antolini and Rechtschaffen, 2008). With regard to liability for environmental damage, the law is still unsettled. For instance, the European Union but not the United States recognizes a similar exemption from liability based on lack of knowledge (United States Congress, 1980, sec. 9601 – 9675; European Union, 2004). Similarly, in European law, a defendant is not responsible if the state of scientific knowledge at the time did not enable the discovery of a product defect (European Commission, 1985). In the United States, many states recognize a similar limitation in cases involving defective product design (Dana, 2009). For GHGs, some legal scholars suggest that culpability arose after the express international determination of the harmfulness of such emissions in 1990, but others argue in favour of earlier dates (Faure and Nollkaemper, 2007; Hunter and Salzman, 2007; Haritz, 2011).

Legal systems also require a suitable causal link connecting a defendant's conduct and some identified harm to the plaintiff (Tunc, 1983; Kosolapova, 2011; Brunée et al., 2012). Plaintiffs would need attribution evidence to connect a specific harmful event to climate (Faure and Nollkaemper, 2007; Kosolapova, 2011; Kysar, 2011; Brunée et al., 2012; Ewing and Kysar, 2012; Goldberg and Lord, 2012). A causal link might be easier to establish between emissions and adaptation costs (Farber, 2007). Legal systems generally also require also some degree of causal foreseeability or directness (Mank, 2007; Kosolapova, 2011; van Dijk, 2011; Ewing and Kysar, 2012), although a few statutes relax this requirement in certain specific situations (such as the US CERCLA/Superfund). In both civil law and common law systems, emitters could argue that their contribution to GHG levels was too small and the harmful effects too indirect and diffuse to satisfy legal requirements of proximate cause or legal cause (Sinnot-Armstrong, 2010; Faure and Peeters, 2011; Hiller, 2011; Kysar, 2011; van Dijk, 2011; Gerrard and Wannier, 2012).

Climate change claims might also be based on a theory of unjust enrichment, which does not necessarily require a tort (Kull, 1995; Birks, 2005). But legal systems do not attempt to remedy all forms of enrichment that might be considered unjust from an ethical perspective (Zimmermann, 1995; American Law Institute, 2011; Laycock, 2012). In various national legal systems, liability turns on whether benefits have been conferred without legal obligation or through a transaction that is insufficient to work a conclusive alteration in ownership (Zimmermann, 1995; American Law Institute, 2011; Laycock, 2012). Application of these principles to climate change is unclear.

As the preceding discussion has indicated, legal systems do not recognize liability whenever a positive or negative externality exists, but instead engage in line-drawing based on the type of conduct creating the externality and the nature of the causal connection between an actor's conduct and the resulting gain or loss to another.

3.3.7 Procedural justice

Procedural justice requires that public decisions be taken in a fair way. The core idea is that relevant actors are included or represented in the political process and that they have a fair say in the decision (Albin, 2001; Caney, 2005b, chap. 5). Procedural justice is to be contrasted with distributive justice, which is concerned with the distribution of benefits and burdens in the outcome of a decision. Procedural justice – as employed in discussions of climate governance – focuses more on how decisions are made (Paavola et al., 2006; Paavola and Adger, 2006; Walker, 2012, p. 10).

3.3.7.1 The nature of procedural justice

Accounts of procedural justice have at least three components.

The first concerns the types of agents who should be included. At the international level, it is assumed that the primary actors to be included are representatives of states. Some argue that representatives of civil society (such as members of NGOs or social movements) also have some right to be included. Others argue that different normative perspectives must be represented in the process (Dryzek, 2010; Stevenson and Dryzek, 2012a; b).

Second, accounts of procedural justice must specify and justify the normative principle that determines which particular actors are entitled to be included in a political process. One common view appeals to what has been termed the “all-affected principle” (Whelan, 1983) , which holds that all of those who are affected by a political process should be included in the process. More recent versions of this principle hold only that those whose vital interests are profoundly and involuntarily affected by a political processes should be included in it (Goodin, 2003; Held, 2004; Caney, 2005a; Pogge, 2008). An alternative to the “all-affected” principle maintains that those who are legally bound by the decisions of a political body should be included in the body’s processes (Karlsson, 2008).

A third component concerns the nature of the rights to which participants are entitled.

Procedural justice is normally understood to entail that affected parties are entitled to be included in the decision-making process. This entails that they have a right, at a minimum, to be *consulted* about decisions. More substantive versions hold that those affected or their representatives are entitled to *participate* in the political process, to shape the agenda and decide which policies are to be adopted. Procedural justice is thus often, though not necessarily, associated with democratic decision-making, and in particular with an ideal of ‘deliberative democracy’ (Dryzek, 2010). Deliberative democracy would require that all relevant parties participate in the decision-making process (Habermas, 1998; Gutmann and Thompson, 2004). Crucially, the decisions eventually reached are to be justified on the basis of reasons that none of the parties could reasonably reject (Barry, 1995; Scanlon, 1998). For that the parties have to be understood as free and equal persons who are trying to secure fair terms of cooperation (Rawls, 1993, 1999). One corollary of this approach is that assistance would be required to ensure that all parties can genuinely participate effectively and on an equal footing (Roberts and Parks, 2007).

3.3.7.2 Contexts for procedural justice

Levels. Procedural justice can apply at different levels of governance, and the form it should take will vary with the context. Some have emphasized the importance of ensuring that international negotiations on climate change should take a multilateral form and include all affected agents. Some have argued that international negotiations should seek to embody democratic principles and are sympathetic to the vision of a ‘cosmopolitan democracy’ (Bäckstrand, 2011; Held and Hervey, 2011). The precise form that procedural justice will take at these different levels, and the extent to which it can realize democratic ideals, will depend, in part, on what is feasible.

Scope. Since climate change is a global problem, some have argued that procedural justice requires international climate negotiations to be maximally inclusive (Bäckstrand, 2011; Held and Hervey, 2011). Since climate change is also an intertemporal problem, some have proposed reforming existing political institutions and practices to make them more forward-looking, and to induce them to take into account the interests of future generations (Dobson, 1996; Goodin, 2003; O’Neill, 2007).

3.3.7.3 Justification

Procedural justice is valued for a number of distinct reasons. First, many hold that political institutions should adopt inclusive decision-making processes because it is intrinsically fair, and is the only legitimate way to make political decisions (Paavola et al., 2006; Paavola and Adger, 2006). The argument is that other modes of decision-making – ones that do not include affected parties in the decision-making process – fail to treat them with respect. This line of reasoning is sometimes grounded in a commitment to an ideal of “recognition” (Schlosberg, 2007). Second, it is argued that procedural justice increases compliance with the decisions made and thus contributes to the effectiveness of the policies selected.

A third justification holds that procedurally fair decision-making processes are likely to produce outcomes independently identified as just by the relevant criterion of justice (Rawls, 1971, sec. 14). The value of procedural justice on this view lies in the fact that it contributes to the achievement of just outcomes rather than in the intrinsic value of certain procedures as opposed to others.

3.3.8 Geoengineering, ethics, and justice

Geoengineering (also known as climate engineering), is large-scale technical intervention in the climate system that aims to cancel some of the effects of GHG emissions. It represents a third kind of response to climate change, besides mitigation and adaptation. Various potential options for geoengineering have been put forth, including different types of solar radiation management and carbon dioxide removal. This section reviews the major moral arguments for and against climate engineering (for surveys see (for surveys see Keith, 2000; Robock, 2008; Corner and Pidgeon, 2010; Ott, 2010; Betz and Cacean, 2012; Preston, 2013).

There is moral debate about the possible future deployment of geoengineering technologies and preparatory research into them. Geoengineering poses major ethical dilemmas and challenges for international cooperation and global climate change governance. While scientific research on different geo-engineering options is in its infancy, indications are that they could potentially be implemented at relatively low cost, but that they might have considerable adverse side-effects, or address only some aspects of change in natural systems.

Three types of arguments have been used to support the view that geoengineering technologies should be made ready for deployment. First, it has been argued that we might end up in a situation where deploying geoengineering is a lesser evil than allowing uncompensated and catastrophic climate change to happen (Crutzen, 2006; Gardiner, 2010; Keith et al., 2010; Svoboda, 2012a; Betz, 2012). Second, it has been argued that geoengineering is a more feasible and cost-effective response to climate change than mitigation or adaptation, and not just a last resort (Barrett, 2008). Such efficiency arguments have been criticized in the ethical literature (Gardiner, 2010, 2011; Buck, 2012). Third, it has been argued that some aggressive climate stabilization targets cannot be achieved through mitigation measures alone and thus that geoengineering may be necessary (Greene et al., 2010; Sandler, 2012).

The objections to geoengineering deployment can be grouped into different clusters. Some stress the substantial uncertainties of deployment (for overviews of geoengineering risks see also (Schneider, 2008b; Sardemann and Grunwald, 2010): both intended and unintended effects of geoengineering are irreversible (Jamieson, 1996); current uncertainties are persistent (Bunzl, 2009); geoengineering might make things worse rather than better (Hegerl and Solomon, 2009); and − the ‘termination problem’ – some geoengineering methods lack a viable exit option (The Royal Society, 2009).

Arguments regarding fairness and justice are concerned with the intra- and inter-generational distributional effects of geoengineering. Geoengineering schemes might aggravate some inequalities because they only partially control climate change and modify regional precipitation and temperature patterns (Bunzl, 2008; Svoboda et al., 2011; Preston, 2012).

Further objections to geoengineering deployment include geopolitical arguments (e.g., Schelling, 1996; Hulme, 2009), arguments based on environmental ethics (Hale and Grundy, 2009; Preston, 2011; Hale and Dilling, 2011; Svoboda, 2012b; Hale, 2012b), and arguments – such as the “technical fix” objection (Scott, 2012) or the “hubris” argument (Fleming, 2010) – that rely on a critical assessment of technology and modern civilization in general.

One of the most prominent arguments – referred to as the moral hazard argument – suggests that geoengineering research activities might hamper mitigation efforts (e.g., Jamieson, 1996; Keith, 2000; Gardiner, 2010). The central idea is that research increases public awareness of geoengineering, which might come to be thought of as a serious (less painful and more cost-effective) alternative to emission reduction (for a discussion of different versions of this argument see Hale, 2012a; Hourdequin, 2012). Other authors have argued that geoengineering research might make ultimate deployment inevitable (Jamieson, 1996; Bunzl, 2009), and that large-scale field tests might virtually amount to full-fledged deployment (Robock et al., 2010).

It has also been argued that geoengineering would constitute an unjust imposition of risks on future generations, because the underlying problem would not be solved but only counteracted with risky technologies (Gardiner, 2010; Ott, 2012; Smith, 2012).

Arguments have been made in favour of R&D on geoengineering technologies as a precaution. Should climate change accelerate with an elevated risk of catastrophe, geoengineering may be the only viable way of addressing it quickly and it would be wise to be aware of its characteristics (Leisner and Müller-Klieser, 2010). It has been argued that research does not necessarily prepare for future deployment but can, on the contrary, uncover major flaws of currently proposed geoengineering schemes, help to avoid premature geoengineering deployment and eventually foster mitigation efforts (Keith et al., 2010). At present, there appears to be no blueprint for how the international community might agree on geoengineering research, let alone on its deployment.

3.4 Economics, rights and duties

Sections 3.2 and 3.3 have outlined some of the ethical principles that can guide decision-making for climate change. The remainder of this chapter is largely concerned with the concepts and methods of economics. This section explores the links between ethics and economic analysis. It lays out the role and limits of normative economics in guiding decision-making about climate change. In the subsequent section (3.5), we examine the converse: if economic analysis (cost-benefit analysis) is being used to make climate policy decisions, what are the implicit ethical assumptions that are implied?

3.4.1 The role of ethics and economics in decision-making about climate change

Ethical considerations have a central role in decisions about climate policies: how much action to undertake, who should undertake action, and who should shoulder the cost of the mitigation, adaptation and whatever impacts remain after the action. Normative economics contributes to decision-making about climate change by evaluating alternative actions and policies, assuming specific underlying ethical positions.[13] Using economics normatively to help make policy decisions implicitly involves make ethical assumptions.

Economics at its core is the evaluation of trade-offs. Its methods can be used to aggregate values at different times and places, and weigh aggregate value for different policy actions. Economic methods can also be used to draw information about value from the ubiquitous data provided by prices and markets. Economics can measure diverse benefits and harms, taking account of uncertainty, to arrive at overall judgments of value. But economic analysis yields correct normative conclusions only under very specific ethical assumptions. These methods of economics build on some of the ethical principles discussed elsewhere in this chapter. Economics also has much to contribute to the choice and design of policy mechanisms (section 3.6 and later chapters).

Valuations provided by economics can be used at different scales. On a large scale, integrated assessment models can be used simulate the evolution of the world's economy under different climate regimes and determine an economically efficient reduction in GHG emissions. On a smaller

[13] More precisely, normative economics can be used to make decisions which implicitly reflect ethical and behavioural assumptions. Positive economics, which is used to make observations about how the economy operates (for example, how the EU Emissions Trading System works), is less constrained by ethical assumptions.

scale, economic methods of cost-benefit analysis can be used in choosing among particular policies and particular technologies for mitigation.

3.4.2 Limits of economics in informing ethical decision-making

The methods of economics have their limits. Economics can measure the aggregate of individual human value (at least many types of value), but sections 3.2 and 3.3 explain that this may be only one of several criteria for choosing among alternative mitigation policies. Other ethical considerations may not be reflected within economic valuations, and those considerations may be extremely important for particular decisions that have to be made. For example, some have contended that countries that have emitted a great deal of GHG in the past owe restitution to countries that have been harmed by it. If so, this is an important consideration in determining how much finance rich countries should provide to poorer countries to help with their mitigation efforts. Should this ethical position be adopted, economics cannot be used to determine who should mitigate, even if the overall level of mitigation can be determined.

What ethical considerations can economics cover satisfactorily? Since the methods of economics are concerned with value, it might seem that economics could not take any account of the principles of justice considered in section 3.3. But actually the theory of fairness within economics (Fleurbaey, 2008) is an account of *distributive* justice. It assumes that the level of distributive justice within a society is a function of the wellbeings of individuals, which means it can be reflected in the aggregation of wellbeing. In particular, it may be measured by the degree of inequality in wellbeing, using one of the standard measures of inequality such as the Gini coefficient (Gini, 1912), as discussed in the previous section. The Atkinson measure of inequality (Atkinson, 1970) is based on an additively separable social welfare function, and is particularly appropriate for representing the prioritarian theory represented in Equation 3.2.3. Furthermore, distributive justice can be reflected in weights incorporated into cost-benefit analysis, as section 3.5 explains.

Economics is not well suited for taking into account many other aspects of justice, including procedural justice and compensatory justice. For example, a cost-benefit analysis might not show the drowning of a Pacific island as a big cost, since it has few inhabitants, a limited amount of infrastructure and relatively little economic activity. It might conclude that more good would be done in total by allowing the island to drown: the cost of the radical action that would be required to save the island by mitigating climate change globally would be much greater than the benefit from saving the islands. This might be the correct conclusion in terms of overall aggregation of costs and benefits. But the island's inhabitants might have a right not to have their homes and livelihoods destroyed as a result of GHG emissions of richer nations far away. If that is so, their rights may override the conclusions of cost-benefit analysis. It may give those nations who emit GHG a duty to protect the people who suffer from it, or at least to make restitution to them for any harms they do suffer.

Even in areas where the methods of economics can be applied in principle, they cannot be accepted without question (Jamieson, 1992; Sagoff, 2007). Particular simplifying assumptions are always required, as shown throughout this chapter. These assumptions may not always be accurate or appropriate, and decision-makers need to keep in mind the resulting limitations of the economic analyses. For example, climate change will shorten many people's lives. This harm may in principle be included within a cost-benefit analysis, but it remains highly contentious how that should be done. Another problem arises because economics can provide concrete, quantitative estimates of some but not all values. Consequently, less quantifiable considerations may receive less attention than they deserve.

Moreover, the extraordinary scope and scale of climate change raises particular difficulties for economic methods. First, some (but not all) of the common methods of valuation in economics are best designed for small, marginal changes, and some impacts of climate change and some efforts at mitigation may be large and non-marginal. Second, the very long time scale of climate change makes the discount rate crucial at the same time as it makes it highly controversial (see section 3.5.2). Third, the world-wide scope of the problem means it encompasses the world's extremes of wealth and poverty, so questions of distribution become especially important and especially difficult. Fourth, measuring non-market values to an individual – such as the existence of species, iconic natural environments, or traditional ways of life of local societies – is fraught with difficulty and valuations are contestable. Fifth, the uncertainty that surrounds climate change is very great. It includes the likelihood of irreversible changes to societies and to nature, and even a small chance of catastrophe. This degree of uncertainty sets special problems for economics.

3.4.3 Role of economics in policy choice and design

The contribution of economics to the analysis of climate change mitigation is not confined to measuring value and directly providing guidance in how much mitigation should be undertaken and how the effort should be shared.

One of the greatest achievements of economics has been to show how decision-making can be decentralized through market mechanisms. This has important applications in policy instruments for mitigation (section 3.6 and Chapter 15). For example, if a carbon price is established, either by a carbon tax or by creating a market in emission permits, then every agent that emits GHG will bear the cost of doing so. Each agent – concerned only for its own interest – will therefore make sure that the private benefits of emissions are greater than the private costs at the margin. In many applications, this approach will yield cost-effective outcomes and if the carbon price is appropriate, efficient outcomes (Chapter 6).

Nevertheless, governments have the fundamental role of providing and managing the public good of climate change mitigation, even when specific decisions are decentralized in markets. Governments need so set carbon prices or limit emissions through tradable emissions allowances or some other regulatory device (section 3.6 and Chapter 15). In making these interventions, governments will need to measure values, and make decisions that have wide-ranging ethical dimensions.

Furthermore, economics has much to contribute in the analysis of how groups of individuals interact with each other in decisions about climate change mitigation. Economic analysis can also give guidance on how policy mechanisms for international cooperation on mitigation can be designed to overcome free-rider problems (Chapters 13 and 14).

Box 3.4.1. Who mitigates vs. who pays?

To mitigate climate change, emissions of GHG will need to be reduced to a greater or lesser extent all over the world. Economic analysis tells us that, for the sake of cost-effectiveness, the greatest reductions should be made where they can be made most cheaply. Ideally, emissions should be reduced in each place to just the extent that makes the marginal cost of further reductions the same everywhere. One way of achieving this result is to have a carbon price that is uniform across the world. A carbon price is a cost that emitters of GHG are made to pay for each unit of emissions. It can be created by a number of means, including a carbon tax on emissions, and by 'cap and trade': by issuing emissions permits that can be traded in a market.

Since, for efficiency, mitigation should take place where it is cheapest, emissions of GHG should be reduced in many developing countries as well as in rich ones. However, it does not follow that they must be paid for by those developing countries. Rich countries may pay for mitigation that takes place in poor countries. Financial flows between countries make it possible to separate the question of where mitigation should take place from the question of who should pay for mitigation.

These financial flows redistribute wealth. Because mitigating climate change demands very large-scale action, they may become a significant factor in the international distribution of wealth. The question of where mitigation should take place is largely a matter for the economic theory of efficiency, but the distribution of wealth is a matter for ethical judgement. It is commonly described as an issue of fairness among countries, and it is a major issue in the politics of climate change.

This does not mean it is beyond the scope of economic methods. It is partly an issue of distributive justice. How much of the cost of mitigation should be borne by the poor in comparison to what is borne by the rich? The theory of fairness within economics can offer insights on this question. It is an application of the ethics of distributive justice. It would be a mistake to expect a definitive answer from economics, but economics might make a useful contribution.

However, a different question of justice is also involved. Most of the anthropogenic GHG that is now in the atmosphere has been emitted by rich countries. Much of the harm that is being done by these gases is suffered by people in poorer countries. A case might be made for saying that the poor should be compensated for the harm done them by the rich. This consideration may be a large factor in determining what financial flows should be. This type of compensatory justice is beyond the scope of economic methods.

3.5 Aggregation of costs and benefits

3.5.1 Aggregating individual well-being

Section 3.2 introduced a number of different values that are relevant to climate change. For the purposes of planning our response to climate change, it is helpful to measure these values to the extent that they can be measured. The methods of economics are suitable for measuring just one of them: people's wellbeing. Some non-monetary measures of wellbeing were mentioned in 3.2.2.3 . This section turns to monetary measures, which are used in cost-benefit analysis, in intertemporal optimization within integrated assessment models (e.g., Stern, 2007; Nordhaus, 2008), and elsewhere. Section 3.4 describes the important limitations on the validity of these methods.

We need to measure the overall value of aggregate wellbeing and not merely the wellbeing of each individual. A measure of overall value may be based on ethical analysis, through a social welfare function of the sort introduced in section 3.4. This ethical basis of valuation is considered in sections 3.5.1.1 and 3.5.1.2 . A putative alternative basis is considered in section 3.5.1.3 .

3.5.1.1 Routes to aggregation

One approach to measurement sets out from the additively separable social welfare function Equation 3.2.1 in section 3.2.2 , and makes specific assumptions about individuals' lifetime wellbeing functions and the social welfare function.[14] Various different assumptions might be made.

For example, we might assume that person *i*'s lifetime wellbeing is $w_i = \beta_i^1 w_i^1 + \beta_i^2 w_i^2 + \ldots + \beta_i^T w_i^T$. Here w_i^t is the temporal wellbeing of person *i* at time *t* if she is alive at that time, and zero if she is not. This formula makes a person's lifetime wellbeing a discounted total of her temporal wellbeings during her life: the β_i^t are private discount factors attached to the person's temporal wellbeings. They might be derived from the person's preferences. (β_i^t will be set at 1 at the time the person is born and less than 1 for later times in her life.)

Next we might assume this discounted prioritarian social welfare function:

$$V = \delta_1 v(w_1) + \delta_2 v(w_2) + \ldots + \delta_I v(w_I)$$

[14] For example, Fullerton and Rogers (1993) use a multi-sector computable general equilibrium model of the U.S. to measure lifetime utility of individuals in twelve different lifetime income groups. They calculate lifetime tax incidence as the effect on each group's lifetime utility from a change in any tax. A social welfare function could then aggregate those effects over different income groups. Other examples are Murphy and Topel (2006) and Kaplow et al. (2010).

This function is prioritarian if the function *v*() is strictly concave. The δ_i is a social discount factor attached to the value of person *I*'s lifetime wellbeing. It is common to make it depend on the date when the person is born. The δ_i discount lifetime wellbeings for the purpose of interpersonal aggregation; they may be quite distinct from the β_i^t, which discount temporal wellbeings for the purpose of intra personal aggregation. If the individual is calculating her own lifetime wellbeing, then she might discount future consumption at her own net-of-tax market interest rate. In contrast, the social welfare function could choose to weight all generations equally, in which case the social discount factors are all one (with a social discount rate of zero).

Combining these assumptions gives this formula for social welfare:

Equation 3.5.1. $$V = \delta_1 v(\beta_1^1 w_1^1 + \beta_1^2 w_1^2 + \ldots + \beta_1^T w_1^T) + \delta_2 v(\beta_2^1 w_2^1 + \beta_2^2 w_2^2 + \ldots + \beta_2^T w_2^T)$$
$$+ \ldots + \delta_I\, v(\beta_I^1 w_I^1 + \beta_I^2 w_I^2 + \ldots + \beta_I^T\, w_I^T)$$

Using this formula for aggregating wellbeing implies first aggregating temporal wellbeings across time to determine each individual's lifetime wellbeing, and then aggregating lifetime wellbeings across people using a social welfare function.

However, aggregation is more often done in the opposite direction in practical economic valuations. In that case, the first step is to aggregate temporal wellbeing across people alive at each time, to determine a social value for each time period. In Figure 3.2.2 this means aggregating along a vertical line such as the dotted line shown. The result may be called a 'snapshot value'. Then all the snapshot values are aggregated across times.

To aggregate this way is to assume that times are *separable*, which means that the overall value of the distribution is truly an aggregate of snapshot values. Combined with the assumption made in section 3.2.2 that each person's wellbeing is separable, this has the very strong consequence that the social welfare function is additively separable throughout (Gorman, 1968). Granted an appropriate assumption of symmetry between different people and times, it leads to the social welfare function:

Equation 3.5.2. $$V = \delta 1[v(w11) + v(w21) + \ldots + v(wI1)] + \delta 2\, [v(w12) + v(w22) + \ldots + v(wI2)]$$
$$+ \ldots + \delta T[v(w1T) + v(w2T) + \ldots + v(wIT)]$$

Each bracket shows social value at a particular time *t*. The function *v*() shows the value of temporal wellbeing: how much a person's temporal wellbeing at a time contributes to social value at that time. δ^t is a *pure discount factor*, which discounts social value at the time *t*. Equation 3.5.2 says that aggregate social value is the discounted total, over time, of the total value of people's wellbeing at each time.

This formula for value is assumed in the account of valuation that follows. But it has a number of unsatisfactory consequences. First, it cannot give value to lifetime equality. It can value equality among the people who live at any particular time: if the function *v*() is strictly concave, it expresses prioritarianism for temporal wellbeings, which gives an indirect value to equality at a time. But suppose lifetime inequality is nil, because each person's life follows the same path of increasing wellbeing. At each time the old are better off than the young, so Equation 3.5.2 treats the society as unequal and it attaches no value to its lifetime equality. Second, Equation 3.5.2 is inconsistent with average utilitarianism, or with valuing per capita temporal wellbeing at any time, whereas per capita wellbeing is a common object of climate-change policy. Third, Equation 3.5.2 makes no distinction between discounting within a single person's life and intergenerational discounting. Yet a case can be made for treating these two sorts of discounting differently as Equation 3.5.1 does, and the difference may be particularly important for climate-change policy (Kaplow et al., 2010). These unsatisfactory consequences of Equation 3.5.2 arise from the assumption that times are separable in the social welfare function.

3.5.1.2 Monetary values and cost-benefit analysis

Practical decision-making requires some alternative policies or actions to be assessed as better or worse than others; it therefore needs an assessment of differences in value rather than absolute values. We may treat one of the alternatives as a standard of comparison – for instance, the status quo or business as usual – and assess the value of other alternatives relative to this standard. Relative to the standard, each option will have costs and benefits. Their values need to be measured and aggregated together. Costs and benefits are such things as an increase or decrease in the consumptions of particular commodities by particular individuals, external harms such as pollution and damage to health caused by climate change, public goods and bads such as environmental damage, and so on.

The first step in a practical economic valuation is to assign a *monetary value* to the costs and benefits that come to each person at each time. Whether a change is a cost or a benefit, two different monetary values can be assigned to it: the equivalent variation and the compensating variation. The *equivalent variation* (EV) is the amount of money that would cause the same change in the person's wellbeing as the change itself. The *compensating variation* (CV) is the amount of money that would exactly offset the effect on wellbeing of the change. If the change reduces wellbeing, EV corresponds to the person's maximum willingness to pay (WTP) to avoid the change, while CV corresponds to the minimum compensation that the person would be willing to accept (WTA) to suffer the change; conversely if the change involves an increase in wellbeing. If a change is marginal, the compensating and equivalent variations will be equal. If the change is a marginal increase or decrease in the person's consumption of a marketed commodity, consumer theory shows its CV and EV will both be equal to the price of the commodity. Monetary values may in practice be estimated by various methods, which are described in section 3.8.1 .

The EV of a change for a person is the amount of money that would have the same effect on the person's wellbeing as the change itself. So once the EV is established, the effect of the change on the person's wellbeing can be derived. It is the EV multiplied by the rate at which money contributes to her wellbeing. This latter is the *marginal benefit of money* to the person (or sometimes the 'marginal utility of money'). The marginal benefit of money is generally treated as an empirical feature of the person. It is commonly assumed to diminish with increasing income (Marshall, 1890; Dalton, 1920; Pigou, 1932, p. 89; Atkinson, 1970). That is to say, a person's wellbeing is generally taken to be a strictly concave function of her income or of her aggregate consumption.

The effects of the change on each person's wellbeing at each time must next be aggregated across people to determine the effect on social value at that time. Equation 3.5.2 shows what is required. Social value is the sum of the values of each person's wellbeing. Each person's wellbeing contributes to social value through the value function $v()$. The change in wellbeing must therefore be multiplied by the *marginal social value of wellbeing*, which is the first derivative of this function. It is an ethical parameter. According to utilitarianism, it is constant and the same for everyone. According to prioritarianism, it diminishes with increasing wellbeing.

