TECHNICAL ANNEX

Uncertainty in the Determination of Public Policies to Fight Climate Change

In order to determine the best climate change policies to adopt, it is necessary to have a proper understanding of the scientific conclusions of experts on the matter. The acquisition of scientific knowledge being a long, rigorous, constantly evolving process, these conclusions are always tinged with margins of error and uncertainty. This does not mean that the conclusions of scientists are false, but rather that they are perfectible and that they will become more precise with each new discovery.

From an economic point of view, it is essential to evaluate the impacts of climate change. Once these impacts have been quantified, it is then possible to compare the economic and social costs of proposed policies with the benefits resulting from the avoided climate change. According to economic theory, the ideal GHG mitigation policy is the one that minimizes the sum of the current value of net mitigation costs and the harm resulting from future climate change.[235]

The Six Steps of Scientific Projections

This calculation is not simple to carry out, however. In order to do so, scientists and economists use integrated assessment modelling, which integrates climate models and socioeconomic models. These models allow us to calculate the total damages caused by climate change, the cost of mitigation policies, and the social cost of carbon. Most models include hypotheses on the six following steps, as illustrated in Table A-1.[236]

Step 1. Projections of GHG Emissions

First of all, it is necessary to develop different GHG emissions scenarios. The development of these scenarios requires hypotheses on the different factors that affect GHG emissions, connected by the Kaya identity, explained in Chapter 3. In addition to those influencing GDP growth, such as demographic trends, it is also necessary to produce hypotheses regarding carbon intensity (the quantity