In sum, the effect of a change on social value at a time is found by taking the monetary value of the change to each person, weighted appropriately, and adding up these weighted amounts (Fleurbaey, 2009, pp. 1051–2). The weights – often called 'distributional weights' or 'welfare weights' – are the marginal social value of money, which is the marginal benefit of money multiplied by the marginal social value of wellbeing. Since the marginal benefit of money is generally assumed to diminish with increasing income, the marginal social value of money can be assumed to do the same.

In a monetary measure of value to a person, money serves as the unit of value or *numeraire*. Other things that have value to the person could serve instead. Time is another possible numeraire; a CV could be measured as the amount of time that a person would be willing to sacrifice in order to receive a benefit (Somanathan, 2006). Health is another numeraire and has been used in environmental cost-benefit analyses (Portney and Stavins, 1994). Money is a convenient numeraire because many things are regularly exchanged for money. However, assumptions are implicit in choosing a numeraire. A numeraire can measure only the values of things it is commensurable with, so an assumption of commensurability is implicit in choosing money. Money is a poor measure of the value of cultural inheritance, for instance. Moreover, if values are added up across people, this is to assume that the numeraire has a constant social value that is the same for each person. That assumption is false of money. That is why distributional weights must be applied to monetary values before they are added up across people.

Nevertheless, much practical cost-benefit analysis values costs and benefits according to monetary values, added up without any weighting factor. This is implicitly to assume that the social value of money is the same for each person (which is unlikely to be the case). It is a particularly egregious error in cost-benefit analysis concerned with climate change, which often needs to take into account the extreme differences of wealth in rich and poor countries. An important example was described in the Second Assessment Report of the IPCC (1995, pp. 196–197), where it considered the value of human life (see Box 3.5.1). The Report showed that the effect of ignoring weighting factors would be to assign perhaps twenty times more value to an American life than to an Indian life. Even within a single country, weighting makes an important difference. Drèze (1998) examines the benefits of reducing pollution in Delhi (India) and contrasts the relatively rich New Delhi with the poorer Old Delhi. If the criterion is reducing pollution for the greatest number of people, projects in Old Delhi will be favoured; whereas projects in New Delhi will be favoured if the basis is unweighted net benefits.

Box 3.5.1. The value of life.

Climate change may shorten many people's lives, and mitigating climate change may save many people's lives. Lives must therefore be included in any cost-benefit analysis that is concerned with climate change. CBA needs to set a quantitative value on the harm done a person when her life is shortened, or, equivalently, on the good done her when her life is extended.

This task has been approached in the literature from two different directions. One approach is based on the length of the period of life that the person gains or loses, adjusted for the quality of her life during that period. This gives a measure of the value of life known as the 'quality-adjusted life year' or qaly (Sassi, 2006, pp. 402–408). Qalys are widely used to value lives in health economics and in public health. The World Health Organization uses the 'disability-adjusted life years' or daly, which is similar (Murray, 1994).

The other approach values the extension of a person's life on the basis of what she would be willing to pay for it. In practice, this figure is usually derived from what she would be willing to pay for an increased chance of having an extended life. If, say, a person is willing to pay $100 to reduce her chance of dying in a road accident from 2 in 10,000 to 1 in 10,000, then her willingness to pay for extending her life is $100 x 10,000 = $1,000,000. Willingness to pay measures of the value of life are widely used in environmental economics (e.g., U.S. Environmental Protection Agency, 2010 Appendix B).

The main differences between these approaches are:

1. Since willingness to pay is measured in money, it is immediately comparable with other values measured in money. Qalys need to be assigned a money value to make them comparable (Mason et al., 2009).

2. The use of qalys implies a theoretical assumption about the value of extending a life – that it is proportional to the length of the extension, adjusted for quality – whereas willingness to pay methods generally leave it entirely to the individual to set a value on extending her own life (Broome, 1994).

3. Implicit in each measure is a different basis for interpersonal comparisons of value. When qalys are aggregated across people by addition, the implicit assumption is that a year of healthy life has the same value for each person. When willingness to pay is aggregated across people by addition (without distributional weights), the implicit assumption is that a dollar has the same value for each person. Neither assumption is accurate, but for comparisons involving very rich countries and very poor ones, the former seems nearer the truth.

The two approaches can converge. The text explains that distributional weights should be applied to monetary values before they are aggregated, and this is true of willingnesses to pay for extending life. If appropriate weights are applied, willingness to pay becomes more nearly proportional to qalys. Indeed, if we adopt the assumption that a year of healthy life has the same value for each person, it gives us a basis for calculating distributional weights (Somanathan, 2006). For example, suppose willingness to pay for a thirty-year extension to healthy life in the US is $5,000,000, and in India it is $250,000. Then on this assumption, $1 to an Indian has the same value as $20 to an American.

GDP is another example of a monetary measure of value that does not incorporate distributional weights. To evaluate changes by their effect on GDP is, once again, to assume that the value of a dollar to a rich person is the same as its value to a poor person (Schneider et al., 2000).

It is sometimes assumed that cost-benefit analysis is conducted against the background of efficient markets and an optimal redistributive taxation system, so that the distribution of income can be taken as ideal from the society's point of view. If that were true, it might remove the need for distributional weighs. This is not an acceptable assumption for most projects aimed at climate change. Credit and risk-sharing markets are imperfect at the world level, global coordination is limited by agency problems, information is asymmetric, and no supra-national tax authority can reduce worldwide inequalities. Furthermore, intergenerational transfers are difficult. In any case, the power of taxation to redistribute income is limited by the fact that redistributive taxes create inefficiency (Mirrlees, 1971). Even optimal taxation would therefore not remove the need for distributional weights. Thus even the assumption that incomes are optimally redistributed does not necessarily eliminate the need of welfare weights in aggregating costs and benefits.

The need for these weights makes valuation more complicated in practice. The data available for costs and benefits is generally aggregated across people, rather than separated for particular individuals. This means that weights cannot be applied directly to individuals' costs and benefits, as they ideally should be. This difficulty can be overcome by applying suitably calculated weights to the prices of commodities, calculated on the basis of income distribution of each commodity's consumers.[15]

3.5.1.3 The Paretian approach

The Paretian approach to valuation is motivated by the assumption that the wellbeings of different people cannot be compared, so no social welfare function exists. It does not require distributional weights.

The *Pareto criterion* claims that one of the options in a decision problem is better than another if it is better for someone and at least as good for everyone (Arrow et al., 2002, p. 42). It is uncontroversial, but it provides only a sufficient condition for betterness, and can rarely be applied directly in practical decision-making (in other words, many alternatives cannot be ranked). Nevertheless, it does have one important implication for the economics of climate change, which is explained in Box 3.5.2.

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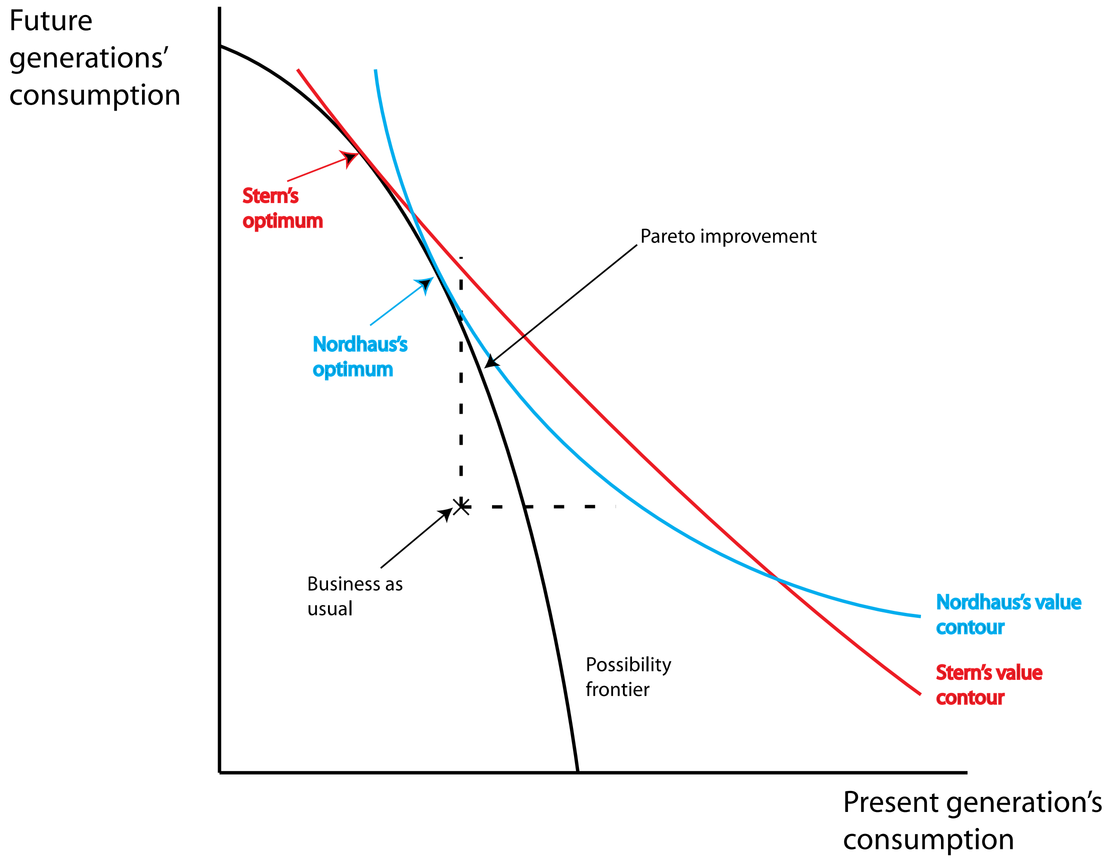
[15] The method is presented in Drèze and Stern, (1987, pp. 909–989). Applications of distributional weights to climate change appear in Azar and Sterner, (1996); and Fankhauser et al. (1997).

Box 3.5.2. Optimality versus Pareto improvement

GHG is an externality: a person whose activities emit GHG does not bear the full cost of her activities; some of the costs are borne by those who are harmed by the emissions. Consequently, climate change causes Pareto inefficiency. This means it would be possible to correct the externality, making some people better off without making anyone worse off. Indeed it would be possible to remove the externality in a way that requires no sacrifice by anyone in any generation. To achieve this result, the present generation needs to switch some of its conventional investment towards projects that reduce emissions of GHG, while maintaining its own consumption. Because it maintains its own consumption, it is no worse off. Because it reduces its conventional investment, it bequeaths less conventional capital to future generations. Other things being equal, this would make future generations less well off, but the reduction in emissions will more than compensate them for that loss (Foley, 2009; Rezai et al., 2011).

The diagram illustrates the situation. The possibility frontier shows what combinations of consumption are possible for present and future generations. Because of the externality, business as usual lies below this frontier. The frontier can be reached by a Pareto improvement. Two value contours are shown; they illustrate different social welfare functions in terms of the relative value placed on consumption in the present with consumption in the future. One contour (labelled Stern) places more value on future consumption relative to the present than the contour labelled Nordhaus. The labels are only illustrative, reflecting the assumptions in Stern (2007) and Nordhaus (2008) respectively. Each contour links together combinations of consumptions that are equally good according to its social welfare function. The point where a contour touches the possibility frontier is the social optimum according to that function. Note that neither optimum is a Pareto improvement on the status quo (Business as Usual) – we cannot conclude whether either the Nordhaus optimum or the Stern optimum is an improvement, based only on the Pareto criterion.



Another criterion is variously known as the potential Pareto criterion, the compensation test or the Kaldor-Hicks criterion (Hicks, 1939; Kaldor, 1939). Compare two options A and B. Suppose it would be possible, by starting from A and simply redistributing income or wealth among the people, to reach a state that is better than B according to the Pareto criterion. Then the potential Pareto criterion claims that A is better than B. Imagine the economy moves from B to A. If the gainers from this move could fully compensate the losers in such a way that some people are made better off by the move and no one is made worse off, then A is better than B according to the potential Pareto criterion. This is so whether or not the compensation is actually paid.

The potential Pareto criterion is sometimes held to offer a basis for cost-benefit analysis, if benefits and costs are measured according to their compensating variations (CVs) and aggregated without any distributional weights. If the economy moves from B to A, gainers from the move have positive CVs and losers negative ones. If benefits exceed costs measured by CVs, the sum of all CVs is positive. This is held to show that the gainers could fully compensate the losers, so that A is better than B according to the potential Pareto criterion. But this Paretian basis for cost-benefit analysis is hard to justify, for the following reasons.[16]

First, a positive sum of CVs does not guarantee that the potential Pareto criterion is satisfied – that the gainers could fully compensate the losers. By definition, CVs are calculated at the prices prevailing after the move from A to B is made. If compensation was then actually paid, prices would change, and some people might consequently end up worse off (Boadway, 1982).

Second, for some pairs of options A and B, the potential Pareto criterion implies both that A is strictly better than B and that B is strictly better than A (De Scitovszky, 1941). This is a contradiction. It follows by reductio ad absurdum that the potential Pareto condition has problems. A fix for this problem is to amend the criterion by specifying that it applies only to cases where the contradiction does not arise. The result is the so called reversal criterion, which says that A is better than B if, first, it is better according to the potential Pareto criterion and, second, B is not better than A according to the potential Pareto criterion (De Scitovszky, 1941).[17]

However, third, for some triples of options A, B and C, the reversal criterion implies that A is better than B, B better than C and C better than A (Gorman, 1955). This cannot be true, so it follows by reductio ad absurdum that this reversal criterion is also false.

Fourth, the potential Pareto criterion has incredible implications. Suppose a rich country proposes some activity that would emit GHG. Its impoverished neighbouring country would be harmed as a result. Suppose the benefit of the activity to the people of the rich country is trivial, and the harm that will be suffered by the people of the poor country is considerable. But suppose that, because the difference in wealth is so great, the amount the people of the rich country are willing to pay for their trivial benefit would be enough to compensate the people of the poor country for the considerable harm they suffer. Then the potential Pareto criterion implies it would be better for the rich country to go ahead with this activity, rather than refrain from doing so, even if it actually pays no compensation to the poor country. This is not credible.

Box 3.5.3. Social Decisions Based on Unweighted CBA: Implicit Ethical Assumptions

Cost-benefit analysis is a powerful tool for examining the costs and benefits of mitigation policy. But as is often the case with powerful tools, it can be (and often is) inappropriately used. Although conceptually benefits and costs accruing to different individuals can be weighted before summing,

[16] The difficulties are reviewed in Blackorby and Donaldson (1990).

[17] Some have questioned the significance of the Scitovsky reversal for cost-benefit analysis (e.g., Just et al., 2012).

reflecting a prioritarian view of social welfare, in most applications "welfare weights" are assumed to be the same for all individuals so a simple sum of benefits and costs is used as a measure of welfare. Although it is certainly appropriate for unweighted CBA to be one input of several in making a policy decision, reliance on it exclusively implies a number of ethical assumptions, assumptions that are restrictive and probably not correct in most applications. Anyone using cost-benefit analysis, particularly unweighted cost-benefit analysis (i.e., costs and benefits are simply summed with no attention to who bears those costs or benefits), should be aware of the assumptions necessary for the analysis to be valid.

This is the subject of a large literature dating back decades (e.g., see Blackorby and Donaldson, 1990). Some selected conditions, necessary for unweighted CBA to yield a valid societal decision, are listed below. This is not meant to be a set of sufficient conditions; thus simply concluding that these conditions hold does not mean unweighted CBA is valid for social decisions (see Blackorby and Donaldson, 1990).

(1) Social value is an aggregate of individual values (i.e., individual wellbeing is all that matters to society). In section 3.2.2 , the sources of individual and social value were discussed at length. Although individual human wellbeing is important, it is not the only source of value, at least for some decision-makers.

(2) The preferences of the individual being aggregated are unambiguous and are measured correctly. There are a number reasons why measured preferences may be problematic, including (a) whether future individuals will share the same preferences as the present population; or (b) whether an individual may have different preferences when acting in the marketplace than in the voting booth (which goes to the issue of the validity of the method used to elicit preferences).

(3) The marginal value of money is the same for all individuals in the population. This means that from a societal point of view, giving (or taking) an extra euro to or from a poor person is societally equivalent to giving (or taking) and extra euro to or from a rich person. If the policy-maker believes this not to be the case, rather that society benefits more from an extra euro to a poor person, then unweighted CBA gives a greater emphasis to the interests of the rich than society does. Even if incomes are optimally redistributed within a country, the marginal benefit of money may not be equalized across the population. And in the case of climate change, where benefits in different countries are being compared, it is highly unlikely that income redistribution among countries is considered optimal.

(4) The distribution of wealth/income is socially optimal. This is related to point #4 above, though for a different reason. Demand for goods and services depends on income. The demand for first-class air travel is different for a poor person than for a rich person. Since demand functions are closely related to willingness-to-pay, different income distributions will result in different willingnesses-to-pay and thus different measures of benefits of environmental improvement. In other words, the aggregate measure of net benefits will change if the income distribution changes.

If all of these conditions are not met then the ranking of policies based on the unweighted cost-benefit criterion may be wrong. As stated before, even if all conditions are met, that is not sufficient to conclude that unweighted CBA provides a reliable guide for social decisions.

3.5.2 Discounting future goods

In climate change decisions, the choice of discount rates heavily affects the net present value of alternative policies. Discounting allows economic costs and benefits incurred at different points in time to be compared. If one believes that one kilogram of good *i* consumed in 12 months has an effect on the intertemporal social welfare equivalent to 960 grams of the same good consumed today, this means that one uses a discount rate of 4% on good i. The relative valuation of economic and environmental assets with respect to time is crucial to decisions on how much sacrifice should be done today for the benefit of future generations. Discounting has a crucial impact on the evaluation of long-lasting projects or investments, as is relevant for climate change mitigation. To illustrate, a benefit of $1 million occurring in 100 years has a present value of $369,000 if the discount rate is 1%, $52,000 if the discount rate is 3%, or $1,152 if the discount rate is 7%. Clearly the discount rate matters. This illustrated in Figure 3.5.1, where a similar calculation is done for different numbers of years from the present, up to 100 years, and for four different discount rates.

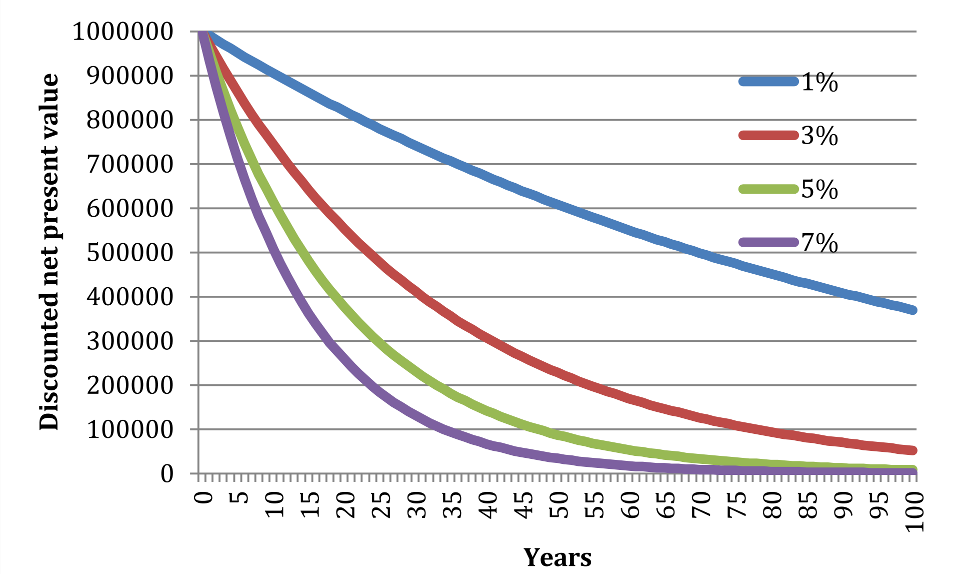


Figure 3.5.1. Net present value of 1 million dollars over a 100-year time span using different discount rates (horizontal axis is years in the future from the present).

This section offers a normative analysis on the effect of time on value. Under a normative approach, the discount rate tells us how much one should do for the future—how to compare the present and future. An important debate in economics since AR4, spawned by the Stern (2007) Review, has been about the discount rate that should be applied in evaluating climate change impacts and mitigation costs (Nordhaus, 2007b; Stern, 2008; Dasgupta, 2008; Smith, 2010; see also Quiggin, 2008).

A positive approach by contrast examines how human beings actually do trade-off the present with their own future. The positive perspective focuses on how individuals and markets actually make intertemporal financial decisions, as revealed by the market interest rate.[18] Positive approaches to discounting have received a lot of attention from economists, with special focuses on hyperbolic discounting and time inconsistency (Laibson, 1997), and on the separation between aversion to risk and aversion to consumption fluctuations over time (Epstein and Zin, 1991). We do not examine these problems in this section (the issues are discussed in 3.8.4 and are relevant to behavioural economics, discussed in section 3.9 and in Chapter 2). As in the previous sections, we examine the problem of a social policymaker who must make climate policy choices using a social welfare function (SWF) discussed earlier.

In CBA, in order to make things comparable across long periods of time, one values consumption changes in the future by equivalent changes in consumption today. These changes in the structure of consumption should be evaluated in monetary equivalent terms by using values described in section

[18] Data on historic international market rates may be found in Dimson et al. (2002).

3.5.1.2 . Economists offer two equivalent ways to take into account of the anticipated evolution of relative values of the different impacts of an action. One strategy is to use a unique monetary discount rate to discount the monetary impacts using these evolving prices. The alternative strategy is to use different discount rates for different impacts, the discount rate for asset *i* being equal to the monetary rate minus the rate of change of the relative value of asset *i* (Malinvaud, 1953; Guesnerie, 2004; Sterner and Persson, 2008; Guéant et al., 2012). For example, due to the anticipated increased relative scarcity of environmental assets, Gollier (2010) recommends using a 3% rate to discount economic impacts, but a much smaller 1% rate to discount environmental impacts. Hoel and Sterner (2007) suggest an ecological discount rate between -1% and +2%.

The incorporation of the intergenerational equity objective has challenged the traditional CBA approach for the evaluation of climate change policies. CBA practitioners and evaluators are expected to use discount rates that are consistent with the pre-specified social welfare function (SWF) that represents the Society's intergenerational values. To make this link clear (as was done in the Second Assessment Report of the IPCC (1995, pp. 196–197), consider the representative bundle of commodities as a single aggregate good, measured using the relative values of goods and services as explained in section 3.5.1.2 . Let us call this single aggregate good the GDP. Let c_t denote the GDP per capita at date *t*. This yields a utility $u(c_t)=v(w(c_t))$ for people living at time t. [19] It is generally assumed that *u* is increasing (more consumption is better) and concave (the marginal utility of consumption is decreasing), as represented in the following graph.

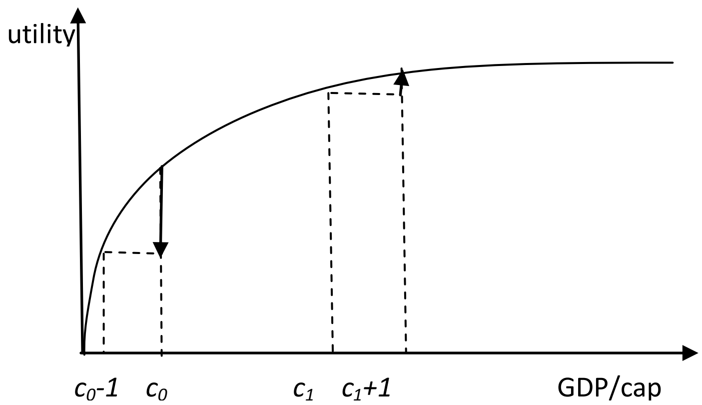


Figure 3.5.2. Transfer of one unit of consumption from present (t = 0) to future (t = 1)

Suppose then one expects future consumption c_1 to be larger than current consumption c_0, and consider an action that transfers one unit of consumption to the future (from time 0 to time 1). Figure 3.5.2 suggests that this would reduce the intertemporal welfare, because the negative impact on current utility is greater than the positive impact on future utility. This "wealth effect" comes from the combination of the two assumptions: (1) one is currently relatively poor and getting richer, and (2) poorer people have a larger marginal utility of consumption. This latter prioritarian assumption implies that one is collectively averse to inequalities, in the sense that one would prefer to spread consumption over time more equally. This aversion to inequality implies that, in a growing economy, one will value more immediate increases in consumption than future increases in consumption. One will accept to invest for the future in spite of the increased intergenerational inequality that it generates only if the return of that investment is large enough to compensate for

[19] Problems with this approach are discussed in section 3.5.1.1 above. That sub-section also introduces an alternative based on calculation of the lifetime wellbeing of each individual or cohort (the present value of lifetime utility using each group's own private rate of discount). Those lifetime well-beings can then be aggregated by a SWF using the social rate of discount discussed here.

this welfare loss. The trade-off between consumption of those alive today and consumption of those alive in the future is the main economic justification of social discounting.

This analysis is perhaps best understood as one where people alive during period t can be aggregated by a utility function $u(c_t)$, as if only one generation is alive at one time. Then no individual reallocates consumption across time periods using a private discount rate. In other words, the only discount rates employed in this section are social discount rates.

Assuming a standard constant elasticity in consumption utility function (e.g., $u(c)=c^{1-\eta}/(1-\eta)$), the wealth effect mentioned above is quantified in the Ramsey formula for the social discount rate ρ_t, used to discount a sure increase in consumption in t years (Ramsey, 1928):

Equation 3.5.3. $$\rho_t = \delta + \eta g_t$$

where δ is the "pure rate of time preference" or "pure discount rate": the rate at which the flow of future well-beings is discounted (not future consumption), an ethical parameter that determines the relative weight of future generations in the welfare function. This ethical parameter is different from the monetary social discount rate ρ_t. Then g_t is the annualized growth rate of monetized consumption anticipated at date t, and η is relative inequality aversion. The larger the economic growth rate g_t or the aversion η to inequality, the larger the social discount rate ρ_t. The growth rate g_t is an empirical variable that represents our collective beliefs on economic growth, whereas the aversion to inequality (η) is a parameter that combines collective ethical attitudes (embedded in function v) and individual preferences (embedded in function w) contained in the utility function $u=v(w(c))$. In Box 3.5.4, we discuss plausible values for η.

We have no consensus on the pure discount rate δ (Frederick et al., 2002). In the macroeconomic literature and in finance, a rate around 2% is often suggested (Skinner, 1989; Moore and Viscusi, 1990). Many authors have argued for a rate of zero or near-zero (Ramsey, 1928, p. 543; Pigou, 1932, pp. 24–30; Harrod, 1949, p. 40; Parfit, 1986, pp. 480–486; Cowen, 1992; Broome, 2004, pp. 68–76; Stern, 2008, p. 35). Their argument is intuitive: it is simply implausible that people's wellbeing can be less valuable just because it occurs later in time. Cowen (1992) points out that discounting violates the Pareto principle for a person who might live either at one time or at a later time. Some have argued for a positive rate (Dasgupta and Heal, 1980; Arrow, 1999). One additional argument against a zero rate is that it places an extremely heavy moral burden on the current generation (Dasgupta, 2007). Stern (2008) used delta =0.1% to account for risk of extinction.

Box 3.5.4. Plausible values for collective inequality aversion

Consider the following thought experiment. A country has two equally populated social groups. The wealthy group consumes twice as many goods and services as the poor group. Contemplate an economic policy whose aim is to increase consumption by 1 unit for every person in the poor group. This implies a reduction of consumption for every wealthy person by x units, which may not be equal to 1 due to inherent inefficiencies in the tax system. If one is neutral to inequalities, one would not accept this policy if x is larger than 1. Inequality aversion justifies accepting some productive inefficiency, so that an x larger than 1 may be allowed. What is the maximum value of x that one would accept to implement the policy? Answering this question tells us something about inequality aversion, with a large x being associated with a larger η. A simple marginalist argument yields $\eta=\ln x/\ln 2$ (Gollier, 2012). If one is collectively ready to sacrifice as much as x=2 units of consumption from the rich to provide one unit of consumption to the poor, this is compatible with an inequality aversion index η=1. An x of 4 or 8 would correspond to an index of inequality aversion of 2 and 3, respectively.

Different authors have taken different positions on the values of δ, η, and g, yielding different recommendation for the social discount rate ρ. We summarize them in Table 3.5.1.

Table 3.5.1. Calibration of the discount rate based on the Ramsey rule (**Equation 3.5.3**)

Reference	δ	η	g	Implied social discount rate ρ
Weitzman (2007a)	2%	2	2%	6%
Nordhaus (2008)	1%	2	2%	5%
Stern (2007)[20]	0.1%	1	1.3%	1.4%
Garnaut (2008)	0.05%	1 or 2	1.3%	1.35% or 2.65%
UK: Green Book (HM Treasury, 2003)	1.5%	1	2%	3.5%*
France: Rapport Lebègue (2005)	0%	2	2%	4%*
Cline (1992)	0%	1.5	1%	1.5%

*Decreasing with the time horizon.

In Table 3.5.1, the Ramsey formula can be seen to yield a wide range of discount rates (1.4-6%), though it is true that most or all of the estimates reflect developed country experience.[21] The Stern Report (2007) has put on the international research agenda a comprehensive debate in the literature on the discount rate that should be applied in governments' analysis of climate change mitigation options, in particular mounting an argument for a near-zero value for the rate of pure time preferences.

Due to differences in time and equity preferences, different countries may use different discount rates when credit and risk-sharing markets are incomplete, since they may also face differing levels of development and expectations about the growth of their economy. For example, using the Ramsey rule for recent high economic growth rates in China would yield a discount rate above 15% per year (depending on η), whereas using it for some shrinking economies could generate a negative discount rate. This is another source of international disagreement about the appropriate strength of GHG mitigation efforts. The global discount rate to be used to evaluate global actions will then depend upon how costs and benefits are allocated across countries.

The discount rate described here should be used to discount risk-free costs and benefits (Anthoff et al., 2009). The rates that appear in Table 3.5.1 are typically larger than real interest rates observed on financial markets, in particular for long durations. This discrepancy between the prediction of interest rates from the Ramsey rule and observed interest rate is the risk-free rate puzzle (Weil, 1989). The puzzle comes from the inability of the theory under certainty to explain why people saved so much in the 20th century in spite of the low interest rates. Compared to the state of the art on discounting that was discussed in Second Assessment Report of the IPCC (1995, pp. 196–197), the

[20] Stern (2007) does not use the marginalist approach that forms the basis of the discount rate. Rather, he relies on a SWF with the corresponding parameter.

[21] The US Government (US Office of Management and Budget, 2003) recommends using 7%, with the reason: "7% is an estimate of the average before-tax rate of return to private capital in the U.S. economy" (US Office of Management and Budget, 2003). OMB (2003) also suggests using an alternative (for sensitivity analysis), 3%, justified by the "social rate of time preference. This simply means the rate at which society discounts future consumption flows to their present value. If we take the rate that the average saver uses to discount future consumption as our measure of the social rate of time preference, then the real rate of return on long-term government debt may provide a fair approximation" (US Office of Management and Budget, 2003). These figures are omitted from the table since the Ramsey Equation cannot be directly applied.

recent literature on discounting has tried to solve this puzzle by taking into account the uncertainty surrounding economic growth. Prudent agents should care more about the future if the future is more uncertain, in line with the concept of sustainable development. This leads to an extended Ramsey rule in which a negative precautionary effect is added:

Equation 3.5.4. $$\rho_t = \delta + \eta g_t - 0.5\, \eta(\eta+1)\sigma_t^2$$

where σ_t is the annualized volatility of the growth rate of GDP/cap, and g_t is now the expected annualized growth rate until time horizon t. Under reasonable parameter values, Gollier (2008) shows that this precautionary effect reduces the discount rate by 1% for short time horizons and up to 3% for the distant future. These results are related to the literature on Gamma discounting (Weitzman, 1998, 2001, 2010b; Gollier and Weitzman, 2010), in which a permanent shock to the rate of return of productive capital in the economy is expected to occur in the near future. This also justifies a decreasing term structure on discount rates.

It is important to observe that this literature has been mostly devoted to the rate at which safe projects should be discounted. In most cases however, actions with long-lasting impacts are highly uncertain, and that should be taken into account in their evaluation. It is important to give a bonus in the evaluation of actions that reduce the aggregate risk borne by individuals, and to penalize actions that raise this risk. The traditional method to perform this is to raise the discount rate of a project by a risk premium $\pi=\beta\pi_g$ that is equal to the project-specific β and a global risk premium π_g. The project-specific beta is a measure of the statistical correlation of the growth of the net benefit of the project with the growth of aggregate consumption. It measures the additional risk that the project imposes to the community. On average, it should be around 1. The global risk premium is usually assumed to be between 3% and 6%, but there is still no consensus about its socially desirable value, as shown by the equity premium puzzle first explained by Mehra and Prescott (1985). This is due to the fact that the equilibrium price of risk observed on financial markets during the last century has been much larger than what we believe about the level of risk aversion of human beings. There has been almost no research up to now about the value of the climate beta. The only exception is Sandsmark and Vennemo (2006), who suggested that it is almost zero.[22] To illustrate, the discount rate with a $\beta=0.5$ should be discounted at a rate equal to the risk free rate discussed in this section plus 0.5x4%=2%.

Although there remains a significant amount of uncertainty and debate regarding the social discount rate for evaluating mitigation options, a selection of typical analyses in the literature presented in the chapter implies a social discount rate between 1% and 7% per annum (medium agreement) or between 0% and 8% per annum (high agreement). Note that most evidence comes from developed countries.

3.5.3 Co-benefits

This section explains the definition of co-benefits and provides a general framework for analysis in other chapters. We describe some pitfalls and a few key examples. Then we provide more specific analysis using an economic model.

A climate policy's primary objective is to reduce emissions of CO_2 and other GHGs that contribute to future climate change. A major example of a co-benefit in existing literature is that carbon policy would also likely reduce the use of coal and other fossil fuels, and thereby reduce emissions of other local pollutants like SO_2, NO_X, and gases that contribute to ozone, a major health hazard.

[22] Barro (2006, 2009) and Martin (forthcoming) recently showed that the introduction of rare catastrophic events (such as climate catastrophes) can justify using at the same time a low safe discount rate around 1% and a large aggregate risk premium around 4%.

3.5.3.1 A general framework for evaluation of co-benefits

As a simple example, suppose social welfare W is a function of different goods or objectives z_i ($i = 1, \ldots, m$), and that each of those objectives might be influenced by a set of different policy instruments, p_j ($j = 1, \ldots, n$). In other words, each policy may have an impact on more than one objective: $W(z_1, \ldots z_m)$ with each z_i a function of $(p_1 \ldots p_n)$. Now consider a small change in policy #1: p_1. Taking the total derivative of W with respect to a small change of one policy dp_1 yields:

Equation 3.5.5. $$dW = \frac{\partial W}{\partial z_1}\frac{\partial z_1}{\partial p_1}dp_1 + \frac{\partial W}{\partial z_2}\frac{\partial z_2}{\partial p_1}dp_1 + \cdots + \frac{\partial W}{\partial z_m}\frac{\partial z_m}{\partial p_1}dp_1$$

For example, suppose $dp_1 > 0$ is additional GHG abatement (tightening the cap on CO_2 emissions). Then the "direct" benefits of that climate policy might include effects on climate objectives such as mean global temperature (z_1), sea level rise (z_2), lost agricultural productivity (z_3), lost biodiversity (z_4), and health effects of global warming (z_5). The "co-benefits" of that climate policy might include changes in a different set of objectives such as sulphur dioxide emissions (z_6), energy security (z_7), labour supply and employment (z_8), the distribution of income (z_9), and the degree of urban sprawl (z_{10}).

Here, the co-benefit is defined as the *physical effect* on a non-climate objective ($\partial z_i / \partial p_1$), without yet evaluating social welfare (not multiplied by $\partial W / \partial z_i$). The reason is so that co-benefits can be measured by engineers or other experts on health effects or urban sprawl. In contrast, the *value* of the co-benefit is the effect on social welfare ($\partial W / \partial z_i$), which requires a different kind of evaluation, one that might be conducted by economists using valuation methods discussed later in this chapter.[23] Moreover, it may require use of a "second-best" analysis that accounts for multiple market distortions.[24] If the externality from SO_2 is already partly corrected by a tax or permit price on SO_2, for example, then the welfare gain from one ton reduction in SO_2 may be less than its marginal external damage (MED). Indeed, if the price per ton of SO_2 is equal to its MED, then the welfare gain from a reduction in SO_2 is zero.

The full evaluation of dW in the equation above requires four major steps. First, identify the various multiple objectives z_i ($i = 1, \ldots, m$). Second, for a particular climate policy such as a CO_2 emissions cap, identify physical effects on all those objectives (direct effects and co-benefits $\partial z_i / \partial p_1$, for $i = 1, \ldots, m$). Those steps are examined, for example, in chapters 8-12 of this volume. Third, evaluate each effect on social welfare (multiply each $\partial z_i / \partial p_1$ by $\partial W / \partial z_i$). Fourth, sum the effects on social welfare in Equation 3.5.5.

3.5.3.2 The valuation of co-benefits

The list of goods or objectives z_i ($i = 1, \ldots, m$) could include any commodity, but it is not necessary to include goods sold in markets with no market failure or distortion, because in those cases the social marginal benefit (to the consumer) is equal to the social marginal cost (to the producer). With no distortion, a change in quantity has no net effect on welfare ($\partial W / \partial z_i = 0$). The effect on welfare is *not* zero, however, if climate policy affects the quantity of a good sold in a market with a "market failure" (or a "market distortion") such as non-competitive market power, an externality, or any pre-existing tax. In general, either monopoly power or a tax would raise the price paid by consumers relative to the marginal cost faced by producers. In such cases, any increase in the

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[23] We distinguish here between the welfare effect of the co-benefit ($\partial W / \partial z_i$) and the welfare effect of the policy operating through a particular co-benefit ($\frac{\partial W}{\partial z_i}\frac{\partial z_i}{\partial p_1}dp_1$).

[24] Following the logic of Lipsey and Lancaster (1956), the optimal carbon tax is equal to "marginal environmental damages" (MED) in a first-best setting with no distortion in any other market. But with any unchangeable tax or externality in some other market, then the second-best choice for carbon tax is not necessarily equal to MED. It could be higher or lower than the MED of carbon emissions, if that choice helps offset some other distortion(s).

commodity would have a social marginal benefit higher than social marginal cost (a net gain in welfare).

We now describe a set of studies that have evaluated welfare effects of co-benefits. For one example, oligopolies may exert market power and raise price above marginal cost in large industries such as natural resource extraction, iron and steel, or cement. And climate policy may affect that market power. Ryan (2012) finds that a prominent environmental policy in the United States actually increased the market power of incumbent cement manufactures, because it decreased competition from potential entrants that faced higher sunk costs. That is, it created barriers to entry. That effect led to a significant loss in consumer surplus that was not incorporated in the policy's initial benefit-cost analysis.

For another example, Ren et al. (2011) point out that a climate policy to reduce CO_2 emissions may increase the use of biofuels, but that "corn-based ethanol production discharges nitrogen into the water environment … [which] … can cause respiratory problems in infants and exacerbate algae growth and hypoxia in water bodies" (p. 498). In other words, a change in climate policy (dp_1) affects the use of nitrogen fertilizer and its runoff ($\partial z_i/\partial p_1$). If nitrogen runoff regulation is less than optimal, the effect on social welfare is negative ($\partial W/\partial z_i$<0). The effect is an "adverse side effect".

Perhaps the most studied co-benefits of climate policy are the effects on local air pollutant emissions, air quality, and health effects of ground-level ozone. Burtraw et al. (2003) conclude that a $25 per metric ton carbon tax in the U.S. would reduce NO_X emissions and thereby provide health improvements worth $8 per metric ton of carbon reduction in the year 2010 (in 1997 dollars). Importantly, these health co-benefits tend to accrue locally and in the near-term. More recently, Groosman et al. (2011) model a typical U.S. climate policy proposal (specifically Warner-Lieberman (S.2191)). They calculate effects on health from changes in local flow pollutants that are worth $103 billion to $1.2 trillion for the years 2010-2030 (in present value 2006 dollars). That total amount corresponds to $1 to $77 per ton of CO_2 (depending on model assumptions and year). These health co-benefits mainly come from reductions in particulate matter and ozone, attributable to reductions in use of coal-fired power plants.[25]

Researchers have calculated climate policy co-benefits in many other countries. For instance, Riekkola et al. (2011) find significant ancillary benefits domestically in Sweden from climate policy. Aunan et al. (2004) conclude that China could reduce its CO2-emissions by 17.5% without suffering a welfare loss, because of co-benefits of climate policy (evenly split between agricultural gains and health benefits). Similarly, Dessus and O'Connor (2003) find that Chile could reduce GHG emissions by 20% without welfare loss, where the ancillary benefits come from reductions in health risks.

Examples of other co-benefits may include changes to other objectives such as economic and social development, energy security, employment, and public health. The full analysis of climate policy needs to measure all such physical effects or co-benefits ($\partial z_i/\partial p_1$), but then welfare evaluation needs to bear in mind that those other markets may be functioning properly or already optimally regulated (in which case $\partial W/\partial z_i$ = 0). Below, we discuss regulation that is less than optimal. Changes in those physical outcomes only affect social welfare in the presence of some market failure such as transactions cost or an externality that is not optimally regulated. If labour is fully employed and mobile, for example, then climate policy may have direct costs from use of that labour, but no welfare gain from changes in employment. If other energy policies already achieve the right amount of energy security (at some cost), then any further energy security has no net gain. In other words,

[25] Both Burtraw et al. (2003) and Groosman et al. (2011) estimate the dollar value of health improvements, but these are "gross" benefits that do not account for the offsetting effects of existing controls on these local pollution emissions. That is, these estimates are *not* net welfare gains, as discussed below.

in measuring the welfare effects of co-benefits, it is generally not appropriate simply to use gross marginal damages associated with the co-benefit.

Even external effects on public health could be either direct benefits of climate policy or co-benefits. After all, the social cost of carbon (μ_C) includes the increased future incidence of heat stroke, heart attacks, malaria, and other warm climate diseases. Any reductions in those health-related costs of climate change are therefore direct benefits of climate policy. The definition of co-benefits is limited to effects of reductions in other health effects such as from sulphur dioxide, as just discussed.

Similarly, if climate policy reduces global warming and thus the number of warm sunny days that contribute to creation of ozone, then *direct* effects of climate policy could include that portion of the reduction in future local ambient air quality problems. In other words, reduced ozone effects from reduced SO_2 and NO_X are co-benefits of climate policy, but reduced ozone effects from the reduced number of warm sunny days is a direct benefit of climate policy.

Use of the terminology should be clear and consistent, but then a proper cost-benefit analysis needs to add *all* gains and losses from the climate policy being analyzed – as shown in Equation 3.5.5 – the sum of welfare effects from direct benefits plus the welfare effects of co-benefits.

3.5.3.3 An economic model of the second best, with multiple taxes and externalities

As a specific example of the general framework in Equation 3.5.5 above, the simple general equilibrium analysis of Fullerton and Metcalf (2001) can be used to account for several markets simultaneously when some of those markets might have a pre-existing distortion such as a tax or an externality that is not optimally regulated. These other distortions make it a “second-best setting”. It is a special case, because the model assumes no monopoly power, many identical consumers, and a closed economy where all markets clear with no transactions costs. Fullerton and Metcalf solve for the effects of a small change in an environmental tax such as a carbon tax. With some modification of their notation to match the notation used above, their approach provides the change in economic welfare:

Equation 3.5.6.

$$\frac{dU}{\lambda} = \sum_{i=1}^{m} (t_i - \mu_i) \frac{\partial z_i}{\partial p_1} dp_1$$

where U is utility a representative individual gains from a vector of commodities z_i $(i = 1, \ldots, m)$, which may include various outputs, inputs, and pollutants. Then λ is the marginal utility of income $(\partial U / \partial Income)$, so the left side of this equation is the change in utility, converted into monetary equivalent when divided by λ. It is the monetized net benefit of the policy. In other words, the left side of Equation 3.5.6 corresponds directly to the left side of Equation 3.5.5, dW. On the right side of the equation, dp_1 is the change in climate policy; μ_i is the marginal external damage (MED) from the i^{th} commodity; and t_i is its tax rate (or permit price, or the effect of a mandate that makes an input such as emissions more costly).[26]

The effect of each good on welfare ($\partial W / \partial z_i$ in Equation 3.5.5 above) is reduced in this model to just $(t_i - \mu_i)$. The intuition is simple: t_i is the buyer’s social marginal benefit minus the seller’s cost; the externality μ_i is the social marginal cost minus the seller’s cost. Therefore, $(t_i - \mu_i)$ is the social marginal benefit minus social marginal cost. It is the net effect on welfare from a change in that commodity.

For a pollutant, t is most easily understood as a tax on emissions. However, it is more appropriately thought of as the effective price placed on pollution by regulation. Regulation makes it costly for a firm to emit another tonne of pollution, whether through a pollution tax, a cap and trade system, or some other kind of regulation.

[26] One input may be labour, for example, with a pre-existing tax rate (even if labour has no externality). We return to labour and labour taxes shortly.

A static example is useful. Suppose one of the goods is sulphur emissions, a tonne of which generates marginal external damage μ_s. Assume sulphur is regulated with an emission fee (or other regulation which has the same effect) equal to t_s. The net welfare gains of one more tonne of sulphur is (t_s-μ_s), the negative of which might be called to "net social cost of sulphur." Absent any sort of regulation, the net social cost of sulphur would be μ_s.

Although the model underlying Equation 3.5.6 is static and climate change is inherently dynamic, the concepts represented in the static model can be used to understand the application to climate. Climate policy reduces carbon emissions, but Equation 3.5.6 shows that this "direct" effect does not add to social welfare unless the damage per ton of carbon (μ_C) exceeds the tax on carbon (t_C). The social cost of carbon, which is somewhat ambiguously defined in the literature, is discussed in section 3.8.4 of this chapter. To see a co-benefit in this equation, suppose z_S is the quantity of sulphur dioxide emissions, t_S is the tax per ton, and μ_S is the MED of additional SO_2. If the tax on SO_2 is too small to correct for the externality ($t_S - \mu_S < 0$), then the market provides "too much" of it, and any policy such as a carbon tax that reduces the amount of sulphur dioxide ($\partial z_S / \partial p_1 < 0$) would increase economic welfare. The equation sums over all such effects in all markets for all other inputs, outputs, and pollutants.[27]

If those local pollution externalities are already corrected by a tax or other policy ($t_S = \mu_S$), however, then a reduction in SO_2 adds nothing to welfare. The existing policy raises the firm's cost of SO_2 emissions by exactly the MED. That firm's consumers reap the full social marginal benefit per ton of SO_2, through consumption of the output, but those consumers also pay the full social marginal cost per ton SO_2. In that case, one additional ton of SO_2 has social costs exactly equal to social benefits, and so any increase or decrease in SO_2 emissions caused by climate policy provide no net social gain. In fact, if $t_S > \mu_S$, then those emissions are already over-corrected, and any decrease in SO_2 would reduce welfare.

3.5.3.4 The double dividend hypothesis

Another important example of a co-benefit can arise from the interaction between carbon policies and other non-environmental policies (Parry, 1997; Parry and Williams, 1999). Though enacted to reduce GHG emissions, a climate policy may also raise product prices and thus interact with other taxes that also raise product prices. Since the excess burden of taxation rises more than proportionately with the size of the overall effective marginal tax rate, the carbon policy's addition to excess burden may be much larger if it is added into a system with other taxes on output or on inputs. Instead, economic efficiency can be enhanced by using a carbon tax or sale of permit revenue to reduce other distorting taxes.

This logic has given rise to the 'double dividend hypothesis' that an emissions tax can both improve the environment and provide revenue to reduce other distorting taxes and thus improve efficiency of the tax system (e.g., Oates and Schwab, 1988; Pearce, 1991; Parry, 1995; Stern, 2009).[28] Parry (1997) and Goulder et al. (1997) conclude that the implementation of a carbon tax or emission trading can increase the deadweight loss of pre-existing labour tax distortions (the "tax interaction effect"), but revenue can be used to offset distortionary taxes (the "revenue recycling effect"). Parry and Williams (1999) investigate the impacts of existing tax distortions in the labour market for eight

[27] An interpretation is that $(\mu_S)(\partial z_S/\partial p_1)$ is a "gross" gain from reducing sulphur emissions – the reduction in damages from acid rain and health hazards. Then $(t_S)(\partial z_S/\partial p_1)$ is the gross social cost of reducing sulphur – what has to be given up to reduce sulphur emissions. The net effect on welfare is $(t_S - \mu_S)(\partial z_S/\partial p_1)$.

[28] The literature contains two versions of the double dividend hypothesis. A "strong" version says that efficiency gains from diminishing distortionary taxes can more than compensate the costs of pollution taxes. Another "weak" version says that those gains compensate only part of the costs of pollution taxes (Goulder, 1995).

climate policy instruments (including energy taxes and performance standards). They conclude that pre-existing tax distortions raise the costs of all abatement policies, and that the superiority of carbon taxes or emissions trading depends on whether generated revenues can be directed to reduce other distortionary taxes.[29] A lesson is that forgoing revenue raising opportunities from a GHG regulation can significantly increase inefficiencies, as is reflected in recent practice of carbon pricing. The European Union is auctioning an increasing share of permits with revenue going to member states. Australia is using a large share of carbon pricing revenue to reduce income tax (Jotzo, 2012).

To put this discussion into the context of co-benefits, note that Fullerton and Metcalf (2001) use Equation 3.5.5 above (and the special case of Equation 3.5.6 above) to consider labour (z_L), taxed at a pre-existing rate t_L (with marginal external damages of zero, so $\mu_L = 0$). The only other distortion is from carbon emissions (z_C), with marginal environmental damages (μ_C). Thus the economy has "too little" labour supply, and "too much" pollution. The combination "policy change" is a small carbon tax with revenue used to cut the tax rate t_L. Other taxes and damages are zero ($t_i = \mu_i = 0$) for all goods other than z_L and z_C. Thus, the Equation 3.5.6 above simplifies further, to show that the two key outcomes are just the net effect on pollution (dz_C) and the net effect on labour (dz_L):

$$\frac{dU}{\lambda} = t_L dz_L + (t_C - \mu_C) dz_C$$

Thus, an increase in the carbon tax that reduces emissions ($dz_C < 0$) has a direct benefit of increased economic welfare through the second term, but only to the extent that emissions damages exceed the tax rate ($\mu_C > t_C$). If the labour tax cut increases labour supply, then the first term also increases welfare (a double dividend). But the carbon tax also raises the cost of production and the equilibrium output price, which itself *reduces* the *real* net wage (the tax interaction effect). If that effect dominates the reduction in the labour tax rate (from the revenue recycling effect), then labour supply may fall ($dz_L < 0$). In that case, the first term has a negative effect on well-being. In other words, the double-dividend is possible under some circumstances and not others. If the revenue is *not* used to cut the labour tax rate, then the real net wage does fall, and labour supply may fall. Then Fullerton and Metcalf (2001) show cases where the very first step to introduce a carbon tax may *reduce* economic welfare, if the welfare cost of exacerbating labour supply distortions (the first term) exceeds the gain from reducing the pollution externality (the second term).

3.6 Policy instruments and regulations

By climate mitigation policy instruments we mean action taken to prevent or reduce emissions of GHGs in response to measures implemented by governments. Policy instruments can be categorized in several ways. "Direct" policy instruments are those that aim to reduce GHG emissions explicitly (including taxes, tradable allowances and regulations of GHG emissions). "Indirect" instruments are not specifically directed at reducing GHG emissions, but may have significant climate-related effects like, for instance, reduction of GHG emissions due to increased energy efficiency or the promotion of renewable energy. We categorize instruments into groups: economic instruments, regulatory approaches (prescriptive regulations), information programmes, government provision, and voluntary actions. For details about applications and assessments, see Chapters 8-11 (sectoral level), Chapter 13 (international level) and Chapter 15 (national and sub-national level).

[29] If existing income taxes reduce the real net wage and distort labour supply decisions, then pollution taxes or restrictions such as quotas may raise output prices further, reduce the real net wage, and exacerbate the deadweight loss of taxes.

3.6.1 Economic instruments

Economic instruments involve incentives that alter the conditions or behaviour of target participants with a resulting reduction in aggregate emissions. This group of instruments includes emission taxes or fees, tradable allowances, subsidies and other property-rights assignments.

An important distinction in economic instruments is between price and quantity policies (Weitzman, 1974, 1978; Nordhaus, 2007a). A tradable allowance or permit system is an example of a quantity policy whereby the total quantity of pollution (a cap) is defined, and trading in emission rights under that cap is allowed. A price instrument involves polluters paying a fixed price per unit of emissions, regardless of the quantity of emissions. With perfect information, a fixed price would lead to a known quantity and vice versa (Weitzman, 1974). In practice, however, abatement costs and marginal climate change damage costs are unknown in advance. Therefore the price policy may lead to an uncertain quantity of pollution than anticipated, while the quantity policy leads to an uncertain marginal cost of abatement. Another issue is how to determine the tax rate or the cap on emissions (see section 3.8).

3.6.1.1 *Taxes*

Taxes are levies imposed on each unit of undesirable activity by a source. *GHG taxes* (or slightly more narrowly, carbon taxes) are defined as a payment for each unit of GHG released into the atmosphere. In well-functioning markets, uniform GHG taxes imply equal marginal abatement costs for all emission sources. This results in the emission reduction being accomplished at minimum cost. A tax also provides incentives to the introduction of cleaner technologies. If the tax is set equal to the marginal cost of GHG emissions, then in principle an emissions tax would facilitate an efficient level of mitigation. If the revenue is used to reduce inefficient taxes, additional social benefit can be obtained (see section 3.5.3). An emissions tax need not apply the full amount of emissions covered. Tax thresholds can exempt part of the overall amount of any emitter's liabilities, while charging the tax rate on any extra emissions, analogous to free permits under emissions trading (Pezzey, 2003).

3.6.1.2 *Tradable allowances*

Tradable allowances (also known as marketable permits or cap-and-trade systems) establish a cap on aggregate emissions by specified sources. The system requires each source to hold permits equal to pre-specified emissions, and allows permits to be traded among sources. The EU GHG emission trading system (EU ETS) is an excellent example. The marginal abatement costs for the emission sources are determined in the market and equal to the market price for allowances. The system implies cost-effective fulfilment of the cap and encouragement for innovation in cleaner technologies, as is the case for optimally formulated GHG taxes. Allowances can be distributed for free (grandfathering) or through auctioning. The latter allows the use of revenues in the same way as an emission tax, as discussed in section 3.5.3 .

3.6.1.3 *Subsidies*

In the presence of positive externalities, a third party benefits from a good at no cost to them. From a welfare perspective, too little of the good is produced or consumed. This typically applies to R&D, innovation, learning-by-doing and diffusion of new technologies (Griliches, 1992; Jaffe et al., 2005). Empirical research demonstrates that social rates of return to research and development can be higher than private rates of return, since spillovers are not fully internalized by the firms (see section 3.10). Both theory and empirical evidence suggest that the rate and direction of technological advance is influenced by market and regulatory incentives, and can be cost-effectively harnessed through the use of economic-incentive based policy. Subsidies can correct the market prices to reflect the full social benefits and thus stimulate the development of GHG friendly technologies.

Other provisions aim at reducing carbon intensity by subsidizing more efficient energy appliances and renewable energy production. The first problem with paying polluters to reduce emissions is that funds need to be raised to finance the subsidy, and, inefficiencies arise with raising public funds through taxation (Ramsey, 1927). A second problem is that subsidies can lead to excessive entry – firms that should go out of business do not. All energy subsidies bring about environmental costs, and fossil fuel subsidies have proven difficult to eliminate (IEA (International Energy Agency) et al., 2011).

3.6.2 Prescriptive regulatory approaches

Regulations establish rules and/or objectives that must be fulfilled by the polluters who would face a penalty in case of non-compliance with the norm. Examples are performance standards, mandated technology standards, and building codes. Emission standards (also termed performance standards) specify the maximum allowable discharges of pollutants into the environment. Technology standards mandate specific pollution abatement technologies or production methods, while product standards define the characteristics of potentially polluting products (Folmer and Gabel, 2000). Examples are standards and labelling for appliances in buildings, industry, and transportation sectors (Freeman and Kolstad, 2006).

3.6.3 Information programmes

To act in full compliance with their own preferences, agents need complete information about the consequences of their actions including social costs and benefits. Information is essential for adjusting to environmental challenges, and for optimal design and monitoring of environmental policies. The lack of relevant information among firms and consumers of total social costs and benefits of their actions can lead to poor decisions (compared to perfect information). National and international research programmes are core initiatives to increase knowledge and spread information about the potential consequences of GHG emissions and how to handle the risks (including the IPCC). At the national level, informative instruments include governmental financing of research and public statistics, along with programmes to increase the awareness of individuals with regard to consumption and production choices via education, media channels and labelling (Mont and Dalhammar, 2005).

3.6.4 Government provision of public goods or services

Governmental funding of public goods and services can directly aim at reducing GHG emissions. Examples are provision of infrastructure and public transportation services with less emission-intensive energy use (McCollum and Yang, 2009; Creutzig et al., 2011). Other examples are provision of government R&D aimed at generating innovative approaches to mitigation, and the physical and social infrastructure to reduce emissions (Gupta et al., 2007).

3.6.5 Voluntary actions

Voluntary agreements are agreements between a government authority and one or more private parties with the aim of achieving environmental objectives or improving environmental performance beyond compliance with regulatory obligations. These include industry agreements, self-certification, environmental management systems, and self-imposed targets.

Voluntary agreements can be developed in different ways: in most cases the voluntary commitment is assumed as a consequence of an explicit negotiation process between the regulator and the pollutant. In other cases a spontaneous commitment may be viewed as a way to avoid future mandatory alternatives from the regulator. The regulator may also promote standard environmental agreements on the basis of estimation of costs and benefits to firms (Croci, 2005). It is hence debatable whether voluntary agreements are truly voluntary; some include rewards and/or penalties associated with participating in the agreement or achieving the commitments. The literature is ambiguous as to whether any additional environmental gains are obtained via voluntary agreements (Koehler, 2007; Lyon and Maxwell, 2007; Borck and Coglianese, 2009).

3.6.6 Policy interactions

Whereas the majority of the literature has been concerned with the use and assessment of one instrument, or comparison between alternative options, the reality shows a portfolio of instruments in operation. In fact, multiple objectives surrounding climate change mitigation, such as energy security and energy prices, and distributional consequences of climate policy have been addressed through numerous policy instruments.[30] The coexistence of different instruments creates synergies, overlaps and problematic interactions (see section 3.5.3).

Energy policy instruments include regulated renewable energy shares in energy production (renewable energy certificates), requirements for demand-side energy savings (white certificates), and direct subsidies to renewable energy production and savings. As suggested by Böhringer and Rosendahl (2010), tradable certificates for renewable energy imposed on top of emission trading not only induces substantial excess cost but serves the dirtiest power technologies as compared to an emission trading regime only (because tradable certificates reduce the shadow cost of the emission constraint, mainly benefiting the most emission-intensive technologies). Fankhauser et al. (2010) found that simply adding a carbon tax to an existing cap-and-trade system reduces the carbon price in the market to such an extent that the overall price signal may remain unchanged, and that feed-in tariffs or renewable energy obligations within a capped area undermine the carbon price in the rest of the trading regime, likely increasing costs without reducing emissions.

Another important type of interaction is between carbon policies and other environmental or non-environmental policies (Parry, 1997; Parry and Williams, 1999). A carbon tax or other policy may be enacted to reduce GHG emissions, but it may also increase or reduce other emissions. It may thus require changes in other non-carbon policies, such as sub-national restrictions on sulphur dioxide or other local pollutants.

Policy interactions also create important implementation and enforcement challenges when policies are concurrently pursued by different legal or administrative jurisdictions (Goulder and Parry, 2008), like state and federal programmes in the context of US climate change policy (Goulder and Stavins, 2011).

3.6.7 Different conditions in developed and developing countries and implications for suitability of policy instruments

Differences in economic structure, institutions and policy objectives between low income and high income countries can imply differences in the suitability and performance of policy instruments. Overriding policy objectives in most developing countries tend to be strongly oriented toward facilitating development (Kok et al., 2008) or alleviating poverty (particularly in least developed countries). For more detail, refer to Chapter 15, section 15.9.

Many developing countries have less human and financial resources, advanced technology, and poorer institutional and administrative capacity compared to developed countries. This may constrain their ability to evaluate, implement and enforce policies. Thus, the use of certain market mechanisms, such as carbon trading schemes, can be difficult to implement, and require significant efforts for creating the institutional prerequisites. Capacity building has a critical role to play in creating support mechanisms for policy choice and implementation. In addition, entrenched distortions in regulatory and pricing mechanisms may need reform before price-based instruments can be effective.

The opportunity cost of capital, and of government resources in particular, may be higher in developing countries than in developed countries, and consequently the payoff from mitigation

[30] Complete descriptions of all the (potential) combinations of policy instruments can be found in sectoral Chapters (8-11) and policy assessment Chapters (13, 15 and 16).

policies need to be higher than in developed countries in order for mitigation investment to be judged worthwhile. Thus, developing countries may require significant international financial resources in order to support their mitigation activities or make them economically viable.

3.7 Assessing methods of policy choice

Programme evaluation or policy evaluation refers to the "process of determining the merit, worth or value of something or the product of that process (Scriven, 1991, p. 191).[31] It is the systematic application of social research procedures to assess the design, choice, and implementation of policy (Majchrzak, 1984; Rossi et al., 2004). Most importantly, the choice of specific climate policy instrument (or mix of instruments) depends upon many economic, social, cultural, ethical, institutional, and political contexts.

3.7.1 Policy objectives and evaluation criteria

In addition to reducing GHG emissions, climate policy may have many other objectives. Here, we organize these many objectives into four broad categories, following on the lead in the fourth assessment report of the IPCC (Gupta et al., 2007).[32] First, climate policy may have economic objectives that involve lowering economic costs, including transactions costs, losses in economic efficiency, and any adverse effects on economic development, innovation, and growth. Second, climate policy may have distributional objectives. It may need to avoid interfering with goals to alleviate poverty, if it is to be viewed as fair. These distributional and other fairness considerations are often decisive in the political sphere. Third, climate policy can have multiple environmental objectives at the local, regional, and global levels. Fourth, climate policy will need to be institutionally feasible for it to be adopted, in terms of administrative burden and other political considerations.[33]

Any policy option then can be evaluated by the extent to which it meets each of these policy objectives. That is, the list of "evaluation criteria" is the same as the list of policy objectives: does the policy appropriately balance economic costs, distributional considerations and environmental objectives in a way that is institutionally feasible? However, the relative importance of the different policy objectives is likely to differ among countries, especially between developed and developing countries. Each country has its own conditions, circumstances, and national priorities. While all objectives discussed here are relevant, different countries may apply different weights to them.

In this section, we discuss elements of those four categories of policy objectives and criteria. In doing so, we expand upon recent policy evaluation studies, leaving more details to Chapters 13-15. In fact,

[31] The literature on programme/policy evaluation is vast. For comprehensive overviews of history, theories, views and influences in the field of evaluation see, e.g., Alkin (2004), Pawson and Tilley (1997), Bardach (2011), and Chen (1990).

[32] The 3rd IPCC Assessment Report acknowledged many evaluation criteria but emphasized cost-effectiveness (see Bashmakov et al., 2001). The 4th IPCC Assessment Report broadened the scope; it emphasized the four dimensions of performance we use in this subsection (see Gupta et al., 2007). Here, we elaborate further.

[33] Political factors have often been more important than economic ones in explaining instrument choice (Hepburn, 2006). Existing industries have influenced policy to ensure that a large number of permits are allocated free to emitters (Smith et al., 1983); (Pezzey et al., 2010). Revenue can be used to achieve desired distributional outcomes and to offset adverse effects on employment (Freebairn, 2011). Redistribution to low-income households is an important feature in Australia's emissions pricing, along with features such as emissions price controls that reflect preferences of different groups in society (Jotzo and Hatfield-Dodds, 2011).

the literature stresses a broad variety of objectives and criteria (e.g., Opschoor and Turner, 1994; Ostrom, 1999; Faure and Skogh, 2003; Sterner, 2003; Mickwitz, 2003; Blok, 2007).

The basic economic framework for policy analysis can be depicted using a simple partial equilibrium diagram adapted from Fullerton (2011). This diagram (Figure 3.7.1) illustrates both the impacts of policies and the criteria to evaluate them in the context of the production of a polluting good (i.e., emissions are associated with producing the good – think electricity). To introduce the topic and focus on basic concepts, we initially abstract from various forms of complexity. We note, however, that many "non-economic" values can still be incorporated within this diagram, at least to the extent that values can be placed on those other considerations such as effects on natural preservation, culture, biodiversity, and "dignity" (see 3.2.2.1 and 3.2.2.2 above). We do not mean here to downplay other ethical considerations discussed in sections 3.2 and 3.3, but rather just to use the diagram here as a simple way to integrate many of the economic as well as non-economic objectives of climate policy.

As shown in Figure 3.7.1, the quantity of GHG emissions associated with production of a good such as electricity is shown on the horizontal axis, and the price or cost per unit of that good is shown on the vertical axis. The demand for those emissions is derived from the demand for electricity, as shown by the curve called Private Marginal Benefits (PMB). The private market supply curve is the Private Marginal Cost (PMC) of production, and so the unfettered equilibrium quantity would be Q^0 at equilibrium price P^0. This polluting activity generates external costs of climate change, however, and so each unit of output has a Social Marginal Cost (SMC) measured by the vertical sum of Private Marginal Cost (PMC) plus Marginal External Cost (MEC).

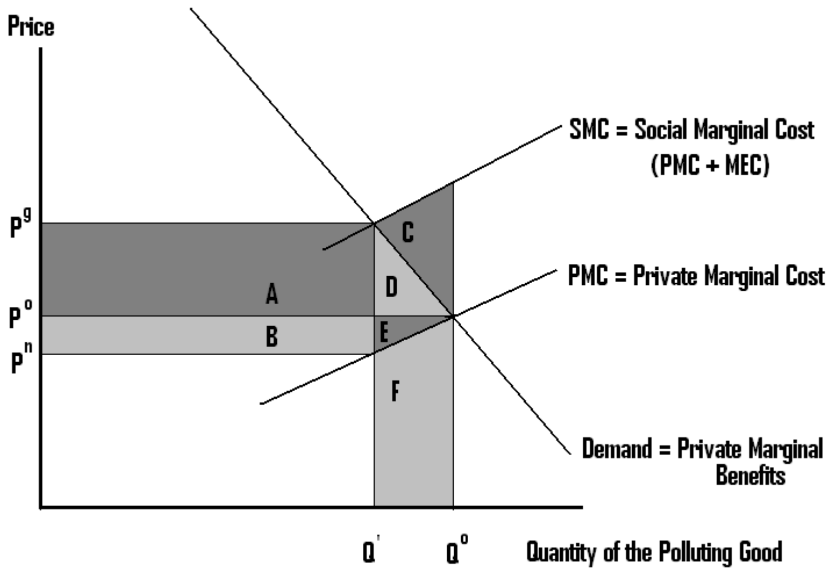

Figure 3.7.1. A partial equilibrium model of the costs and benefits of a market output
Assumptions of the simplest version of this model can be relaxed and discussed below but for now include perfect competition, perfect information, perfect mobility, full employment, and many identical consumers (so all individuals equally benefit from production, and they equally bear the external cost of pollution). We relax these assumptions as we discuss more general conditions below.

Under the simplifying assumptions, the social optimum is where SMC=SMB, at Q'. The first point here, then, is that the optimal quantity can be achieved by several different kinds of policies under these simple conditions. A simple regulatory quota could restrict output to Q', or a fixed number of tradable permits could restrict pollution to the quantity Q'. In that case, P^n is the equilibrium price *net* of permit cost (the price received by the firm), while P^g is the price *gross* of permit cost (paid by the consumer). The permit price is the difference, P^g - P^n. Alternatively, a tax of (P^g - P^n) per unit of pollution would raise the firm's cost to SMC and result in equilibrium quantity Q'.

This diagram will be used below to show how the equivalence of these instruments breaks down under more general circumstances, and it will be used to show gains and losses to various groups. In other words, we use this diagram below not only to discuss economic objectives, but also to discuss distributional objectives, other environmental and cultural objectives, and institutional feasibility.

3.7.1.1 Economic objectives

Economic efficiency. Economic Efficiency refers to an economy's allocation of resources (goods, services, inputs, productive activities). An allocation is efficient if it is not possible to reallocate resources so as to make at least one person better off without making someone else worse off. An allocation is inefficient if such a reallocation is possible. This is also known as the Pareto Criterion for efficiency (discussed in section 3.5.1.3).[34] In Figure 3.7.1, any reduction of output from Q^0 improves efficiency, because it saves costs (height of SMC) that exceed the benefits of that output (height of SMB).[35] Further reductions of output generate further net gains, by the extent to which SMC exceeds SMB, until output is reduced to Q' (where SMC=SMB). Hence, the gain in economic efficiency is area C in that diagram. Perfect efficiency is difficult to achieve, for practical reasons, but initial steps from Q^0 achieve larger gain (SMC>SMB) than the last step to Q' (because SMC≈SMB near the left point of triangle C).

An element of economic efficiency across time is the extent to which a policy encourages the right amount of investment in the future, including research, innovation, technical change, development, dissemination and commercialisation of low-carbon technologies (Jung et al., 1996; Mundaca and Neij, 2009). In other words, economic efficiency of carbon policy requires minimum cost abatement, which itself will require R&D into new technologies to abate GHG emissions more cheaply. See section 3.10 .

Cost-effectiveness. Pollution per unit of output in Figure 3.7.1 is fixed, but actual technologies allow many different ways to reduce pollution per unit of output. Some policies may require expensive means of reducing pollution per unit of output. A policy is more cost-effective if it achieves a given level of pollution abatement at lower cost. A critical condition for cost-effectiveness is that marginal compliance costs be equal among obliged parties.

Transaction costs. In addition to the price paid or received, market actors face other costs to initiate and complete transactions -- including the costs of search for information, due diligence, negotiation of contracts, and measurement. These costs alter the relative effectiveness of different policies.[36]

3.7.1.2 Distributional objectives

Six distributional effects. Because individuals are *not* all identical, a policy may generate gains to some and losses to others. The fairness or overall welfare consequences of these distributional effects is important to many people and can be evaluated using a social welfare function, as discussed in section 3.2.2.6 . These distributional effects fall into six categories (Fullerton, 2011). In

[34] If all consumers are identical, as in the simplest model, then all share in the net gain. This framework is a possible foundation of cost-benefit analysis (CBA), an operational and pragmatic approach to economic efficiency. In practice, of course, CBA can be ambitious, challenging, and sometimes impracticable, because it requires intensive data collection, assessment, and processing (see, e.g., Sterner, 2003; Harrington et al., 2004; Tietenberg, 2006).

[35] This approach supposes rational self-interested agents that maximize utility (and other assumptions listed). These are heroic and counterfactual assumptions but provide a rigorous and organized treatment. Other approaches are also valid, as discussed in section 3.9 , but may not generate definitive conclusions.

[36] In particular, this criterion often examines "the costs of arranging a contract *ex ante* and monitoring and enforcing it *ex post*, as opposed to production costs" (Matthews, 1986, p. 906).

Figure 3.7.1, any policy instrument might reduce the quantity of polluting output, such as from Q^0 to Q', which reduces the polluting emissions, raises the equilibrium price paid by consumers (from P^0 to P^g), and reduces the price received by the firms (from P^0 to P^n). It thus has six effects illustrated in Box 3.7.1. The box uses the example of coal-fired electricity, but the framework can be applied to any environmental problem and any policy to correct it.

Box 3.7.1. Six Distributional Effects of Climate Policy, illustrated for Coal-Fired Electricity

(1) The policy raises the cost of generating electricity and thus the consumer's price (from P^0 to P^g), so it reduces consumer surplus. In Figure 3.7.1, the loss to consumers is the sum of area A+D. Losses are greater for those who spend a relatively high fraction of income on electricity.

(2) It reduces the net price received by the firm (from P^0 to P^n), so it reduces producer surplus by the sum of area B+E. The effect is reduced payments to factors of production such as labour and capital. Losses are greater for those who receive more income from the displaced factor.

(3) Pollution and output are restricted, so the policy generates "scarcity rents" such as the value of a restricted number of permits (area A+B). If those permits are handed out to firms, these rents accrue to shareholders. The government could capture these rents by selling the permits or if the policy is a tax per unit of emissions (Fullerton and Metcalf, 2001).

(4) Because the policy restricts GHG emissions, it confers benefits to those who would otherwise suffer from climate change (including reduced losses to culture, biodiversity, etc.). The value of those benefits is area C+D+E.

(5) The electricity sector employs less labour, capital, and other resources. It no longer pays them (areas E+F). With perfect mobility, these factors are immediately re-employed elsewhere, with no loss. With imperfect mobility, however, those workers may suffer substantial social cost, not only in monetary terms but in loss of human dignity from, e.g., extended unemployment.

(6) Any gain or loss described above can be capitalized into asset prices, with large immediate effects on current owners. The value of a corporation's stock may rise by the expected present value of future scarcity rents; the value of a person's waterfront home may fall by the expected present value of sea level rise (or rise by a policy that protects it).

The connection between these distributional effects and "economic efficiency" can be noted by adding up all the gains and losses just described: the consumer surplus loss is A+D; producer surplus loss is B+E; the gain in scarcity rents is A+B; the environmental gain is C+D+E. The net sum of those gains and losses is just area C, described above as the net gain in economic efficiency.

Referring to Box 3.7.1, and regarding the first effect on consumers, carbon policy is generally found to be regressive (though most analyses are for developed countries), because the higher price of electricity would impose bigger proportional burdens on lower income groups who spend higher fractions of income on electricity (Metcalf, 1999). The second effect, on factors of production, is generally ambiguous. The third effect is regressive if permits are handed out to firms, because then profits accrue to shareholders who tend to be in high-income brackets (Parry, 2004). But if government captures the scarcity rents by selling permits or through a carbon tax, then it can use the funds to help offset burdens on low-income consumers and make the overall effect progressive instead of regressive. Other effects are quite difficult to measure.

Nonetheless, Figure 3.7.1 provides a framework for consistent measurement of effects on each group in society, effects than can then be inserted into a social welfare function such as discussed in 3.2.2.6 .

A major literature on "environmental justice" discusses the potential effects of pollution policy on different neighbourhoods with residents from different income or ethnic groups (Sieg et al., 2004).

This issue focuses on how climate policy affects pollution in particular neighbourhoods. Climate policy affects not only GHG emissions but other local pollutants such as SO_2 or NO_X, whose concentrations can vary widely in space. Furthermore, the cost of GHG mitigation may not be shared equally among all income or ethnic groups. And even "global" climate change can have different temperature impacts on different areas, or other differential effects (e.g. on coastal areas through sea level rise).

The distributional impacts of policies include aspects such as fairness and equity (Gupta et al., 2007). A perceived unfair distribution of costs and benefits could prove politically challenging (see below), since efficiency may be gained at the expense of equity. For a comparative analysis of the 'optimal' distribution of costs and benefits, see, e.g., Feldstein (1972).

3.7.1.3 Environmental objectives

Environmental effectiveness. A policy is environmentally effective to the extent it achieves its expected environmental target (e.g., GHG emission reduction). The simple policies mentioned above might be equally effective in reducing pollution (from Q^0 to Q' in Figure 3.7.1), but actual policies differ in terms of enforcement, administration, and compliance.

Co-Benefits. Climate policy may reduce not only GHG emissions but also local pollutants such as SO_2 emissions that cause acid rain or NO_X emissions that contribute to ozone. As described in the "co-benefits" section of this chapter (3.5.3), these reductions in other pollutants do not yield any net gain to society if those other pollutants are already optimally regulated (where their marginal abatement costs are equated to their marginal damages). If those pollutants are inefficiently regulated, however, then climate regulations can yield positive or negative net social gains from reductions of other pollutants.

Climate policy is also likely to affect other national objectives, such as energy security. For a country that wants to reduce dependence on imported fossil fuels, climate policy can bolster energy efficiency and domestic renewable energy supply, even while cutting GHG emissions.

3.7.1.4 Institutional feasibility

Administrative burden. Part of "institutional feasibility" is the extent of administrative workload, both for public authorities and for regulated entities. These human and financial costs depend on how the policy is implemented, monitored, and enforced (Nordhaus and Danish, 2003). This burden is related to the complexity of the institutional framework, the policy objectives, the number of regulated firms, and the accessibility of necessary data about these firms. Administrative costs matter in public policy, but they are often overlooked (which generates evaluation biases).

Political feasibility. Another part of institutional feasibility is the extent to which the policy is "viewed as legitimate, gain acceptance, adopted and implemented" (Gupta et al., 2007, p. 785). This criterion focuses on obstacles that hamper or enhance the political viability of a policy instrument. It aims to identify key design elements that can generate or reduce resistance among political parties (Nordhaus and Danish, 2003). Political feasibility may also depend on environmental effectiveness, costs, and how equitably the regulatory costs burden is distributed across society.[37] It depends on how distributional impacts align with power in the society; if the policy creates rents, it depends on whether these rents can be used to purchase support of a winning coalition of interest groups.

Ex ante, all these criteria can be used to help understand the effects of policies, improve their design, and assess which policies can achieve outcomes that would justify their implementation. *Ex post*, these criteria can be used to verify results, to withdraw inefficient policies, or to provide

[37] A critical issue when considering administrative burden and political feasibility is whether policy makers choose the most suitable institution to handle the policy's implementation and enforcement (Rist, 1998).

corrections to improve performance of policy. Different policies perform differently on these four evaluative criteria. Chapters 14 and 15 summarize performance of different instruments on the basis of these four criteria. Table 3.7.1 summarizes the policy instruments discussed in section 3.6 and the evaluative criteria discussed in this section.

Table 3.7.1. Policy types and evaluation criteria

Policy Types	Evaluation Criteria

• Economic Instruments (e.g., taxes, subsidies, tradable allowances, other property-rights assignments)
• Regulatory Approaches (e.g., performance standards, building codes, mandated technologies)
• Information Programmes (e.g., labeling, public awareness initiatives, certification programmes)
• Government Provision of Public Goods or Services (e.g., provision of infrastructure, government research activities, provision of public transportation services, removal of institutional or legal barriers)
• Voluntary Actions (e.g., industry agreements, self-certification, environmental management systems, self-imposed targets)
	• Environmental effectiveness
	  ○ Units: physical terms (emissions, concentrations, temperature, biophysical changes, etc.)
	  ○ Can encompass: environmental co-benefits, emissions leakage, interactions with other environmental objectives
	• Economic effectiveness (cost-effectiveness and economic efficiency)
	  ○ Units: value terms (money-metric equivalents to welfare changes)
	  ○ Can encompass: administrative costs, transaction costs, economic interactions across sectors or regions, interactions with other economic goals
	• Distributional equity and broader social impacts
	• Institutional, political, and administrative feasibility and flexibility

FAQ 3.3. What criteria should policy makers use when developing policies and measures to mitigate climate change?

The main goal of climate policy is to mitigate climate change. Cost efficiency is a core criterion to reach a climate goal at the lowest possible costs to present and future generations. Any policy will have distributional effects. These distributional considerations are often decisive in the political sphere. This brings in the ethical considerations related to the distribution of costs and benefits and need for compensatory instruments. A second criterion is to use one instrument per political goal. For instance if distribution and reduced GHGs are both targets, then it is likely that two instruments will be necessary. As an example, the practical formulation of economic instruments are usually undermined with exemptions to protect certain groups, rather than using cost efficient instruments to reduce emissions and then compensate prioritized groups directly. Climate policy will also need to be institutionally feasible for it to be adopted, in terms of administrative burden and other political considerations.

3.7.2 Analytical methods for decision support

Previous assessment reports have addressed analytical methods to support decision-making, including both numerical and case-based methods. Bruce et al. (1996), Chapter 2 and 10, focus heavily on quantitative methods and Integrated Assessment Models (IAM). In Metz et al. (2001), Chapter 10 provides a wider review of approaches, including emerging participatory forms of decision-making. In Metz et al. (2007), Chapter 2 briefly elaborates on quantitative methods and lists sociological analytical frameworks.

3.7.2.1 Quantitative-oriented approaches

To assist decision-making processes, quantitative methods can organize and manage numerical information, provide structured analytical frameworks, and generate alternative scenarios – with different levels of uncertainty (Majchrzak, 1984). Important challenges include measurement, causality, generalization, and replication (Bryman, 2004).

One specific quantitative approach is Cost-Benefit Analysis (CBA), as discussed extensively throughout this chapter. CBA attempts to estimate and aggregate monetized values of all costs and benefits that could result from a policy. It may require estimating non-market values, and choosing a discount rate to express all costs and benefits in present value. When benefits are difficult to estimate in monetary terms, however, then a Cost-Effectiveness Analysis (CEA) may be preferable. A CEA can compare the costs of different policy options (Tietenberg, 2006) in achieving a well-defined goal. CEA can estimate and identify the lowest possible compliance costs, generating a ranking of policy alternatives (Levin and McEwan, 2001). Otherwise, CEA and CBA have similar limitations with respect to data, measurement, and valuation of future intangible costs.

Various types of models may help provide information for Cost-Benefit Analysis, including energy-economy-environment (E^3) models that study energy systems and transitions towards more sustainable technology. Two methodologies for modelling E^3 system interactions are "bottom-up" and "top-down" approaches. Hybrids of these two approaches can compensate for some known limitations (Rivers and Jaccard, 2006):

- Given exogenously defined macroeconomic and demographic scenarios, "bottom-up" models can provide detailed representations of supply- and demand-side technology paths that combine both cost and performance data. Conventional bottom-up models may lack a realistic representation of behaviour and may overlook critical market imperfections such as transaction costs and information asymmetries (e.g.,Craig et al., 2002; De Canio, 2003; Greening and Bernow, 2004).
- In contrast, "top-down" models represent technology and behaviour using an aggregate production function for each sector to analyze effects of policies on economic growth, trade, employment, and public revenues (see, e.g., De Canio, 2003). They are often calibrated based on real data from the economy. However, such models may be too aggregated for some applications (Hourcade et al., 2006). Parameters are estimated from historical data, so forecasts may not predict a future that is fundamentally different from past experience, though that is a tall order for any model (Scheraga, 1994).

Multi-Criteria Analysis (MCA) is an approach to deal with the multiple evaluation criteria listed above (Greening and Bernow, 2004); it attempts to assess and compare the impacts and potential outcomes from competing policies (Mundaca and Neij, 2009). Some argue that the analysis of environmental and energy policies is a multi-criteria problem, entailing numerous decision makers with diverse objectives and levels of understanding of the science and complexity of analytical tools (Greening and Bernow, 2004). However, even with MCA, one must ultimately determine the appropriate trade-off rates among the different objectives. MCA often leads to complex analysis of trade-offs (Sterner, 2003).

Integrated Assessment Models (IAM) may be either top-down or bottom-up models (see also Chapter 6). Using insights from different disciplines, IAMs include complex relationships between atmospheric composition, climate and sea level, human activities, and ecosystem functions (Weyant et al., 1996). They can incorporate connections and feedbacks that allow examination of future paths of both natural and human systems (Morgan and Dowlatabadi, 1996). Also, computational limits may preclude the scales required for some climatic processes (Donner and Large, 2008).[38] For a critique of conventional IAMs, see Ackerman et al. (2009).

General equilibrium and other computational models can specify consumer and producer behaviour and "simulate" effects of climate policy on various outcomes including real gains and losses to different groups (e.g., households that differ by income, region, or demographic characteristics). With behavioural reactions, direct burdens are shifted from one taxpayer to another through changes in prices paid for various outputs and received for various inputs (Metcalf, 1999). A significant challenge is the definition of a 'welfare baseline' (i.e. what would be each welfare level in the absence of the policy).

Other quantitative-oriented approaches to support policy evaluation include tolerable windows (Bruckner et al., 1999), safe-landing/guard rail (Alcamo and Kreileman, 1996), and portfolio theory (Howarth, 1996). Outside of economics, others in the study of decision sciences emphasize the importance of facing difficult values-based trade-offs across objectives and the relevance of various techniques to help stakeholders address trade-offs (see, e.g., Keeney and Raiffa, 1993).

3.7.2.2 Qualitative-oriented approaches

Various qualitative policy evaluation approaches focus on social, ethical, and cultural dimensions of climate policy. They might complement quantitative economics approaches, by considering contextual differences, multiple decision makers, bounded rationality, information asymmetries, and political and negotiation processes (Toth et al., 2001; Halsnæs et al., 2007).

Sociological analytical approaches seek to examine human behaviour related to climate change (Blumer, 1956), including beliefs, attitudes, values, norms, and social structures (Rosa and Dietz, 1998). Focus groups can capture the fact that "individuals' attitudes and beliefs do not form in a vacuum: people often need to listen to others' opinions and understandings to form their own" (Marshall and Rossman, 2006, p. 114).

Participatory approaches focus on process, involving various actors actively participating in a given decision-making process (Van den Hove, 2000). Participatory approaches to support decision-making include Appreciation-Influence-Control (AIC), Goal Oriented Project Planning (GOPP), Participatory Rural Appraisal (PRA), and Beneficiary Assessment (BA). For pros and cons of various participatory approaches, see Toth et al. (2001, p. 652). Other qualitative-oriented approaches include systematic client consultation, social assessment, and team up (Toth et al., 2001; Halsnæs et al., 2007).

The literature on participatory approaches is vast, as further reviewed in Roberts (2004).

3.8 Metrics of costs and benefits

This section focuses on metrics and issues that arise in the measurement of benefits and costs associated with mitigation (and in some cases, adaptation). Ultimately, any climate policy seeks to balance the sacrifices (if any) necessary to reduce GHG emissions with the negative consequences of climate change should little or no mitigation take place. As this chapter has repeatedly emphasized, how that balancing is done in evaluating a climate policy is a matter for ethics. The information of this section is largely based on the economic paradigm of balancing costs of mitigation with benefits of mitigation, though the underlying information can be useful for policymakers adopting other ethical perspectives.

To put the organization of this section in context, it is useful to begin with the chain of cause-and-effect shown in Figure 3.8.1. The chain starts with human activity which generates emissions that

[38] Stanton et al. (2009) also place climate change models into categories (welfare maximization, general equilibrium, partial equilibrium, cost minimization and simulation models).

may be reducing with mitigation. (Of course, nature also contributes to emissions of GHGs.) The global emissions of various GHGs lead through multiple steps illustrated in the Figure to physical, ecological and human consequences. The last three boxes embody a distinction between physical/ecological effects (impacts) and the resultant changes in human wellbeing (damages).[39] Working Group II is largely concerned with identifying impacts and less with damages. The loop is closed by indicating that human wellbeing ultimately drives human activity, which brings us back to the top box in the figure. This representation of course is an oversimplification; for instance, each of the boxes in Figure 3.8.1 has a time dimension, since emissions at a particular point in time lead to radiative forcings at future points in time, which lead to subsequent impacts and damages. The emissions also have a spatial dimension as do climate change, impacts and damages. From an analytical perspective, two major issues are (1) the relationships between successive boxes, and (2) the relationships among the various items within a given box.

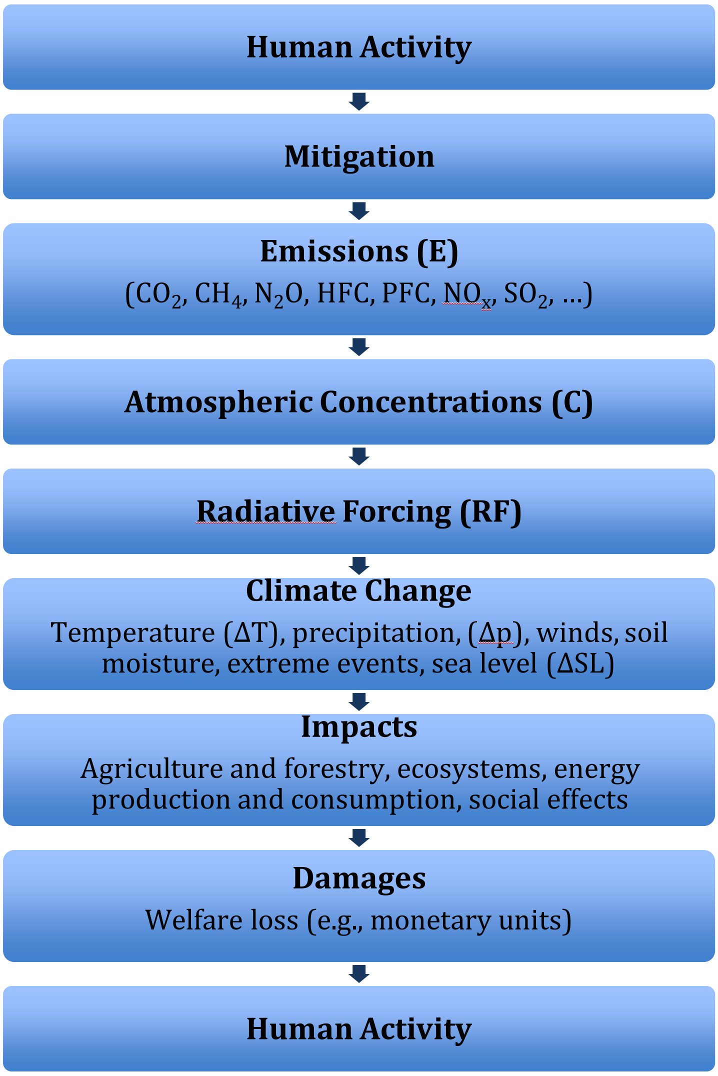

Figure 3.8.1. Cause-effect chain from emissions to climate change and damages (adapted from Fuglevestedt et al. (2003)).

[39] This term is meant to include non-human losses that might be of concern to humans; see also sections 3.2.2.1 and 3.2.2.3 .

From a practical point of view, models[40] play a key role in defining those relationships. Global climate models (GCMs) translate emissions through atmospheric concentrations and radiative forcing into changes in climate. Other models – including crop models, forest growth models, vegetation models, hydrology models – translate changes in climate into impacts on crops, forests, vegetation, stream flow at particular locations. Economic models translate those impacts into monetary measures of welfare loss (or gain). Those models also provide a means of aggregating items within given boxes. GCMs aggregate emissions of various gasses into an overall level of radiative forcing; hydrology models aggregate precipitation at multiple locations within a watershed into stream flow at a given location; economic models aggregate different impacts into an overall measure of welfare loss.

Several important issues are considered in this section. The first and fundamental point is to review and define mitigation costs and damage, particularly aggregate measures of costs and damage. Most studies, understandably, consider costs and damages for specific sectors at specific points in time and often at particular geographic locations. However, to be useful for policymakers, it is important to aggregate the costs and damages so that they can be compared. Another important issue is the social cost of carbon, which is itself an output from the aggregation of costs and damages along a particular emissions trajectory – the social cost of carbon for a given emission trajectory is the extra costs and damages imposed on society from one more ton of carbon emissions (assuming some trajectory of carbon emissions and regulatory control). A final issue involves metrics that allow differential regulation of different GHGs. In mitigating methane and carbon dioxide, for instance, what relative weight should regulators place on those two gases? Presumably, if one is more damaging than the other, then more effort should be put into mitigating the more damaging gas. How to do that in a rigorous fashion has proved surprisingly elusive, in part because impacts and damages are so poorly known.

The remainder of this section is organized as follows. Section 3.8.1 describes the application of economic valuation to make the translation from impacts to damages, largely ignoring the aggregation issue. Section 3.8.2 shows how this information can be aggregated into a global or regional damage function (often used in Integrated Assessment Models). Section 3.8.3 describes the representation of the economic costs of mitigation in those models. Section 3.8.4 describes efforts at merging estimates of aggregate damage and aggregate mitigation costs to generate summary measures of the social cost of carbon. Section 3.8.5 extends the aggregation of emissions of different GHGs into a single metric, an issue that is also addressed in Chapter 8 of WG I.

3.8.1 The damages from climate change

Climate change (as distinct from mitigation) may affect people in different ways. Some people may benefit; others may be harmed. In some cases, it is their livelihood that is affected; in others, it is their health, access to food or clean water, amenity of life, or the natural environment around them. While many non-monetary metrics can be used to characterize particular components of the impacts of climate change, we have no unambiguous way to aggregate those metrics for the purpose of assessing the overall change in welfare. In principle, the economic theory of monetary valuation provides a way to perform this aggregation although, as explained below, many issues arise. This sub-section focuses on the application of economic valuation to make the translation from impacts in Figure 3.8.1 to an assessment of damages.

The changes that affect human wellbeing can be classified as *market* and *non-market*. The market effects involve changes in market prices, changes in revenue and net income, changes in the

[40] Conceptually, a model is simply a mapping from the inputs to the outputs. Occasionally this mapping is analytically specified (such as $y = 2x^2$) but more often, the mapping is defined numerically by large computer models.

quantity or quality of market commodities, or changes in the availability of commodities. Non-market changes are changes in the quantity, quality or availability of things that matter to people, even though they are not obtained through the market. Examples of such non-market items that people value include health, quality of life, culture, environmental quality, natural ecosystems, wildlife, and aesthetics. A given change in a physical or biological system can generate both market and non-market damage to human wellbeing. For example, an episode of extreme heat in a rural area may cause heat stress for exposed farm labourers and dry up a wetland that serves as a refuge for migratory birds, while killing some crops and impairing the quality of others that survive. From an economic perspective, the damages would be conceptualized as a loss of income for farmers and farm workers; an increase in prices of crops for consumers and/or a reduction in their quality; and non-market impacts including the impairment of human health (though some of these effects may be captured in the wage of farm workers) and ecosystem harm.

Following Garnaut (2008), the categories of market and non-market damages can be further refined. Garnaut distinguishes between market damages that are currently amenable to measurement and those that are not amenable to measurement in the current state of knowledge but are, in principle, amenable to quantitative analysis. In the same spirit, one can distinguish non-markets damages currently amenable to measurement from those that are not currently amenable because of either a lack of knowledge or the inherent difficulty of quantification. For example, some regard the valuation of human life as belonging to the latter category. Garnaut adds one more type of damage which is the value placed on the risk of extremely damaging, although perhaps low probability, climate outcomes. This "risk value" is based on risk aversion which could generate a significant WTP value to avoid extreme climate risks. One important point to make is that the damages need not be positive. Certain impacts may in fact yield negative damages (a good outcome). For instance, some agricultural areas may benefit from modest warming, generating negative damage.

Economists define value in terms of a trade-off. As discussed in section 3.5.1 , the economic value of an item to a person, measured in terms of a numeraire commodity, is defined as the amount of the numeraire that the person would be willing to exchange for the item if such an exchange were possible. With monetary valuation, the numeraire is income; the monetary value placed on an item is the change in income that would be equivalent to the item in terms of its effect on the person's wellbeing. This income equivalence is measured through the WTP or WTA measures, introduced in section 3.5.1.2 .[41] As we have discussed, the item in question may be a marketed commodity, but it need not be: it can be *anything* that the person values. Thus, the economic value of an item is not in general the same as its price.[42] Some things that people value do not have a market price. And, even if the item does have a price, the person might be willing to pay *far more* than the price to obtain it; if so, this extra WTP is part of its value to the person. The economic concept of value based on a trade-off is not without critics. In some cases, the item being valued may be seen as incommensurable with money: in that case, it is impossible to formulate a trade-off. In other cases, the trade-off may be deemed inappropriate or unethical.[43] Another concern is that, while the

[41] As noted earlier, for other than pure income changes, the WTP and WTA measures are generally expected to be somewhat different unless the changes are very small. Where they do differ, the WTP measure is generally expected to be somewhat smaller than the WTA measure (Willig, 1976; Hanemann, 1991). The climate economics literature has commonly focused on the WTP measure.

[42] Price measures value only for the marginallast unit purchased of a marketed commodity. For non-marginal changes in a marketed commodity, the price understates value. The changes involved in climate change are generally likely to be non-marginal and, also, to involve non-marketed goods.

[43] For example, Kelman (1981) has argued that, for some items, the mere idea of valuing them in money debases them; see also Jamieson (1992) and Sagoff (2007).

economic concept of value is defined for an individual, it is typically measured for aggregates of individuals, and the issue of equity weighting is often disregarded.[44]

Although the idea of WTP as a measure of economic value goes back to Dupuit (1844) and Marshall (1890), the theoretical foundation for the WTP and WTA measures was clarified and the economic methods of measurement were formalized only about forty years ago, first for the valuation of marketed commodities[45] and soon thereafter for non-market valuation.[46]

The valuation methods fall into two categories, known as revealed preference and stated preference. For marketed items, an individual's purchase behaviour reveals information about his value for the item. Observation of purchase behaviour in the marketplace is the basis for the revealed preference approaches. In the demand function approach,[47] one estimates a demand function from data on observed choice behaviour. From the estimated demand function it is possible to infer the purchaser's WTP or WTA values for changes in the price, quantity, quality or availability of the commodity.[48] Another revealed preference approach, known as the hedonic method, is based on finding an observed relationship between the quality characteristics of marketed items and the price at which they are sold (e.g., the relationship between the price of farmland and the condition and location of the farmland). From this one can infer the *marginal* value of a change in characteristics.[49] Besides being used to value marketed commodities, these approaches can also be used to value certain non-market items. The key requirement is to find a marketed commodity whose consumption also reflects a preference for the non-market item of interest. For example the choice of which beach to visit reflects in part a preference for bathing water quality. By estimating a person's demand function for the choice among beach sites it is possible to infer his WTP or WTA value for changes in water quality.[50]

With stated preference, the analyst employs a survey or economic experiment through which subjects are confronted with a trade-off. With contingent valuation, for example, they are asked to choose between making a payment (for example, a tax increase) and having the government undertake an action that accomplishes a specific outcome (for example, protection of a particular ecosystem), versus making no payment and not securing that outcome. By varying the cost across subjects and then correlating the cost offered with the percentage of "for" responses, the analyst traces out a form of demand function from which the WTP (or WTA) measure can be derived. With choice experiments, subjects are asked to make repeated choices among alternative options

[44] Nyborg (2012). The disregard of equity weights is the most frequent complaint against conventional cost-benefit analysis. As noted above, nothing in economic theory rules out equity weighting. In fact, as explained in section 3.5.1.3 , equity weighting has a firm theoretical foundation.

[45] Hurwicz and Uzawa (1971), Willig (1976).

[46] Maler (1971).

[47] Known as the "travel cost" approach when employed for non-market valuation.

[48] For changes in quality or availability, it is necessary to infer the "cutoff" price at which no purchases would occur, something that may not be directly observed in the data.

[49] Details of these methods can be found in Becht (1995) and the chapters by McConnell and Bockstael (2006), Palmquist (2006) and Phaneuf and Smith (2006) in Mäler and Vincent (2005) or in textbooks such as Kolstad (2010), Champ, Boyle and Brown (2003), Haab and McConnell (2003) or Bockstael and McConnell (2007).

[50] To the extent that the person has preferences for water quality unconnected with his own use of the beach for recreation, that part of his preferences – known as the *non-use value* – will not be measured through revealed preference methods; it can only be measured through stated preference.

combining different outcomes with different levels of cost.[51] Whereas choice in the marketplace is the paradigm for revealed preference, for stated preference it is often voting in elections or public referenda.

In each case, the reliability of the valuation depends not only on the methodology chosen but also on the details of its implementation. The use of surveys for stated preference has been controversial in economics but was upheld as valid by a Blue Ribbon Panel to the US Government provided that certain protocols are followed in the implementation (Arrow et al., 1993).[52]

Both revealed and stated preference techniques of non-market valuation have been widely used by government agencies for administrative and legal decisions in many contexts including health, education, the arts, transportation and social policy as well as ecosystems and the environment.[53] A small but growing literature also applies them to the valuation of damages from climate change as noted below.

The majority of the economic valuations of climate change in the literature have focused on market impacts, especially impacts on agriculture, forestry, energy, water, sea level rise, and tourism.

The most extensive literature pertains to agriculture. Three approaches have generally been used to assess the economic impact of climate change: crop simulation models to estimate changes in yield; econometric estimation of hedonic models for changes in farmland value and farming profit; and computable general equilibrium (CGE) models simulating the effects changes in supply and demand in agricultural and related markets.[54] Analyses based on crop models and hedonic models often focus on the impact on producer profits. They often either assume no impact on commodity prices or they ignore the effect on consumer wellbeing.[55] By contrast CGE models explicitly track changes in prices and consumer welfare. With crop models and hedonic analysis it is possible to incorporate a high degree of spatial resolution; with CGE models, the spatial resolution is much coarser, involving changes in climate averaged over a regional, national or even multi-country scale. With crop models climate change can be represented on a daily time scale; with hedonic models it has often been represented on a monthly or seasonal basis; and with CGE models it is typically represented on an annual basis. While some recent studies have found that extreme climate events have a disproportionate impact on agricultural systems,[56] because of the relatively high degree of spatial or temporal aggregation these events are not well captured in many of the existing economic analyses. Another issue is the welfare significance of shifts in the location of agricultural production. Markets

[51] Details can be found in Carson and Hanemann (2005), or in textbooks such as Champ, Boyle and Brown (2003), Haab and McConnell (2003) and Bennett and Blamey (2001) .

[52] For examples of the debate in the US, see Diamond and Hausman (1994) and Hanemann (1994); also Kling et al. (2012), Carson (2012) and Hausman (2012).

[53] For the use of economic valuation in the UK National Ecosystem Assessment, see Bateman et al. (2011). For the US, see US EPA (2010) and US National Research Council (2004) and (2010).

[54] Cline (2007) provides a summary of these approaches; see also WGII 3.2 – 3.4.

[55] The demand for many agricultural commodities is often relatively inelastic, so that the short-run consequence of a negative supply shock is a price increase; while a benefit to producers – which shows up in the hedonic estimates – it is harmful for consumers (Roberts and Schlenker, 2010; Lobell et al., 2011). Studies that seek to measure the effect of weather on current profits, rather than that of climate on long-run profitability (e.g., Deschênes and Greenstone, 2007)) are vulnerable to the confounding effects of price changes (Fisher et al., 2012). Papers which simultaneously estimate the effect of weather and climate on profits have difficulty in separately identifying the effect of weather from the effect of climate (e.g., Kelly et al., 2005; Deschênes and Kolstad, 2011).

[56] Schlenker and Roberts (2009); Lobel et al. (2011). See also WGII 7.3.2.1

for agricultural commodities are national and, often, international in scope. Climate change may lead to major shifts in the location of agricultural production. Economic analyses – especially CGE models – often focus on aggregate international producer and consumer welfare. Under the potential Pareto criterion, transfers of income from one agent to another are of no welfare significance. For several reasons, however, the spatial distribution of economic impacts might be of some concern, including differences in income between gaining and losing areas; the stranding of assets when production shifts from one location to another; and the behavioural phenomenon of loss aversion whereby people sometimes place a greater weight on a loss than on a gain of the same magnitude.[57]

With timber, forest growth models combined with economic models of world trade have been used to analyze the economic impact of climate change.[58] As with agricultural trade models, the economic trade models capture the impact on producer and consumer welfare. At least with moderate climate change, forest yields are likely to improve globally, benefiting consumers. However, forest growth models may overestimate the potential beneficial effects of elevated CO_2, and may underestimate the potential negative effects associated with extreme events, including wildfire and pest outbreaks.[59]

With the other market sectors, the literature is both sparse and highly fragmented, with individual estimates of the economic impacts of climate change on energy, water, sea level rise, or tourism at particular locations.[60] With energy, climate change is very likely to reduce energy demand for heating, and increase energy demand for cooling.[61] The balance of those effects depends on circumstances, which are likely to vary by location. Even if the two effects were to offset one another, the economic cost need not be negligible. In many cases, winter-time heating has a large component of baseload energy, while summer-time air conditioning cooling tends to be peak-load energy, with a higher economic cost. Similarly, with water supply, what matters in many cases is not total annual precipitation but the match between the timing of precipitation and the timing of water use.[62] Those questions require analysis on a finer temporal or spatial scale than has typically been employed in the economic literature.

Estimates of the economic costs of sea level rise generally focus on either the property damage from flooding or on the costs of prevention, for example in the form of sea wall construction. They sometimes include costs associated with the temporary disruption of economic activity. They typically do not cover the loss of wellbeing for people harmed or displaced by flooding.[63] Only a handful of studies have used non-market valuation to measure the loss of wellbeing from flooding using revealed preference[64] or stated preference.[65] Similarly, the economic analyses of climate

[57] Kahneman and Tversky (1984).

[58] For example, Sohngen et al. (2001).

[59] Refer to IPCC Working Group II, Chapter 4. For a valuation of wildfire, see Westerling and Bryant (2008).

[60] The sparsity generally reflects the limited availability of spatially detailed characterizations of impacts rather than difficulties of valuation, although those do exist.

[61] Refer to IPCC WGII AR5, Chapter 10.

[62] Moreover, temperature can have a significant influence on the translation of precipitation into usable water supply because it affects the amount evaporation and land surface runoff. Annual precipitation is not a sufficient statistic for usable water supply (Strzepek and Boehlert, 2010).

[63] Cardoso and Benhin (2011) provides a stated preference valuation of protecting the Columbian Caribbean coast from sea level rise.

[64] Daniel et al. (2009).

[65] Botzen and van den Bergh (2012).

change impacts on tourism have examined the shifts in the choice of destination and the income from tourism activities with an increase in temperature and changes in the relative attractiveness of locations for tourist and recreational activities (e.g., skiing). Only a handful of studies have considered the impacts on tourists' wellbeing using non-market valuation based on revealed preference[66] or stated preference.[67]

Some economic studies have assessed the impacts of climate change on labour productivity and national income. Several pathways have been considered. Exposure to high ambient temperatures is known to diminish work capacity and reduce labour productivity (Kjellstrom et al., 2009; Zivin and Neidell, 2010). Measures to reduce CO_2 emissions may also reduce other pollutants associated with fossil fuel combustion, such as NO_x and particulates, that lead to time lost from work and reduced productivity (Östblom and Samakovlis, 2007). Recent studies have focused on the correlation between high temperatures and poverty (Nordhaus, 2006), and the link between fluctuations in temperature, cyclones, and fluctuations in economic activity (Dell et al., 2009, 2012; Hsiang, 2010).[68] The economic metric in these studies is change in productivity and economic output, but not a money measure of the loss of wellbeing, including social disruption, health impacts and loss of life.[69]

Some have attempted to measure the impact of climate on wellbeing using the hedonic approach based on the correlation of residential house prices and climate in different areas.[70] Researchers have also correlated measures of expressed happiness or life satisfaction with climate and income, and then used the inferred trade-off between income and climate to value a change in climate.[71]

An indirect measure of the economic value of avoiding climate change comes from a growing number of stated preference studies that measure the public's willingness to pay for climate mitigation programmes, including policies to reduce the use of fossil fuels. Examples include Berrens et al. (2004), Lee and Cameron (2008), Solomon and Johnson (2009), and Aldy et al. (2012) for the U.S., Akter and Bennett (2011) for Australia, Longo et al. (2012) for Spain, Lee et al. (2010) for Korea, Adaman et al. (2011) for Turkey, and Carlsson et al. (2012) for a comparative study of WTP in China, Sweden and the US.

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[66] Pendleton and Mendelsohn (1998); Loomis and Richardson (2006); Richardson and Loomis (2004); Pendleton et al. (2011).

[67] Tseng and Chen (2008).

[68] Hsiang (2010) finds that the response of economic output in Caribbean-basin countries to high temperatures is structurally similar to that of labour productivity. Output losses occurring in nonagricultural sectors substantially exceed those occurring in agricultural production. Dell et al. (2012) find that higher temperatures substantially reduce economic growth in poor countries, but not rich countries, and also reduce growth rates, not just the level of output. Higher temperatures reduce industrial output and political stability as well as agricultural output. The effect on growth rates is consistent with Hallegatte et al. (2007), who develop a non-equilibrium model of economic growth which acknowledges potential limits on annual investment capacity. If the intensity and frequency of extreme events crosses a threshold, a country's reconstructive ability is overwhelmed and its economic development is impaired.

[69] An exception is Östblom and Samakovlis (2007), which accounts for the monetary value of the disutility associated with illness.

[70] Maddison (2001, 2003); Maddison and Bigano (2003); Rehdanz and Maddison (2009). Rather than house prices, Nordhaus (1996) estimated how real hourly earnings in US counties vary with climate. Cragg and Kahn (1997) used revealed preference to examine how migrants trade off climate against disposable income.

[71] Van der Vliet et al. (2004); Maddison and Rehdanz (2011).

The existing literature on the economic damage from climate change is especially sparse with regard to (1) impacts on ecosystems, and (2) the risk value associated with extremely harmful, if low probability, climate outcomes based on willingness to pay to avoid those extreme risks.[72]

The few attempts at non-market monetization of ecosystem impacts include Velarde et al. (2005) for protected areas in Africa, Shaw et al. (2011) for ecosystem impacts in California, Layton and Brown (2000) for changes in the forest line in the Rocky Mountains, Riera et al. (2012) for vegetation impacts in Spanish shrublands.

With regard to risk aversion value, this would depend on the probability of occurrence of catastrophic climate outcomes,[73] the magnitude of the impact on human wellbeing if these were to occur, and the degree of risk aversion. Nordhaus and Boyer (2000) attempted such a calculation and estimated the possible WTP to avoid an overturning of the thermohaline circulation as equivalent to about $300 per household for the U.S.[74]

There are several approaches to valuing damages that can give incorrect estimates and should not be used: replacement cost and mitigation cost. In the first case, the cost of repairing and replacing a damaged ecosystem or other asset damaged by a change in climate is sometimes used incorrectly as a proxy for damage: in principle the economic damage is the lesser of the value of what was lost or the cost of replacing it if a suitable and appropriate replacement exists. In the second case, applied most often to local air pollutants, mitigation costs are inferred to be a lower bound on damages, based on the assumption that mitigation would not have been undertaken were the benefits not at least equal to the costs (not a valid representation of the political process).

3.8.2 Aggregate climate damages

While the effects of climate change, and therefore the costs and benefits of adaptation, vary by location, the cause is the total global emission of GHGs.[75] The question may arise whether the adverse effects of climate change can possibly justify the costs associated with reducing GHG emissions. Answering that question is, implicitly if not explicitly, a form of cost/benefit trade-off, whether framed in monetary or other terms. Economists have typically framed the trade-off in terms of a monetary comparison of the global damage from climate change versus the global cost of mitigation. The costs of mitigation are discussed in the next subsection. This subsection focuses on the global economic damages from climate change.

The first estimates of the economic damage associated with a specific degree of climate change were made for the US, and were then extrapolated to a global scale.[76] The first studies involved static analyses estimating the damage associated with a particular climate end-point, variously taken to be a 2°C, 2.5°C or 3°C increase in global average annual temperature. This gave way to dynamic analyses which tracked economic output, emissions, atmospheric CO_2 concentration, and damages as those evolve over time in the form of Integrated Assessment Models (IAMs). Because these

[72] Risk aversion generates a WTP to avoid a risk that exceeds the expected value of the risk, the difference being known as the risk premium, a phenomenon that carries over to non-expected utility theory (Machina, 1982). Existing analyses generally measure the expected value of damages but not the risk premium.

[73] Catastrophic impacts might result from tipping points in the climate system (Lenton et al., 2008; Kriegler et al., 2009).

[74] This amount translates their estimate of aggregate WTP as a percentage of US GDP in 1990 dollars into a value per household in 2011 dollars.

[75] An exception is aerosols and some short-lived gasses for which the location of the emissions does matter (Berntsen et al., 2006).

[76] Smith and Tirpak (1989), Nordhaus (1991), Cline (1992), Titus (1992), Fankhauser (1994).

balance costs and benefits associated with different levels of emissions, a damage *function* rather than a point estimate is needed.[77]

Three IAMs have so far received most attention in the literature: the DICE model developed by in 1990 (though with its genesis in (Nordhaus, 1977)) and first published in Nordhaus (1993a; b);[78] the FUND model developed in the early 1990s and first published in Tol (1995); and the PAGE model developed in 1991 for use by European decision makers and first published in Hope and Maul (1996) and Plambeck and Hope (1996).[79] [80] The models have undergone various refinements and updates[81] but, while details have changed, their general structure has stayed the same and there remain reasons for concern about the validity of their damage functions.

The IAMs use a highly aggregated representation of damages. The spatial unit of analysis in DICE and PAGE is the entire world; in FUND the world is divided into 16 broad regions (similar to the regional version of DICE—RICE). The IAMs focus on the increase in regional or global average annual temperature at time t, T_t, and they collapse the mappings from this warming to various types of impact at locations around the globe, plus the mappings from those impacts to economic damages, into a simple reduced form equation representing D_{jkt}, the gain or loss in j of GDP at location k in year t when global average temperature rises by T_t in year t as a simple function of T_t :[82]

Equation 3.8.1. $$D_{jkt} = D_{jkt}(T_t)$$

DICE has a single damage function for reduction in overall global GDP.[83] PAGE has four separate global damage functions for different types of global damages - economic damages, non-economic damages, sea-level rise damages, and climate discontinuity damages. FUND has eight sectoral damage functions for each of 16 world regions, and in some cases the economic damage is also dependent on the rate of change in T_t .[84]

[77] Other models, also known as IAMs, combine the functioning of the economy with a representation of a global climate model, but they lack the damage function component that translates the effects of climate change into impacts and consequent effects on human wellbeing.

[78] A regionally disaggregated version of this model, RICE, was developed by Nordhaus and Yang (1996). Some extensions of DICE include AD-DICE (De Bruin et al., 2009).

[79] Results from Nordhaus (1993a; b) and Tol (1995) were cited in the Second Assessment Report.

[80] Some other IAMs have damage functions, including the MERGE Model (Manne and Richels, 1992, 1995, 2004a); the CETA model (Peck and Teisberg, 1992, 1994); and, more recently, several IAMs developed by European researchers including the WITCH model (Bosetti et al., 2006), its extension the AD-WITCH mode (Bosello, Carraro, and De Cian, 2010), the ENVISAGE model (Roson and Mensbrugghe, 2012), and a model developed by Eboli et al. (2010) and Bosello et al. (2012). These models have received less attention in recent policy debates than DICE, FUND and PAGE.

[81] The most recent versions are Nordhaus (2008, 2011b) for DICE, Anthoff and Tol (2010a) for FUND, and Hope (2011) for PAGE.

[82] The aggregate damage function in FUND, shows a gain in GDP for temperature increases up to almost 3^{o}C. There is a smaller region of gain in GDP in PAGE, and none in DICE.

[83] The global damages in DICE are based on sectoral damages by region developed for the RICE model (Nordhaus and Boyer, 2000).

[84] In FUND, the change in global mean annual temperature, T_t, is mapped into a change in regional mean annual temperature via a fixed multiplier for each region. The economic sectors are agriculture, forestry, water, energy, sea-level rise, ecosystems, human health, and storms. In the case of agriculture and ecosystems, the functions depend on the rate of temperature change. Sectoral vulnerability is also assumed to depend on factors such per capita income, population growth, and the passage of time (representing technological change or improved adaptation).

The damage functions are usually calibrated based on (1) the modeller's choice of a particular algebraic formula for D_{jkt} (T_t), plus (2) the assumption of zero damage at the origin (D_{jkt} (0)=0), and (3) the modeller's estimate of damages at a benchmark change in global average temperature, T*, typically that associated with a doubling of atmospheric CO_2. For example, in PAGE (similarly in DICE) the damage function is a power function

Equation 3.8.2. $$D_{jt} = a_j[T_t/T^*]^b Y_t$$

where Y_t is GDP in year *t*, *b* is a coefficient specified by the modeller, and a_j is the modeller's estimate of the economic damage with the benchmark temperature change.[85] In PAGE, *b* is a random variable taking the values 1, 2 or 3. In DICE, a single global damage function has the form (Equation 3.8.2), which is deterministic and in which *b* = 2 in early versions of DICE.[86] In FUND, the damage functions are deterministic but have a slightly more complicated structure and calibration than (Equation 3.8.2). Figure 3.8.2 is a representation of some of the aggregate estimates of damage associated with different levels of warming. These estimates are reproduced here without an assessment of the reliability of the different analyses. Indeed, some of the studies are quite old. Nevertheless, it is these sorts of studies that are used to calibrate the aggregate damage functions used in IAMs. Graphs of the aggregate damages in DICE, PAGE and FUND as well as several other IAMs as a function of different levels of global warming up to 6°C, T_t, are displayed in Figure 19-5 of WGII AR5.

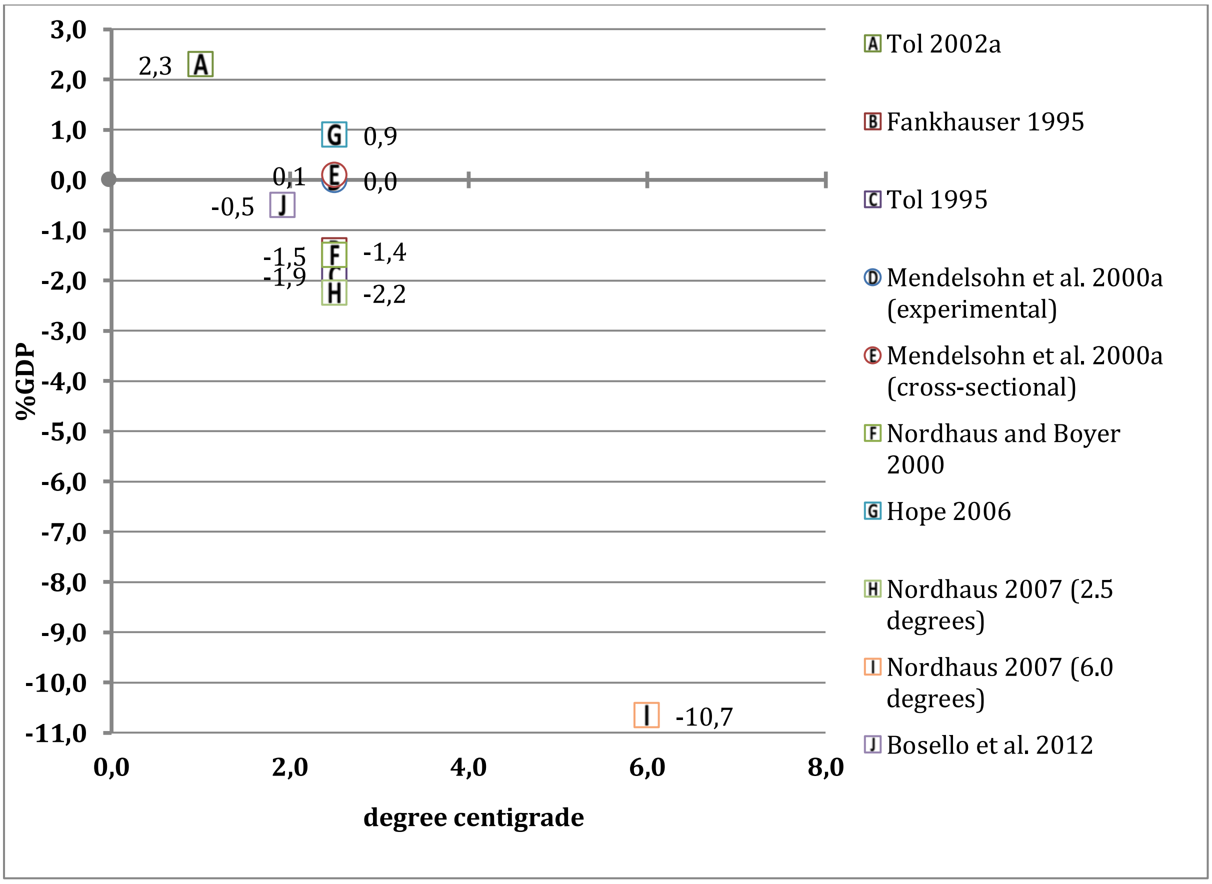


Figure 3.8.2. Climate change damage estimates (Adapted from **(Tol, 2013)**).

[85] When $T_t = T^*$ in (2), $D_{jt} = a_j Y_t$.

[86] The formulation in (2) is also used by Kandlikar (1996) and Hammitt et al. (1996) with *b* = 1, 2 or 3.

Besides conceptual concerns noted in 3.8.4 , there are also some other concerns about the empirical foundation for the damage functions employed in DICE, FUND and PAGE involving both the level and the curvature of those functions.

Because of the extreme sparsity of estimates of climate change impacts (especially aside from agriculture) and damages, the damage functions are essentially guesses by the model developers and involve heroic extrapolation from studies of particular locations to a global scale. [87]

DICE and FUND yield fairly similar conclusions about the economic damage associated with specific emissions scenarios. But they imply markedly different *decompositions* of damages (Kopp and Mignone, 2011). In FUND, the single largest component of the social cost of carbon is damage to energy, which accounts for two thirds of total, followed by water. The damages are offset by a large gain to agriculture, which reduces the total cost by half. DICE has no damage to water, almost zero damage to energy, and a small loss to agriculture. [88] The widely divergent sectoral assessments cast some doubt on the reliability of the total damage estimates.

As IAMs are being put to use for regulatory purposes in the UK and the US, the limitations of the damage functions are receiving more attention. In addition to their incomplete coverage of potential catastrophic damages, they provide limited coverage of some non-catastrophic market damages, including those associated with climate extremes (e.g., wildfire, drought, heat waves), as well as incomplete coverage of non-catastrophic, non-market damages, including human disamenity as well as ocean acidification and impacts on ecosystem services.[89] It has also been observed that they do not account for intersectoral interactions (such as the effects of water resources on agriculture, or the effects of agricultural damage on food supply and health).[90]

A striking feature of the damage functions is the high degree of spatial and temporal aggregation. This is not without consequence, especially when combined with a narrow focus on the increase in global average annual temperature. Global temperature is a poor summary statistic for some impacts on human wellbeing, since the majority of the world's population lives on land and at higher latitudes, where the warming is above the global average. Thus, the value of T_t, inserted into the global damage function is systematically too low in terms of where people live.[91]

Aggregate damage functions also ignore the variation in temperature change within a country or a region. Because the damage functions are convex (increasing marginal damage), this imparts an additional element of understatement to the damages. Applying a standard approximation to the

[87] The core impact estimates in these models are based on literature from 2000 and earlier (Mastrandrea, 2009).

[88] In the WITCH model, the largest damages are to agriculture and tourism (Bosello, Carraro, and De Cian, 2010).

[89] For example, see Ackerman et al. (2009); Interagency Working Group on Social Cost of Carbon (2010); Greenstone et al. (2013) and Watkiss (2011). Watkiss employs a risk matrix (see his Figure 1) to identify gaps in coverage underlying the IAMs and SCC estimates.

[90] Warren (2011); Greenstone et al. (2013).

[91] This is illustrated with results from Hayhoe et al. (2004), who analyze impacts in California under the B1 scenario based on the HADCM3 model. That model projected an increase of global temperature of 2°C by 2100. FUND translates this into an increase of 2.4°C for the USA. Hayhoe et al. (2004) downscale the HADCM3 projections; they find that the downscaled statewide average annual temperature increase in California in 2100 is 3.3°C, the statewide summertime temperature increase (when the impacts on agriculture, eater, energy and health are likely to occur) is 4.6°C. In the Central Valley (where most of the agriculture occurs) and Southern California (where a majority of the population lives) the summertime temperature increase reaches almost 5°C. Using 2°C or 2.4°C in the damage function can significantly understate the impacts.

expected damages associated with a given spatial/ temporal distribution of warming, Λ, with mean $\bar{T}$ and variance σ_T^2, one obtains:

Equation 3.8.3. $$E\{D(T)\} = D(\bar{T}) + 0.5\sigma_T^2 D''(\bar{T})$$

where D''(◦) > 0 is the second derivative of the damage function which implies that D understates true damages. The degree of understatement increases with the heterogeneity of impacts (captured by σ_T^2) and the curvature of the damage function.

Concerns have been raised about the curvature of the damage functions because they are often calibrated to essentially two levels of warming: zero warming and the warming posited to be associated with a doubling of CO_2 concentration. Growing attention is being given to higher levels of warming,[92] and the possibility of tipping points, [93] with much larger increases in global temperature, possibly as large as 10-15°C. These significantly higher temperatures could have disastrous effects on human wellbeing and may generate a risk component of damage as discussed at the beginning of this section.[94]

Finally, there is the issue of equity weighting of damages, a particular concern because of the high level of spatial aggregation.[95] To the extent that the adverse impacts of climate change are likely to be borne more by poor than rich countries, the lack of weighting understates the damages.

Box 3.8.1. Uncertainty and Damages: Are Expected Climate Damages Infinite?

Weitzman (2009) has drawn attention to the significance of uncertainty about potentially large climate change damages – what has become known as the fat-tails problem (refer to a Symposium on this topic: (Pindyck, 2011; Nordhaus, 2011a; Weitzman, 2011)). Weitzman emphasized the existence of a chain of structural uncertainties affecting both the climate system response to radiative forcing and the possibility of a resulting impact on human wellbeing that might be catastrophic. The uncertainties can be represented by a probability distribution, but this case has uncertainty about not only the mean of the distribution but also the variance. The resultant probability distribution of possible economic damage could have not just a long right tail but also a *fat* right tail: that is to say, the likelihood of an extremely large reduction in wellbeing does not go quickly to zero. In that case, conducting a benefit-cost analysis based on expected value can be very misleading. With risk aversion, the expected marginal disutility associated with an increment in emissions today could be very large.[96] Weitzman's argument was framed theoretically; his results depend on the particular choice of functional forms for probability distributions and risk aversion and they have been challenged by some as too pessimistic. [97]

Following Weitzman, several empirical simulations have been conducted using modified versions of DICE or PAGE to explore the sensitivity of model results to uncertainty regarding climate sensitivity and the nonlinearity of the damage function when climate change is large. In simulations with DICE, Newbold and Daigneault (2009) find that, depending on the degree of risk aversion and the severity

[92] For example New et al. (2011) and World Bank (2012).

[93] Lenton et al. (2008).

[94] Sherwood and Huber (2010).

[95] Several studies have applied equity weighting to FUND. See Tol (2001, 2002), Anthoff et al. (2009), and Anthoff and Tol (2010b). See also Fankhauser et al. (1997) and Azar (1999).

[96] Weitzman (2007b, 2009) argued that it could be infinite.

[97] Nordhaus (2011a), Pindyck (2011), and Costello et al. (2010), for example.

of damages associated with extremes increases in global temperature, there is a large risk premium in the WTP to avoid warming, thereby raising the implied damage from a change in the climate.[98] Ackerman et al. (2010) find that a higher climate sensitivity makes a substantial difference in DICE when the exponent in the damage function is large (b = 4 or 5). Dietz (2011) finds that welfare estimates with PAGE do strongly depend on tail risks but, for a set of plausible assumptions, time preferences can still matter.[99]

3.8.3 The aggregate costs of mitigation

Aside from avoided climate damages, the reduction of GHG emissions imposes economic costs on various actors, including firms, households and governments.[100] Those costs may take the form of changes in prices, changes in revenue and net income, and changes in the availability or quality of commodities. Reducing GHG is not totally a technological issue. Behavioural and institutional changes are also an important means by which GHG emissions are reduced. Whatever their form, these changes may lead to changes in wellbeing. The changes in wellbeing are measured in monetary terms through the change in income that is equivalent in terms of the impact on the actor's wellbeing.

Changes in prices and incomes are typically projected through the use of economic models. Chapter 6 describes the models that are commonly used for this purpose; here we provide some brief observations. In many cases, mitigation primarily involves change in the generation and use of energy from fossil-fuels so as to reduce GHG emissions. The initial economic effect is often an increase in the cost of energy, leading to changes energy supply and demand. However, those changes then reverberate throughout the economy: fossil-fuel intensive commodities become more expensive, leading to a drop in demand; energy users find more of their income going to energy and have to forego consumption of other goods and services; non-fossil-fuel intensive substitutes become more attractive, leading to an increase in their supply and their demand. As explained in Section 6.2 of Chapter 6, different models capture different aspects of these economic changes. Partial equilibrium energy models focus solely on the energy-related sectors of the economy (albeit, often with considerable detail) and track the interactions among those sectors when a mitigation policy is imposed. Computable general equilibrium (CGE) models cover all the sectors of the economy and track interactions among all economic sectors, thus allowing for indirect effects elsewhere in the economy resulting from direct changes in the energy sectors (including price changes).

The models listed in Table 6.1 of Chapter 6 are characterized as IAMs because they track the impact of changes in economic production on GHG emissions and feed those emissions into a (representation of a) climate model that tracks the subsequent impact on global temperature. But, they have no feedback from climate change back to market supply and demand. The models in Chapter 6 typically do not translate the effects of climate change into impacts and consequent effects on human wellbeing – they do not include damage functions.[101] Thus, those models differ from the IAMs discussed in the previous section.[102]

[98] The rationale for a risk premium in the damage assessment is discussed by Kousky et al. (2012).

[99] Dietz et al. (2007) also find sensitivity in PAGE to the damage function exponent.

[100] As noted in Chapter 6, economic costs are far from the only consideration that matters in making good decisions since there can be other national and societal priorities as well.

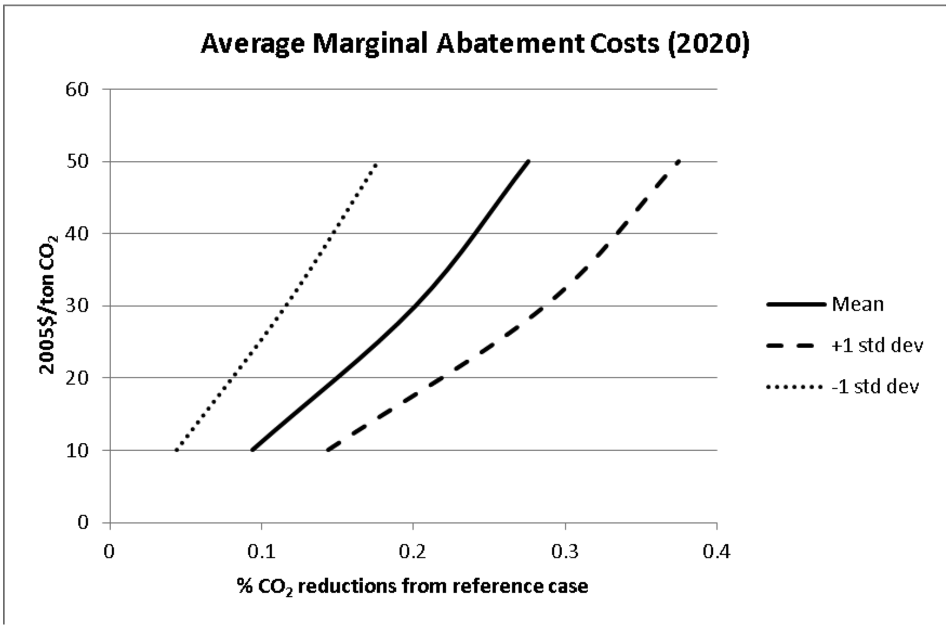
[101] Climate is assumed to be *separable* from market goods in the utility function underlying these models. If that assumption is incorrect, Carbone and Smith (2012) show that significant error in the welfare calculation is possible.

[102] WITCH is the only model listed in Table 6.1 that also has a climate damage component.

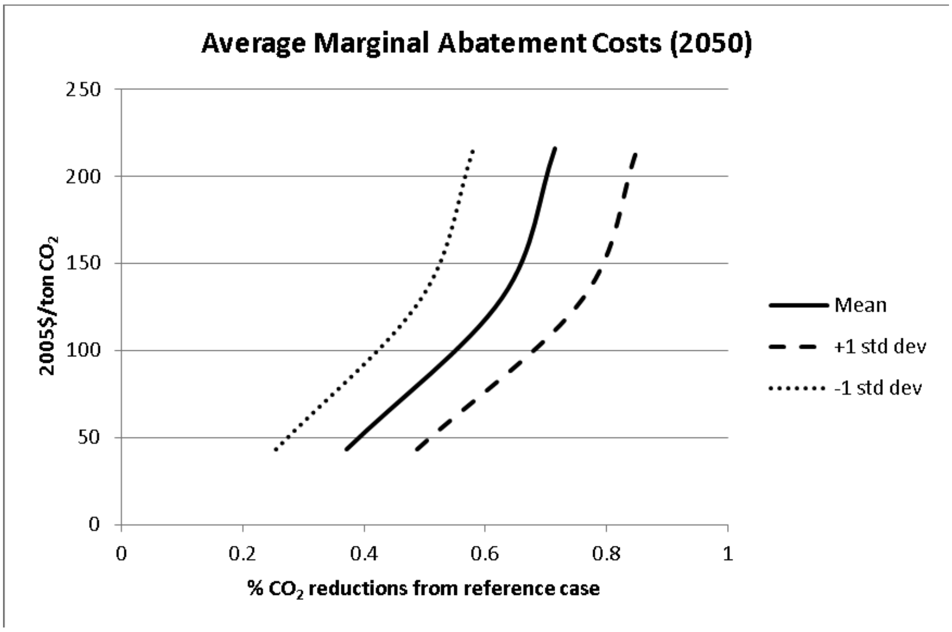
As explained in section 6.3.4.1, various metrics are used to characterize the costs of mitigation, including the reduction in GDP. While the damages associated with climate change are also framed in terms of the loss of GDP, there is a subtle but crucial difference. The damage analyses are conducted in the context of an assumed utility function. The loss of wellbeing is measured using the equivalent variation measure as the loss of GDP that is equivalent in its impact on utility. Some of the models in Chapter 6 also have an underlying utility function and employ GDP loss as the equivalent variation measure, in this case of mitigation cost. However, many of the models do not involve an underlying utility function and are not reporting an equivalent variation measure. In that case, the reduction in consumption is a better (though still inexact) welfare metric than the loss of GDP.

Turning from total to marginal cost, the equilibrium price of emissions in a cap-and-trade market, or equivalently the emission tax that induces the specified level of emission reduction, is used as metric for the marginal cost of GHG mitigation. A marginal abatement (mitigation) cost (MAC) curve graphs this cost against the amount of mitigation for different levels of mitigation. In other words, if an x$ per ton tax on carbon is imposed, how much mitigation can we expect? Letting x vary traces out a marginal abatement cost curve. Under simplified conditions, the area under the MAC curve measures the total economic cost of emission reduction, but it fails to capture some of the economy-wide effects associated with existing distortions, which could be large (Paltsev et al., 2007; Morris et al., 2012). Figure 3.8.3 presents estimates of MAC curves for 2020 and 2050 taken from the models analyzed in Chapter 6.[103]

[103] The difference in mitigation costs between 2020 and 2050 is due primarily to technological change expected to have occurred after 2020.



(a)



(b)

Figure 3.8.3. Marginal Abatement Cost (MAC) curves for 2020 and 2050. Note: These data are from a family of MAC curves generated by different models; for example, the mean is the mean MAC over the various models. This figure is based on data generated as part of the Asian Modelling Exercise, summarized in (Calvin et al., 2012). These curves have been provided by Chapter 6 and reflect the assumptions of the source; we are not able to independently validate the accuracy of these functions.

Despite differences among models, some general observations apply. While the degree of disaggregation by economic sectors varies, all the models are highly aggregated economically, socially and spatially. The aggregation precludes analysis of distributional issues. The conclusions resulting from the models depend on the assumptions made (1) in specifying the model's structure and (2) in calibrating the model's parameters.[104] The models are calibrated to actual economic data, but they are not validated in the sense of generating predictions (or backcasts) of responses to observed stimuli and testing those predictions against actual outcomes. One factor that would complicate such validation is that these are equilibrium models and therefore implicitly assume instantaneous adjustment to changes in economic variables. Most models do not address the speed of adjustment or incorporate a cost of adjustment.[105] In most models, the cost of abating emissions at a given time is independent of whether abatement has occurred previously, or how much; the cost just depends on the amount of abatement undertaken that year.[106]

The economic models generally involve an assumption of fully optimizing behaviour by economic agents. Therefore, aside from technological change, any reduction in emissions must be driven by changes in price or regulation.[107] These models have no scope for behavioural factors such as a change in the norms held by consumers, a change in the business models used by companies, the emergence of new intermediaries or new industries. Behavioural factors lower the efficiency of the economy but, as explained in section 3.9.1 , they might also create some scope for interventions that could lower the cost of changing towards a less carbon-intensive economy.[108] A key determinant of the economic cost of limiting GHG emissions is the feasibility and future cost of using non-fossil fuel energy in electricity generation and in transportation. Another determinant is the feasibility and cost of increasing energy efficiency in end uses. Both of these depend crucially on the possibilities for technological innovation.[109] Both also have a behavioural component – whether or not actors will abandon old habits of behaviour and take up new technologies – which is hard to predict and to model.

Box 3.8.2. Could mitigation have a negative cost?

The preceding discussion has emphasized the (positive) costs associated with the reduction of GHG emissions. Could mitigation sometimes reduce costs? This notion has received considerable

[104] The two are interrelated since the calibration can offset some aspects of the specification (Fischer and Morgenstern, 2006).

[105] What the models tend to show, as Barker and Jenkins (2007) note, is "long-run responses often for undefined dates in the future." This becomes less of an issue to the extent that the unit of time in the model covers a longer span of years, such as a decade. The timing of the turnover of capital stocks is a factor in the speed of adjustment that is not well accounted for in most of the models. In fact, models often convert capital costs into an equivalent annualized cost, thereby erasing the distinction between funding operating costs and financing capital investment.

[106] This implies that abatement can be stopped and started costlessly.

[107] The connection is this: if agents are optimizing fully and there is no technological change, the only way to induce a change in their behaviour is by changing prices. Otherwise they would be doing something that they had formerly rejected, which must entail a welfare loss. However, the US experienced a large reduction in sulphur dioxide emissions between 1995 and 2000, and factors other than price signals and technological change played an important role (Burtraw, 1996; Burtraw et al., 2005). Rather than seeing a response according to existing demand and supply curves, Hanemann (2010) argues that the main response was due to changes that are not captured by conventional CGE models. The extent to which something similar could happen with GHG mitigation is an open question.

[108] While a growing body of evidence shows that behavioural factors have a real influence, their potential overall impact on the cost of mitigation has not been assessed.

[109] It is fair to say that technological innovation is a complex and nuanced process that is not yet well represented in the economic models. It is addressed in section 3.10 and in Chapter 6. Energy efficiency in end uses is examined in Chapters 7-10.

attention as the result of a series of analyses disseminated by McKinsey & Company, starting in 2007,[110] which found a substantial potential for GHG emission reduction at *negative* cost, especially for emissions associated with energy used in residential and commercial buildings for lighting, and heating, as well as for some agricultural and industrial emissions. Those opportunities for emission reduction would be a free lunch.

The assertion that reducing pollution may turn out to increase firms' profits has a long history, perhaps originating in the debate in the 1970s regarding low-cost energy-conservation opportunities. Hausman (1979) examined the question of why consumers did not avail themselves of energy conservation opportunities that from an engineering perspective looked cost effective. Joskow and Marron (1992, 1993) examined the actual cost of energy conservation opportunities in electricity, comparing them with engineering or technical estimates of cost. Their general finding is that the engineering estimates are overly optimistic regarding cost (i.e., costs of saving energy are underestimated). They find actual costs on average approximately twice the technical estimates. This finding on the divergence between actual costs and engineering estimates of costs culminated in a strong exchange with Amory Lovins in *Science*.

Huntington (2011) reviews the energy-efficiency literature, which is at the core of the McKinsey analysis, and concludes: "The most salient differences between estimates of potential energy savings and results from energy-economy models appear to be the behaviour of market participants rather than the performance and costs of different technologies." In other words, it is incompletely representing human behaviour that generates the appearance of the existence of negative mitigation costs. An alternative explanation would be that engineering estimates wrongly assume that all cost-reducing options for saving energy and emissions are automatically implemented.

In a parallel vein, Porter (1991) and Porter and van der Linde (1995) argued that unilateral reductions in pollution could stimulate innovation and improve firms' competitiveness as a by-product. The subsequent literature on what became known as the Porter Hypothesis obtained mixed results, finding empirical support in some cases (e.g., Lanoie et al., 2008), but not others (e.g., Jaffe and Palmer, 1997).[111]

Many analyses which find negative mitigation costs rely on a bottom-up expert assessment of the cost and emission reduction potential of each measure considered, with the measures then arrayed from cheapest to most expensive.[112] Whether the finding of large negative costs is correct has been much debated. It may be that the estimates are flawed – in the field, the savings might not really be as large, or the costs may be higher than estimated.[113] If the benefits accrue to parties who do not bear the costs, this could explain the adoption failure. An example of this is the problem of split incentives: for example renters of buildings have less incentive to invest in improving the energy efficiency of their building because the long-run benefits accrue to the building owner (refer to section 3.9.1). Another explanation is that adoption has hidden barriers that are being overlooked: for example, a lack of information, inattentiveness, a bias towards the present, imperfect capital

[110] Enkvist et al. (2007), McKinsey & Company (2009).

[111] See Ambec et al. (2013) and Ambec and Barla (2006) for a review of this literature.

[112] This type of analysis was first conducted by Meier (1982) for the reduction of electricity use. The costs in each segment are an average cost; the curve is considered a marginal cost curve across alternative technologies because of the ranking based on cost. This type of curve, which became widely used, was first called a conservation supply curve; for a discussion see Kesicki and Strachan (2011).

[113] For example, Anderson and Newell (2004) found that engineering cost estimates omitted certain opportunity costs, physical costs or impediments, and did not account for risks perceived by energy users. Dubin et al. (1986) and Nadel and Keating (1991) found that engineering estimates of energy savings could overstate field returns, sometimes greatly; for a further discussion, see Allcott and Greenstone (2012).

markets or non-financial costs (e.g., inconvenience, uncertainty associated with the unfamiliar). One explanation for the negative cost result is that their MAC's usually refer to a point in the future (such as 2020 or 2030), while abatement costs are relative to today's technology. If in fact technological change has the effect of lowering the marginal abatement cost curve over time, then what appear to be negative cost mitigation opportunities are nothing more than a movement in what is cost-effective mitigation over time, thus lowering the carbon intensity of the economy, autonomously.

3.8.4 Social cost of carbon

Although estimates of aggregate mitigation costs and aggregate damages from climate change can be useful in formulating mitigation policies, there is a more mundane policy need for these estimates. There are many small regulatory decisions faced by governments in implementing energy and climate policy. For instance (and this is a real example), what energy efficiency standards should be imposed on new vending machines? Since carbon isn't regulated to any degree in most countries, the benefits of reducing emissions of carbon will most likely be understated in determining the appropriate level of energy efficiency for the vending machines. What is needed is a social cost of carbon emissions that can then be factored into such regulatory exercises.

To derive such a cost, consider a baseline trajectory of emissions, E_t, resulting in a trajectory of global temperatures, T_t. Assuming a damage function $D(T_t)$, as discussed in section 3.8.2 , this results in a present value of damages of

Equation 3.8.4.
$$PVD \equiv \int_0^\infty D(T_t)dt$$

Taking the derivative with respect to a small change in emissions at t=0, E_0, measures the extra cost (i.e., the increment in the net present value of damages) associated with a one tonne increase in emissions today:

Equation 3.8.5.
$$MDCC = \frac{\partial PVD}{\partial E_0}.$$

When applied to CO_2 this is the marginal gross damage of the climate change from an extra tonne of carbon. However, there are some subtleties in how the measure is calculated empirically in the literature. It clearly depends on the assumed future trajectory of emissions (if we assume high future emissions, damage will be higher than if we assume low future emissions).

The social cost of carbon (SCC) could be viewed as the marginal damage from climate change (MDCC). Alternatively, the social cost of carbon could be viewed as the net welfare cost of an extra tonne of carbon, as discussed in section 3.5.3 .[114]

Which definition of SCC should be used depends on the intended application. The motivating example in the first paragraph suggests the SCC should only reflected the net present value of climate damages from one more tonne of CO_2 (i.e., MDCC). On the other hand, equating SCC to the net welfare effects of one more tonne of carbon (including avoided mitigation costs and damages) is closer to the commonly understood meaning of the words "social cost of carbon." In either case, the empirical estimate of the SCC can vary considerably and is highly dependent on the assumed future mitigation and regulatory trajectories.

[114] Referring to the theoretical discussion in section 3.5.3.3 and allowing for some differences in model structure, the former calculation corresponds approximately to the term μ, while the latter corresponds approximately to (μ - t).

It has been suggested that governments should use $SCC_τ$ to set a price on carbon. In 2002, based on a literature review, the UK government recommended a global SCC value of ₤70/tonne of carbon (= ₤19/tonne of CO_2[115]), with a range of ₤35-140, for use in policy analysis and regulatory impact assessment.[116] In 2008, some US government agencies started using an SCC value for regulatory impact assessment, and in 2010 a standardized range of values was promulgated for use by all agencies, based on simulations with DICE, FUND and PAGE, using alternative projections of emissions and alternative discount rates. [117] The central SCC value is \$22/tCO_2, with sensitivity analyses to be conducted at \$5, \$35 and \$65/tCO_2.[118] Table 19-4 in WGII summarizes some SCC figures from IAMs.

The use of the SCC estimates for regulatory assessments has stimulated further discussion of the validity of the damage functions on which they are based. In addition to the empirical issues mentioned in 3.8.2 , conceptual grounds for concern with the damage functions include (i) the arguments that belong in the damage function, (ii) the multiplicative specification of the relation between T_t and Y_t in the damage function, (iii) the treatment of uncertainty about damages associated with large degrees of warming.

In DICE and PAGE, and in some sectors of FUND, the economic loss/gain from climate change in a given year depends solely on the level of global temperature in that same year. Temperature is the only climate variable that drives damages, with no lagged effects: impacts are independent of the prior trajectory of temperatures. Convenience is the only justification for making this assumption.[119] One could imagine that some impacts and damages might depend on the rate of increase in temperature[120] or the cumulative amount of warming in previous decades (measured, say, in degree years).

Like other IAMs, DICE, FUND and PAGE represent damages as (i) a reduction in the productive capacity of the economy that (ii) is proportional to aggregate output. This combination of assumptions turns out not to be innocuous. An alternative formulation views (at least some of) the damages as affecting wellbeing directly rather than through the production of market commodities. The significance of this formulation depends on what is assumed about the elasticity of substitution in the utility function between market commodities and non-market climate impacts. If the elasticity of substitution is unity, this is equivalent to the conventional multiplicative formulation. If the elasticity of substitution is lower than unity, it turns out that this may generate a higher SCC and a

[115] tCO_2. The value was to grow by 1% per year.

[116] Clarkson and Deyes (2002). The value of ₤70/tC allowed for equity weighting of impacts across countries. The values were subsequently revised in 2007 and 2010.

[117] Greenstone et al. (2013), in describing the US Government approach to SCC, indicates that they stipulate several different baseline "regulatory" models (several with no mitigation and one with stabilization at 550ppm). For each, they increase carbon by one unit at a time point t and measure the net present value at t of the change in the consumption trajectory. In the case of the stabilization scenario, there may be some savings in mitigation costs but some damage from additional climate change in earlier years.

[118] Greenstone et al. (2013). Values are in \$2007. The values are to grow over time; for example, the central value increases to \$26/tcO2 in 2020. See also Kopp and Mignone (2011) and Rose (2012).

[119] The assumption simplifies the calibration of damages to a benchmark warming.

[120] This is the case for some sectors of FUND; also for MERGE (Manne and Richels, 2004a). Peck and Teisberg (1994) specified damages as a function of the rate rather than the level of temperature using the CETA model, and found that the effect (in terms, say, of the magnitude of the optimal carbon tax) can be quite large depending on the nonlinearity of damages and the sensitivity to the rate of warming.

more drastic trajectory of emission reductions (Sterner and Persson, 2008).[121] A related argument is made by Weitzman (2010a) about the distinction between additive versus multiplicative production damages from climate change; he finds that with a high level of global warming the functional specification makes a significant difference, with the additive formulation leading to more drastic emission reductions.

A third issue is the sensitivity of SCC to alternative characterizations of risk preferences. The utility function in DICE, FUND and PAGE, does not distinguish between welfare gains deriving from risk reduction (risk aversion) and welfare gains from smoothing consumption over time (aversion to income change): both preferences are captured by the curvature of the utility function as measured by the parameter, η, in Equation 3.5.3. Kreps and Porteus (1978) and Epstein and Zin (1991) showed that these should be represented by two separate functions with separate parameters for risk aversion and inter-temporal substitution, a result that has been used successfully in the finance literature to explain several anomalies in the market pricing of financial assets, including the equity premium puzzle (Campbell, 1996; Bansal and Yaron, 2004). The insight from the financial literature is that the standard model of discounted expected utility, used in DICE, FUND and PAGE, gets the risk premium too low and the discount rate too high.

A final issue is that the assumed future regulatory regime is critical to the computed social cost of carbon. If no future regulation is assumed, the current social cost of carbon will be high, at least compared to the case where aggressive mitigation is assumed to take place in the future. This issue is an ambiguity in the concept of SCC and suggests that SCC should be used with caution.

3.8.5 Emissions metrics

The composition of emissions among different GHGs varies among countries and over time. For one country, methane may be a large component of its emissions, while CO_2 is a small component; for another country, the reverse may be true. Yet the two gasses have very different physical characteristics. Unit for unit, methane is a more potent GHG than CO_2, yet methane has a much shorter residence time in the atmosphere. If one wants to compare the different countries' emissions, say, or to allocate a given aggregate level of emission reduction among particular countries, or to establish exchange rates for trading different gasses in a cap-and-trade system, a fair way is needed to compare different GHGs.[122] This can be done several ways. The comparison could be based on the differential consequences of emitting each gas, as measured in terms of some outcome metric; or the comparison could be based on the differential cost of abatement for each gas. Many metrics have been proposed. The issue is closely related to that of the social cost of carbon. In this case, we wish to compare the social cost of carbon to the social cost of methane (for example). Unfortunately, the data necessary to compute the social cost for each gas is incomplete; and as the discussion of SCC suggests, assumptions are built into SCC that can significantly change its value.

Starting with the addition of an extra ton of GHG *j* in the atmosphere, let $\phi(\tau)$ denote the fraction of the extra ton that is still resident in the atmosphere τ years after emission, where $\partial\phi/\partial\tau < 0$.[123] Denote the consequence of interest by *O*. The original outcome metric, introduced by Lashof and

[121] Sterner and Persson employ an elasticity of substitution of 0.5. Their finding is related to a point made much earlier by Krutilla (1967). Krutilla argued that, over time, unspoiled natural environment will be irreversibly depleted and, if produced commodities are not a good substitute for the natural environment, the natural environment will become increasingly valuable relative to market commodities. This type of mechanism underlies Sterner and Persson's result.

[122] This issue is also considered in Chapter 8 of WGI.

[123] The initial value $\phi(0)$ may be less than 1, since some of the gas may be immediately absorbed (e.g., into the ocean).

Ahuja (1990) and endorsed by the IPCC (Albritton et al., 1995), was radiative forcing. Suppose an extra ton of gas *j* is injected into the atmosphere in year *0*; the extra forcing in year τ that results is denoted $\Delta_j O(\tau)$. The accumulated effect out to a horizon of T years of an additional emission of gas *j* now (t = 0), expressed in forcing-years, is given by

Equation 3.8.6. $$M_j(T) \equiv \int_0^T \Delta_j O(\tau)\,\phi(\tau)\,d\tau.$$

This is an absolute metric. The relative metric, using radiative forcing as the outcome and taking CO_2 as the base, known as the Global Warming Potential (GWP), is

Equation 3.8.7. $$\rho_j(T) = M_j(T) / M_{CO_2}(T).$$

Aggregate emissions in CO2-equivalent are then calculated as $E_{CO2e} = \sum E_j \rho_j$. This seems relatively benign, but the choice of radiative forcing and the choice of T are very significant. As Schmalensee (1993) pointed out, the GWP for methane for T=20, 100, 500 years is 63, 21, and 9, respectively (using the assumptions he adopted). The choice of T is somewhat arbitrary but as this example illustrates, profoundly important.

This template has been modified many times. One modification uses geometric discounting to calculate the cumulative effect, replacing (Equation 3.8.6) with:

Equation 3.8.8. $$M_j(T) \equiv \int_0^T \Delta_j O(\tau)\,\phi(\tau)\,e^{-r\tau}\,d\tau.$$

The formulation in (Equation 3.8.4) and (Equation 3.8.6) assumes a single pulse change in emissions at time t. An alternative formulation considers the cumulative impact on the outcome variable of a *prolonged* change in emissions lasting for a specified period of years (a step change). [124] Other formulations focus on a different outcome variable, *O*. The Global Temperature Potential, GTP, uses the change in global mean temperature as the outcome, in which case $\Delta_j O(\tau)$ in (Equation 3.8.6) or (Equation 3.8.8) is the change in global mean temperature rather than the change in radiative forcing (Shine et al., 2005, 2007).[125]

As noted earlier, these metrics depend on the choice of the endpoint *T* and, in the case of (Equation 3.8.8), the method of discounting and choice of discount rate, *r*. The formulations in (Equation 3.8.6) and (Equation 3.8.8) are implicitly independent of the timing of the emissions, *t*, which is not strictly correct. For example, an increment in CO_2 emissions produces a smaller increase in radiative forcing at higher CO_2 levels than at lower levels. Thus, the impact term $\Delta_j O$ should really depend on the entire trajectory of emissions (Smith and Wigley, 2000).

Alternatives to metrics based on physical outcomes include economic metrics based on the damages caused by emissions (Eckaus, 1992; Michaelis, 1992; Schmalensee, 1993; Hammitt et al., 1996; Kandlikar, 1996). In these metrics, the outcome variable $\Delta_j O(\tau)$ in (Equation 3.8.8) becomes the incremental damage, measured as equivalent change in global GDP, resulting from an extra ton of gas *j* in the atmosphere in year *τ*. From an economic point of view, this would in theory be the best approach to the formulation of a climate metric, accounting for the full chain of causal impacts. The chief practical obstacles are the inadequacies of the global damage functions presently available, as discussed in 3.8.2 .

[124] Harvey (1993).

[125] Variants of this are the Temperature Proxy Index (Tanaka et al., 2009) and the Mean Global Temperature Potential (Gillett and Matthews, 2010).

Another economic approach that avoids the problems associated with using a damage function frames the issue instead in terms of minimizing the cost of mitigation (Manne and Richels, 2001). This is set in the context of attaining a prescribed climate target, whether a target concentration level or a target degree of warming. The resulting Global Cost Potential (GCP) uses the global marginal mitigation cost associated with the specified climate target as the outcome measure when calculating the term $\Delta_j O(\tau)$ in (Equation 3.8.8).[126] When used with a temperature target, the GCP yields qualitatively comparable results to the GTP (Shine et al., 2007). An even better approximation of the GCP by a physical climate metric is yielded by the Cost-Effective Temperature Potential (CETP), which only considers climate impacts that occur after the climate target has been reached (Johansson, 2012).

The choice of an appropriate metric for policy applications is partly a conceptual problem, depending on what considerations are relevant for the intended application, and partly a practical problem involving a trade-off between the simplicity, transparency and uncertainty associated with the alternative climate metrics (Skodvin and Fuglestvedt, 1997; Fuglestvedt et al., 2003; Plattner et al., 2009). Simple physical metrics, such as the GWP, are easier to calculate and more transparent in their calculation, but are inaccurate in representing the relevant damage trade-offs between different gasses (Fuglestvedt et al., 2003; Deuber et al., 2012).

Different metrics can lead to very different weights ρ_j in (Equation 3.8.5). This is particularly relevant for methane, which has an atmospheric lifetime that is significantly shorter than that of CO_2: a metric that emphasizes impacts occurring in the short term will result in a higher metric value for methane (Boucher, 2012), thus creating stronger emission reduction incentives on CH4 emitting sectors such as agriculture (Reisinger et al., 2012). A few studies have analyzed the economic implications of using alternative metrics (Godal and Fuglestvedt, 2002; O'Neill, 2003; Johansson et al., 2006). These studies conclude that the cost penalty for using the standard 100-year-GWP increases the costs of achieving a prescribed climate target by less than 5% compared to the mitigation costs in a first-best economic approach. On the other hand, individual countries may be significantly affected by different metrics. Further studies using current state-of-the-art models with a detailed representation of non-CO2 emissions would help to corroborate these findings.

3.9 Behavioural economics and culture

This section summarizes behavioural economics related to climate change mitigation. We focus on systematic deviations from the traditional neoclassical economic model, which assumes that preferences are complete, consistent, transitive, and non-altruistic, and that humans have unbounded rational capacity, unbounded attention, and coherent expectations. In relation to behavioural economics issues, social and cultural issues and conditions that frame our attitudes and living conditions are also addressed.

Although the focus of this section is on the behaviour of individuals, some firms and organizations have taken actions that may appear to be inconsistent with the standard neoclassical model of the profit-maximizing firm.[127] The behaviour of firms and non-profit organizations is important but is not considered in this section.

[126] This is related to, but different from, the marginal abatement cost graphed in Figure 3.8.3. The GCP can also be considered a special form of net benefit maximization where damages are assumed to be zero below the specified climate target, and infinite above it.

[127] Refer to Lyon and Maxwell (2007).

3.9.1 Behavioural economics and the cost of emission reduction

Behavioural economics can be broadly understood as the branch of economics that stresses that people have cognitive limitations (and abilities) that affect their economic decision-making processes. Choices can be affected and/or framed by, for instance, perceived fairness, social norms, cooperation, reciprocity, social context, self-serving bias, cognitive load, leadership and modes of thinking.[128] Behavioural economics emphasises these cognitive, social and emotional factors that lead to apparently irrational choices. A growing number of documented systematic deviations from the neoclassical model help explaining people's behaviour, but here we focus on the several that we view to be most relevant to climate change mitigation. [129] Chapter 2 of this volume also treats this issue.

3.9.1.1 Consumer undervaluation of energy costs

Consumers may undervalue energy costs when they purchase energy-using durables such as lighting, air conditioners, and cars or make other investment decisions related to energy use.[130] By "undervalue," we specifically mean that consumers' decisions systematically fail to maximize "experienced" utility (utility as a hedonic experience) instead of "decision utility" (utility as a representation of preferences) (Kahneman and Sugden, 2005),[131] and this misoptimization reduces demand for energy efficiency. Three potential mechanisms of undervaluation may be most important.

First, when considering a choice with multiple attributes, evidence suggests that consumers are inattentive to add-on or unobserved costs and ancillary attributes, such as shipping and handling charges, or sales taxes (Hossain and Morgan, 2006; Chetty et al., 2009). It is possible that energy efficiency is a similar type of ancillary product attribute and is thus less salient at the time of purchase (Gates, 1983; Lutzenhiser, 1992; Metcalf, 1994). Second, significant evidence across many contexts also suggests that humans are 'present biased' (DellaVigna, 2009). If energy costs are paid in the future, this would lead consumers to be less energy efficient than their long-run Pareto optimum. Third, people's beliefs about the implications of different choices may be systematically biased (McKenzie et al., 2007; Jensen, 2010; Bollinger et al., 2011; Kling et al., 2012). Attari et al. (2010) show that people systematically underestimate the energy savings from a set of household energy conservation activities, and Allcott (2011) shows that the average consumer either correctly estimates or slightly systematically underestimates the financial savings from higher-fuel economy vehicles. Each of these three mechanisms of undervaluation appears plausible based on results from other contexts. However, rigorous evidence is limited in the specific context of energy demand, because the present discounted value of energy costs can be difficult to measure in some contexts, and because we don't observe features of choice situations that make it difficult to prove that consumers are misoptimizing (Allcott and Greenstone, 2012).

Three implications arise for climate and energy policy if the average consumer who is marginal to a policy does in fact undervalue energy costs (Allcott et al., 2012).

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[128] See, e.g., Babcock and Loewenstein (1997), Shiv and Fedorikhin (1999), Asheim et al. (2006), Barrett (2007), Levati et al. (2007), Potters et al. (2007), Shogren and Taylor (2008), Dannenberg et al. (2010).

[129] See Rachlinksi (2000), Brekke and Johansson-Stenmann (2008), Gowdy (2008), and the American Psychological Association (2010).

[130] This can even apply to cases in which sophisticated methods are applied to support decisions. For instance, Korpi and Ala-Risku (2008) found that Life-Cycle Costing applications are far from ideal and that deviations from best practices can be attributed, among several aspects, to judgements, opinions, and cognitive load.

[131] The economics literature includes an intensive debate on whether 'experienced utility', or subjective well-being, as the assessment of happiness and satisfaction, should be the focus of social policy evaluation. See, e.g. Fleurbaey (2009).

First is an "internality dividend" from carbon taxes (or other policies that internalize the carbon externality into energy prices): a carbon tax can actually increase consumer welfare when consumers undervalue energy costs. The intuition is that undervaluation is a pre-existing distortion that reduces demand for energy efficiency below consumers' private optima, and increasing carbon taxes helps to correct this distortion.

Second, in addition to carbon taxes, other tax or subsidy policies that raise the relative purchase price of energy inefficient durable goods can improve welfare (Cropper and Laibson, 1999; O'Donoghue and Rabin, 2008; Fullerton et al., 2011).

Third, welfare gains are largest from policies that preferentially affect consumers that undervalue energy costs the most. This fact is related to the broader philosophies of libertarian paternalism (Sunstein and Thaler, 2003) and asymmetric paternalism (Camerer et al., 2003), which advocate policies that do not infringe on freedom of choice but could improve choices by the subset of people who misoptimize. In the context of energy demand, such policies might include labels or other programmes that provide information about and draw attention to energy use of energy-using durable goods in retail stores.

3.9.1.2 Firm behaviour

Some of the phenomena described above in connection with household decision-making may also occur with decision-making by firms. The conventional economic model represents the firm as a single, unitary decision-maker, with a single objective, namely profit maximization. This has been characterized as the 'black-box' model of the firm (Malloy, 2002). There is an alternative view of the firm as an organization with a multiplicity of actors, perhaps with different goals, and with certain distinctive internal features.[132] For example, in the context of a firm's response to a cap and trade system, von Malmborg (2008) notes that the firm's decision to reduce emissions internally versus purchasing emissions permits from the market is isomorphic to the 'make or buy' decision discussed by Coase (1937) and analyzed further by Williamson (1975, 1981), and depends on three main factors: (i) the degree of uncertainty/complexity inherent in the transaction, (ii) how frequently the transaction is to be made (the transaction 'density'), and (iii) the cost of transaction-specific investments.

Lyon and Maxwell (2004, 2008) examine in detail tendency of firms to undertake pro-environment actions, such as mitigation, without being prompted by regulation. Taking a neoclassical approach to the problem, they find that firms view a variety of pro-environment actions as being in their self-interest.

In the U.S. SO_2 market, there was in fact a high degree of autarky (self-reliance on emission reduction), which Kreutzer (2006) suggests might have been influenced by loss aversion on the part of firm managers. Evidence of a compliance norm has been found in other contexts where firms' responses to regulation have been studied.

3.9.1.3 Non-price interventions to induce behavioural change

Aside from carbon taxes and other policies that affect relative prices, other non-price policy instruments can reduce energy demand and therefore reduce carbon emissions. Such interventions include providing information about potential savings from energy efficient investment, drawing attention and awareness about energy use or making available concrete examples on how to use teleworking or save energy via adjustment in room temperature (e.g., Stern, 1992; Abrahamse et al.,

[132] In economics, this view goes back to Coase (1937) and was importantly developed by Williamson (1975). This view also is the central focus of the organizational behaviour literature, where it received a powerful stimulus from Cyert and March (1963).

2005). They also include feedback on historical energy consumption (Fischer, 2008) and information on how one's energy use compares to a social norm (Allcott, 2011).[133]

In some cases, non-price energy conservation and efficiency programmes may have low costs to the programme operator, and it is therefore argued that they are potential substitutes if carbon taxes are not politically feasible (Gupta et al., 2007). However, a critical issue is whether such interventions are appropriate substitutes for carbon taxes (e.g., in terms of environmental and cost-effectiveness). One reason is that these interventions may have a modest impact (Gillingham et al., 2006) and that unaccounted costs may reduce the true welfare gains. For example, consumer expenditures on energy efficient technologies may be unobserved (e.g., transaction costs), as well as the time spent to turn lights off or guilt from being informed that they waste energy.

Research in other domains (e.g., Bertrand et al., 2010) has shown that a person's choices are sometimes not consistent, but instead are malleable by "ancillary conditions," which are non-informational factors that do not affect experienced utility. In the context of energy efficiency, this could imply that energy demand may be reduced at relatively low welfare costs through by advertising campaigns aimed at changing consumer preferences. However, economics may have little to say about the ethical and political issues surrounding publicly-funded persuasion and marketing programmes. The effectiveness of information schemes, both in energy and carbon terms, may depend ultimately on how consumers actually use the information and the effectiveness of the mix of policy instruments (Gillingham et al., 2006; Gupta et al., 2007).[134]

3.9.1.4 Altruistic reductions of carbon emissions

In many contexts, it is clear that people are altruistic: they are willing to reduce their own welfare to increase the welfare of others. For example, in laboratory "dictator games," people voluntarily give money to others (Forsythe et al., 1994), and charitable donations in the United States amount to more than two percent of gross domestic product (List, 2011). Similarly, many individuals voluntarily contribute to environmental public goods such as reduced carbon emissions. For example, $387 million were spent on voluntary carbon offset purchases in 2009 (Bloomberg, 2010).

Cooperation can also play an important role in favour of climate-friendly behaviour. For instance, using a one-shot public good experimental game, Fischbacher et al. (2001) discovered that a substantial amount of individuals (so-called 'conditional cooperators') incremented their contributions if others did so. Likewise, Frey and Meyer (2004) found that individuals were giving larger contributions to social funds in Switzerland after being notified that others were also contributing. This 'conditional cooperation' can be understood as an outcome of 'altruism', 'warm-glow', 'inequity aversion' or 'reciprocity' (Fischbacher et al., 2001).

Reciprocity, understood as the practice of people rewarding generosity and castigating cruelty towards them, has also been analyzed. From a field experiment, Falk (2007) provides evidence about the relevance of 'gift exchange', in which people contribute more to social causes when a small gift is given to them. It also found that generous actions may be less likely to be reciprocated if the motive driving those actions is badly perceived Falk et al. (2008). Thus, perceived intentions are as important as perceived kindness for reciprocity to take place.

Pre-existing altruistic voluntary carbon emission reductions could moderate the effects of a new carbon tax on energy demand. The reason is that when monetary incentives are introduced, this can

[133] The efficacy of these interventions can often be explained within neoclassical economic models. From an expositional perspective, it is still relevant to cover them in this section.

[134] To yield large cost-effective potentials of energy efficiency, modelling studies often assume, among several aspects, a very high effectiveness of informative policy instruments (Worrell et al., 2004; Mundaca et al., 2010).

"crowd out" altruistic motivations (Titmuss, 1970; Frey and Oberholzer-Gee, 1997; Gneezy and Rustichini, 2000). Thus, a carbon tax could reduce voluntary carbon emission reductions even as it increases financially-motivated carbon emission reductions. While this effect may not weaken the welfare argument for a carbon tax, it does reduce the predicted elasticity of carbon emissions to a carbon tax relative to the neoclassical model.

3.9.1.5 Human ability to understand climate change

So far, this discussion has covered deviations from the neoclassical model that affect energy demand. Also, deviations from the neoclassical model can affect the process of making climate policy by affecting perceptions of the costs and benefits of policy action. Here, we highlight several.

First, when making decisions, people tend to overweight outcomes that are low-probability or especially "available" or salient (Kahneman and Tversky, 1974, 1979). If some of the potential costs of climate change such as natural disasters are low-probability in any particular location and are also highly salient, this may make policymakers and voters' more receptive to climate policy.

Second, people are more averse to losses than they are interested in gains relative to a reference point (Kahneman and Tversky, 1979). On the one hand, to the extent that climate change involves a loss of existing environmental amenities, this increases the perceived costs of climate change relative to the neoclassical model. In fact, deviations between willingness-to-pay and willingness-to-accept can be largely attributed to psychological aversion to losses, moreover when unique environmental assets are in question. On the other hand, if the costs of climate change abatement are framed as reductions relative to a reference rate of future economic growth, this increases the perceived costs of climate change mitigation.

Third, uncertainty, risk or perceived risk (as elaborated in Chapter 2), are other important factors that affects people's expectations, understanding and decisions (Slovic et al., 2004). The neoclassical model typically assumes that people have rational expectations about uncertain parameters. In the context of climate change, this would mean that while some people might understate the risks, other people might overstate the risks.

Fourth, cognitive ability and modes of understanding to deal with climate change and related alternatives or long-term considerations also affects people's behaviour. People are likely to be misled if they apply their conventional modes of understanding to climate change (Bostrom et al., 1994). From the social point of view, the understanding of climate change as a physical phenomenon with links to societal causes and impacts is very complex and incorrect mental models are often found regarding climate change (Weber and Stern, 2011). Despite progress to better communicate scientific knowledge, confusion about basic aspects remains widespread (e.g. misunderstanding of the difference between 'climate' and 'weather') (Reynolds et al., 2010). A decision or choice may take large amount time, physical or cognitive effort that can lead to no action (Dinner et al., 2011). A heavy cognitive load can be created when making decisions that entail risky, uncertain or complex considerations over future costs or benefits. This cognitive load can trigger cognitive efforts that discriminate against the future, lead to careless analysis and produce irrational choices and deviations from 'true preferences' (Harsanyi, 1982).

Finally, the literature also shows that the public's beliefs and perceptions about climate change do not correspond with scientific knowledge. As mentioned above, climate change is inherently complex to understand, which explains an 'understanding gap' between scientists and the general public. Some misinterpretations can arise because public's understanding and perception is more vulnerable to emotions, values, views and (unreliable) sources (Weber and Stern, 2011). Research in the UK reveals numerous perceived barriers to engage in mitigation activities, ranging from skepticism to fatalism and distrust in information sources (Lorenzoni, 2005). In the US, whereas 84% of scientists agreed with the view that the global warming is due to human activity, only 49% of the general public in the survey held this conviction (Pew Research Center, 2009, p. 39). Based on Gallup data collected in 127 countries in 2007 and 2008, the figure from the US is close to public perceptions (also about "global warming is the result of human activities") in countries like Norway (47%) the UK (48%), or Belgium (50%) but below the international median (54%), and public perceptions in countries such as Japan (91%), Chile (75%) or Sweden (64%) (Pelham, 2009).[135] Political affiliation (or sympathy) may also drive public's views of climate change.

3.9.2 Social and cultural issues

In recent years, the orientation of social processes and norms towards mitigation efforts has been seen as an alternative and complement to traditional mitigation actions such as incentives and regulation. We address some of the most discussed concepts in the literature that, from the social and cultural perspective, contribute to strengthening climate change actions and policies.

3.9.2.1 Customs

In developed and developing countries, some governments, social organizations and individuals have tried to change cultural attitudes towards emissions, energy use, and in fact the very way in which life is conducted (European Commission, 2009). For example, household energy use patterns for space and water heating differ massively between Japan and Norway due to lifestyle differences and the massive energy use for hot baths in Japan not seen in Norway (Wilhite et al., 1996; Gram-Hanssen, 2010). In some countries, social attitudes have been influenced by experiences with indigenous peoples. In fact, some have argued that the bio-cultural heritage represented in indigenous peoples of the world is a resource that should be valued and preserved, as it constitutes an irreplaceable bundle of teachings on the practices of mitigation and sustainability (Russell-Smith et al., 2009; Kronik and Verner, 2010). In some cases, customary local strategies have morphed into national policies, as is the case with the concepts of *Buen Vivir* and *Gross National Happiness*. In rich countries, and elsewhere in social groups with high levels of environmental awareness, interest in sustainability has given rise to cultural movements promoting significant changes in modes of thought, production, and consumption, giving them new meaning. Including the cultural dimension in mitigation policies facilitate social acceptability.

3.9.2.2 Buen Vivir – Vivir Bien

Buen Vivir (in Ecuador) and Vivir Bien (in Bolivia) are concepts that fosters a particular attitude towards nature, where all living beings are seen as integral to society (Choquehuanca, 2010). This set of thoughts and attitudes are hypothesized to replace the human centeredness relationship with nature. It is grounded in Andean indigenous culture; in Ecuador (in the Quechuan language) Buen Vivir it is termed *Sumak kawsay,* and in Bolivia, Vivir Bien *Qamaña* (Gudynas, 2011). Buen Vivir is an alternative to the notion of welfare based the consumption of materials goods, individualism, and competition. The idea is to promote another set of values, such as "traditional knowledge, social and cultural recognition, and ethical – even spiritual - codes of conduct in the nature/society relation, human values, and vision of the future" (Acosta, 2008).

What distinguishes Buen Vivir from just another theory of alternative lifestyles is that is has been incorporated into the constitutions of Bolivia and Ecuador. One of the great challenges of Buen Vivir is how to develop concrete, viable and effective strategies and actions that are different from conventional practices (Gudynas, 2011). Theoretical debates on Buen Vivir recognize that these alternative world views are not unique to the Andean indigenous communities; in fact, they occur in a variety of cultures both in Latin America and elsewhere. It is a concept that accepts and values cultural diversity, so that *buenos vivires* ("good livings") arise in different manifestations in each

[135] Another study shows that 15-20% of Americans do not believe that global average temperatures are rising, and only 41% of Americans believe that most scientists think that global warming is happening (Leiserowitz et al., 2011).

social and environmental set of circumstances (Gudynas, 2011). Such *good livings* carry a novel world-view, promoted by social movements, academics and non-governmental organizations in various countries around the world. The effect that this approach has on GHG emissions is related to life styles that are based on sustainable patterns of production and consumption.

3.9.2.3 Gross National Happiness

Gross National Happiness (GNH) is a concept formulated by the Kingdom of Bhutan in order to plan and evaluate national development and the welfare of the country´s population. The related GNH Index is seen as an instrument of public policy that measures the progress of the Kingdom based on nine key domains (and 72 core indicators): ecology, living standards, health, education, culture, community vitality, time use, good governance, and psychological wellbeing (Uddin et al., 2007). GNH is both a critique and an alternative to the common global development model (Taplin et al., 2013), as it eschews GDP and sees economic growth not as an end, but a means (one among many) of increasing human happiness. The GNH concept was proposed by the fourth King of Bhutan in 1980, in an attempt to see that the country´s development and modernization policies were in accord with its culture, institutions, and values. In 2008 GNH ceased to be only a philosophy of governance and became a constitutional mandate (Kingdom of Bhutan, 2008). The intention is to increase efforts in social infrastructure (access to health, education, clean water, and electrical power) (Pennock and Ura, 2011) while seeking to maintain a balance between economic growth, environmental protection, and the preservation of Bhutanese culture and traditions. This is termed a "Middle Way" because of a concern about the pressures of pure economic development and the environmental and social costs of unchecked development which are counter to the traditional Buddhist spiritual, ethical and cultural teachings (Frame, 2005; Taplin et al., 2013).

GNH differs somewhat from the standard notion of welfare insofar as its public policy objective is the attainment of a happy population, referred to by the concept of sukha –the human flourishing that arises from mental balance and insight into the nature of reality, rather than a fleeting emotion or mood aroused by sensory and conceptual stimuli (Ekman et al., 2005). Referring back to section 3.2.2 of this chapter, the social welfare function is being defined differently. In this context, happiness does not derive from consumption, which are the basis of the common conception of welfare (Easterlin, 1995), but come from internal factors, such as emotions and feelings, and the prioritizing of the ability to live in harmony with nature, community, and spiritual values cultural teachings (Taplin et al., 2013).

3.9.2.4 Indigenous peoples

Indigenous peoples, numbering millions across the globe, are peoples who self-identify as a collectivity based on their distinct culture and history, and have priority in the occupation and use of the customary land and natural resources (Daes, 1996) on which they depend primarily for their livelihoods. Land and the natural environment are integral aspects to indigenous peoples' sense of identity, culture and belonging, and hold fundamental importance for their collective physical and cultural survival as peoples (Gilbert, 2006, p. 115; Xanthaki, 2007, pp. 237–279).

It has been suggested that the customary lands of indigenous peoples contain 80% of the earth's remaining healthy ecosystems and global biodiversity priority areas, including the world's largest tropical forests in the Americas, Africa and Asia (Sobrevila, 2008, p. xii). Primarily dependent on natural resources and inhabiting biodiversity-rich but fragile ecosystems, indigenous peoples find themselves particularly vulnerable in the face of climate change, with little access to resources to cope with these changes (Henriksen, 2007; United Nations Permanent Forum on Indigenous Issues, 2008). They sometimes feel marginalized in decision-making and unable to participate fully and actively in local, national, regional and international climate change mechanisms. Climate change mitigation can thus be viewed not only an environmental issue but also a human rights issue in which indigenous peoples are key stakeholders.

At the same time, it is increasingly recognized that valuable insights into mitigation can be drawn from indigenous peoples' customary knowledge of environmental phenomena and change, which they have accumulated over centuries of coexistence with and inter-dependence with, the natural environment (Nakashima et al., 2012). Successful strategies of adaptation, such as community-based forest governance (Nepstad et al., 2006; Hayes and Murtinho, 2008; Persha et al., 2011) and the management of ecosystem services, strongly suggest that we have a lot to learn and gain from their full and effective participation in the design and implementation of mitigation strategies.

3.9.2.5 Gender

Women are a sector of society whose mitigation capacity has not been singled out until recently. Since the mid-1980s, several studies have shown that the relation between communities and the environment is not gender-neutral (Dankelman, 2002).

Looking at the effects of climate change from a gender perspective means analyzing how the social construction of gender relates to the operation of the economy, politics, daily life, the environment, migration, and people´s subjectivity, in order to find the means to pose a new balance in terms of access, use, control, and benefits of all types of resources (Agostino and Lizarde, 2012). The investigation of cumulative vulnerability suggests the application of the gender approach at various levels: as a category of analysis, a methodological tool (allowing the visualization of aspects of reality that are often invisible), and through political action (promoting gender equality). Studies using demographic categories for analysis (not only gender but also age) may result in insights on effective mitigation efforts.

3.9.2.6 Social institutions for collective action

People's actions and reactions have a strong connection with climate change, because they both contribute to the problem and can facilitate its mitigation. However, studies about perception (O'Connor et al., 1999; Corner et al., 2012) demonstrate that the general public is unaware of the role that individuals and society play in both phenomena. Collective action against climate change recognizes that the success of policies, strategies, and climate action plans actually relies on the degree of involvement of social agents. It has been suggested that this implies the importance of reinforcing environmental education programmes and public participation in the processes of mitigation.

Societies react collectively when they are faced with the experience of significant events, if structures can give impetus to action, and if applicable solutions are available for problems that require change (Kates, 2007). Collective action to mitigate climate change would involve public policies, public institutions and organized social movements that can promote diffusion of knowledge about collective and individual responsibilities that contribute to the problem, and about the means for social involvement in its mitigation.

As articulated earlier in this section, perceptions of the cause and effect of climate change is variable among the public, both in developed and in developing countries; erroneous ideas persist even among well-informed people. This situation makes it difficult to be clear about collective responsibilities, which in turn is an obstacle to establishing solutions, and reduces the effectiveness of strategies for mitigation (Leiserowitz, 2006). A partial solution may be to reinforce and broaden educational strategies for disseminating scientific information, as well as its practical implications, in a way that is understandable to diverse groups in a population, with respect to age, level of schooling, activities, lifestyles, and culture (González Gaudiano and Meira Cartea, 2009). The challenge for an educational programme in mitigating climate change is to construct a local and individual social representation of a problem that is global and collective. Collective action is reinforced when social actors understand they can take an active part in creating local solutions for a global problem that directly concerns them.

So to stimulate and organize collective action to take in consideration the concepts of social learning and policy learning is relevant. Social learning is the set of activities which depend on the participation of the group members in discourse, imitation, or shared collective or individual actions while policy learning is adaptation to external change by organizations which attempt to retain and strengthen their own objectives and their domination over existing socio-economic structures (Adger and Kelly, 1999).

3.10 Technological change

Meeting aggressive emission reduction targets will be difficult without major changes in the way energy is produced and consumed. Given the current status of alternative technologies, making such changes will be costly. However, technology improvements are likely to occur, leading to lower costs. Understanding the potential for technological change (TC) requires an understanding of the process through which these changes occur. All private sector innovations suffer from market failures. These market failures are even more acute in the case of climate change, as environmental market failures compound the problem. Thus, policy can play a key role in shaping both the direction and magnitude of climate-friendly TC. In turn, these policy-induced innovations will lower the cost of reducing carbon emissions. This section reviews theories, concepts and principles used to study environmentally oriented TC highlighting key lessons from this literature, specially the potential of policy to induce desired TC.

3.10.1 Market provision of TC

Technological change includes three stages: invention (creation), innovation (commercialization of an idea), and diffusion of a new product throughout society. Market forces provide insufficient incentives for investment in either the development or the diffusion of environmentally friendly technologies. For GHG mitigation, the most important is market failure is the problem of environmental externalities. Because pollution is not fully priced by the market, firms and consumers have little incentive to reduce emissions without policy intervention. Thus, without appropriate policy interventions, the market for technologies that reduce emissions will be limited, reducing incentives to develop such technologies.

Other market failures relate to technological advance that are logically and empirically distinct from the environmental externality. First and foremost, creators of new knowledge, new products, or new ways of doing things do not reap all the social returns to these creations, because others can copy and build on them. This “appropriability problem” represents a positive externality that leads to under-investment in technology creation, in the same way that the negative environmental externality leads to over-use of the environment. The positive externality is largest for creations that launch an entire new technology trajectory, along which many parties will earn rewards that are in part dependent on the fundamental development, but will not typically share those rewards.[136] Thus the kind of radical transformative TC that some seek will be underprovided by the market, even in the presence of optimal carbon-price policy.

A second potential positive externality is associated with TC that is less-widely discussed and somewhat more controversial as to its theoretical and empirical significance. A large empirical literature pertains to learning-curve effects, whereby the unit cost of production for a good or component falls with its cumulative industry production. One interpretation of this empirical regularity is that a base of knowledge about production methods grows through the process of

[136] For incremental innovations, the net technology externality can be negative. Depending on market structure and intellectual property rules, the inventor of an incremental improvement on an important existing technology may be able to take the entire market away from the incumbent, earning thereby profits that exceed the incremental value of the improvement.

production itself (Thompson, 2010). Due to the appropriability problem discussed in the previous paragraph, the benefits of knowledge created by first movers has public good properties, including the difficultly of excluding parties from its use that may not have contributed to its generation (see, for example, Geroski, 1995).

Investments in the development of new technology frequently struggle against imperfections in the market for capital. In particular, information about the potential of a new technology will always be held asymmetrically, making parties that invest in others' efforts at technology development subject to the problems of adverse selection. These problems raise the cost of capital for financing technology development, and in some cases may make it impossible to secure financing for projects that have a positive expected present value at the appropriate discount rate (Hall and Lerner, 2010). This may be particularly acute for developing countries.

Finally, evolutionary models of technological change emphasize the path dependence of technological progress, and the importance of specific transformative events in generating or diverting technological trajectories (see chapters 4 and 5 for more on this). These transformative events may be exogenous or endogenous, but even if endogenous, they are unlikely to respond to economic incentives in any kind of smooth or predictable way. This suggests that carbon-price policy alone is unlikely to bring such transformative events forth.

These theoretical arguments for under-investment in TC are generally confirmed by empirical research demonstrating that social rates of return to research and development are not only high, but that they are higher than private rates of return (Griliches, 1992).

3.10.2 Induced innovation

Studies on the effect of policy or prices on innovation draw their motivation from the notion of induced innovation (Hicks, 1932; Binswanger and Ruttan, 1978; Acemoglu, 2002), which recognizes that R&D is a profit-motivated investment activity and that the direction of innovation responds positively in the direction of increased relative prices[137] (see chapter 5). Initial evidence of induced TC focused on the links between energy prices and innovation. Newell et al. (1999) find that most of the response to energy price changes came within five years of those changes. This is confirmed by Popp (2002) who shows that more than one-half of the full effect of an energy price increase on patenting is experienced after just five years.

Policy also plays an important role in inducing innovation. Johnstone et al. (2010) find that patenting activity, measured by applications for renewable energy patents submitted to the European Patent Office, has increased dramatically in recent years as both national policies and international efforts to combat climate change begin to provide incentives for innovation. Recent evidence also suggests that international environmental agreements provide important policy signals that both induce innovation (Dekker et al., 2012) and diffusion (Popp et al., 2011).

Dechezleprêtre et al. (2011) examine climate-friendly innovation using patent data from 1978-2005 for 76 countries for a broad range of technologies, including renewable energy, carbon capture and storage, and energy efficiency technologies for buildings, etc. With the exception of China, which ranked 4th most important inventor, most climate-friendly innovation occurs in developed countries.[138] In fact, the US, Japan, and Germany together account for two-thirds of the innovations in their sample, reflecting the role and impact of policy, as innovation increased after the Kyoto Protocol in all Annex I countries except the US, which had not ratified Kyoto.

[137] It should be pointed out that in economics, "induced innovation" typically means innovation induced by relative price differences. IPCC uses a different definition: innovation induced by policy.

[138] Global R&D expenditures amounted to $1.107 trillion in 2007, with OECD nations accounting for 80 %, and the United States and Japan together accounting for 46 % (National Science Board, 2010).

3.10.3 Learning-by-doing and other structural models of TC

An extensive literature uses experience curves to estimate the rates of cost decreases in energy technology (see chapter 6). In economics, this concept is often described as learning-by-doing (LBD) – the decrease in costs to manufacturers as a function of cumulative output – or "learning-by-using" – the decrease in costs (and/or increase in benefits) to consumers as a function of the use of a technology. While learning curves are relatively easy to incorporate into most integrated assessment models of climate, the application of LBD has limitations as a model of TC. Ferioli et al. (2009) discuss limitations of learning curves for energy policy. Learning curves ignore potential physical constraints. For example, while costs may initially fall as cumulative output expands, if renewable energy is scaled up by an order of magnitude or more, the use of sub-optimal locations for production would increase costs. They also provide evidence that learning can be specific to individual components, so that the savings from learning may not fully transfer from one generation of equipment to the next. So they suggest caution when extrapolating cost savings from learning curves to long time frames or large capacity expansions. Hendry and Harborne (2011) provide examples of how experience and R&D interacted in the development of wind technology.

To further address the problems associated with estimating and interpreting learning curves, Nemet (2006) uses simulation techniques to decompose cost reductions for PV cells and finds that plant size (e.g., returns to scale), efficiency improvements, and lower silicon costs explain the majority of cost reductions. Notably, most of the major improvements in efficiency come from universities, where traditional learning by doing through production experience would not be a factor. Learning from experience (e.g., through increased yield of PV cells) plays a much smaller role, accounting for just 10 % of the cost decreases in Nemet's sample.

3.10.4 Endogenous and exogenous TC and growth

Within climate policy models, TC is either treated as exogenous or endogenous.[139] Exogenous TC (most common) is assumed to progress at a steady rate over time, independent of changes in market incentives. One drawback of exogenous TC is that it ignores potential feedbacks between climate policy and the development of new technologies. Models with endogenous TC address this limitation. Endogenous TC models relate technological improvements in the energy sector to changes in energy prices and policy. These models demonstrate that ignoring induced innovation overstates the costs of climate control.

The Nordhaus (1977, 1994) DICE model is the pioneering example of climate policy models that integrate TC into integrated assessment models (IAMs). In most implementations of DICE, TC is exogenous. Efforts to endogenize TC have been difficult, in large part because market-based spillovers from R&D are not taken into account when deciding how much R&D to undertake. The recent so-called R&DICE Nordhaus (2002) is one attempt in this direction allowing firms the option of investing in innovation aimed at developing new products and processes that are less carbon-intensive. Attempts to endogenize TC include the recent ENTICE model of Popp (2004), which shows that models that ignore directed TC do indeed significantly overstate the costs of environmental regulation (more detailed discussion on TC in these and more recent models is provided in chapter 6).

An alternative approach builds on new growth theories, where TC is by its nature endogenous, to look at the interactions between growth and the environment. Policies like R&D subsidies or carbon taxes affect aggregate growth by affecting entrepreneurs' incentives to innovate. Factoring in firms' innovations dramatically changes our view of the relationship between growth and the environment. More recent work by Acemoglu et al. (2012) extends the endogenous growth literature to the case

[139] Köhler et al. (2006), Gillingham et al. (2008) and Popp et al. (2010) provide reviews of the literature on technological change in climate models.

where firms can choose the direction of innovation (i.e., can decide whether to innovate in more or less carbon-intensive technologies or sectors[140]).

In contrast, LBD models use the learning curve estimates to simulate falling costs for alternative energy technologies as cumulative experience with the technology increases. The tractability of learning curves has led to the use of learning-induced technological change throughout the literature, particularly in disaggregated or so-called "bottom-up" models.

One criticism of models using LBD is that learning curve estimates provide evidence of correlation, but not causation. While LBD is easy to implement, it is difficult to identify the mechanisms through which learning occurs. Goulder and Mathai (2000) provide a theoretical model that explores the implications of modelling technological change via R&D or LBD (several empirical studies on this are reviewed in more detail in chapter 6).

3.10.5 Policy measures for inducing R&D

The combination of environmental externalities and knowledge market failures suggests two possible avenues through which policy can encourage the development of climate-friendly technologies: correcting the environmental externality and/or correcting knowledge market failures. Because knowledge market failures apply generally across technologies, policies addressing knowledge market failures may be general, addressing the problem in the economy as a whole. Examples include patent protection, R&D tax credits, prizes for innovation and funding for generic basic research. Such policies focus on the overall rate of innovation, i.e. how much innovative activity takes place? In contrast, policies aimed specifically at the environment focus on the direction of innovation. Although the latter group of policies includes policies regulating externalities, such as a carbon tax or cap-and-trade system, it also includes environmental and energy policies using more general R&D policy mechanisms with a specific focus on the environment, such as targeted government subsidies for the adoption of alternative energy and targeted funding for basic and applied research.

As discussed in more detail in Chapter 15, studies evaluating the effectiveness of these various policy options find that environmental and technology policies work best in tandem. Although technology policy can help facilitate the creation of new environmentally friendly technologies, it provides little incentive to adopt these technologies (e.g. Popp, 2006; Fischer, 2008; Acemoglu et al., 2012). (See chapters 7 to 13.) For instance, Fischer & Newell (2008) study evaluating a broader set of policies aimed at reducing CO_2 emissions and promoting innovation and diffusion of renewable energy in the U.S. electricity sector find that an optimal portfolio of policies (including emission pricing and R&D) achieves emission reductions at significantly lower cost than any single policy. However, Gerlagh and van der Zwaan (2006) raised the question of whether the cost savings from innovation will be sufficient to overcome the decreasing returns to scale for renewable energy due to limited space for new solar and wind installations assumed by Fischer and Newell (2008).

3.10.6 Technology transfer (TT)

Technology transfer (TT) has been at the centre of scholarly debate on climate change and equity in economic development built on the basic idea that developed countries should assist developing countries access new low carbon technologies.

Modes for TT that have been identified include trade in products, trade in knowledge and technology, foreign direct investment, and international movement of people (Hoekman et al.,

[140] Other works investigating the response of technology to environment regulations include Grübler and Messner (1998), Manne and Richels (2004b), Messner (1997), Buonanno et al. (2003), Nordhaus (2002), Di Maria and Valente (2008), Bosetti et al. (2008), Massetti et al. (2009), Grimaud and Rouge (2008), and Aghion et al. (2009).

2005). Phases and steps for TT involve absorption and learning, adaptation to the local environment and needs, assimilation of subsequent improvements, and generalization. Technological learning or catch-up thus proceeds in stages of importing foreign technologies, local diffusion and industrial upgrading through incremental technological improvements to process and product design and marketing improvements. The appropriate policies to promote technological learning are different at the different stages of the catch-up process requiring different policy measures.

Leapfrogging, or the skipping of some generations of technology or stages of development is one useful concept in the climate change mitigation literature through which developing countries might be able to avoid the more emissions-intensive stages of development previously experienced by industrialized nations (Watson and Sauter, 2011). Examples of successful low-carbon leapfrogging are discussed in more detail in chapter 14.

The issue of whether the status of proprietary rights has an effect on transfer of climate technologies has become a subject of significant debate. Some technologies are in the public domain; they are not patented or their patents have expired. Regarding patented technologies, much of the debate is centered on whether the temporary monopoly conferred by patents has resulted in obstacles to access to technology.

Proponents of a strong intellectual property (IP) regime have argued that patents boost technology transfer because the patent applicants have to disclose information on their claimed invention when submitting their application. Some analysts have also pointed out that in some sectors of climate technology, particularly renewable energy such as wind and solar technology have easily available substitutes and sufficient competition, such that patents on these technologies do not make them costly or prevent their spread. A study by Barton (2007) on three sectors (solar photovoltaic, biofuels, and wind technology) found that despite patents being prevalent in these sectors, competition between the various types of energy kept prices and costs relatively low. Some recent studies that analyzed specific sectors of climate related technologies have also pointed out the potential for IP protection for becoming a barrier to technology transfer (Lewis, 2007). See more discussion on the role of IP on TT in chapters 13 and 15.

Various international agreements on climate change, trade, and intellectual property include provisions aimed at facilitating technology transfer to developing countries. In climate change agreements, these provisions have aimed to encourage participation of developing countries in the agreements and to address barriers for technology adoption, including the need for financing. However, the provisions have been found by some scholars to be ineffective, lacking mechanisms to ensure the effective transfer of technology to developing countries (Moon, 2008). Further discussion of the literature on the role of international cooperation on TT is in chapters 13, 14 and 16.

3.11 Gaps in knowledge and data

As is clear from even a casual reading of this chapter, many questions are not completely answered by the literature. It is prudent for our assessment to end with our findings of where research might be directed over the coming decade so that the AR6 may be able to say more about the ethics and economics of climate change.

1. In order to plan an appropriate response to climate change, it is important to evaluate each of the alternative responses that are available. How can we take into account changes in the world's population? Should society aim to promote the total of people's wellbeing in the world, or their average wellbeing, or something else? The answer to this question will make a great difference to the conclusions we reach.

2. The economics and ethics of geo-engineering: an emerging field that could become of utmost importance to policymakers. Deeper analysis of the ethics of this topic is needed,

and much more research on the economic aspects of different possible geoengineering approaches and their potential effects and side-effects.

3. Developing better and more realistic estimates of the components of the damage function, more closely connected to Working Group II assessments of physical impacts. Quantifying non-market values: measurement of valuations placed by humans on nature and culture is highly uncertain, and could be improved through more and better methods and empirical studies.
4. Ex-post evaluation addressing the effectiveness of different regulatory approaches, both singly and jointly. For instance, understanding, retrospectively, the effectiveness of the EU ETS, the California cap and trade system or the interplay between renewable standards and carbon regulations in a variety of countries can be invaluable.
5. Energy-economy models: Energy models need to provide a more realistic portrait of microeconomic decision-making frameworks for technology-choice.
6. Economics and ethics of the risk of catastrophic climate change impacts: a literature is emerging, but much more probing into the ethical dimensions is needed to inform future economic analysis.
7. Behavioural Economics: More research that incorporates behavioural economics into climate change mitigation is needed. For instance, more work on understanding how individuals and their social preferences respond to (ambitious) policy instruments and make decisions relevant to climate change is critical.
8. Mitigation costs: despite the importance of the cost of mitigation, the aggregate cost of mitigating x tons of carbon globally is poorly understood. To put it differently, a global carbon tax of x dollars per ton would yield y(t) tons of carbon abatement over a time, t. We do not understand the relationship between x and y(t).
9. Evaluation of climate risk: The choice of the rate at which future climate damages are discounted depends upon their risk profile in relation to the other risks in the economy. By how much does fighting climate change reduce the aggregate uncertainty faced by future generations?

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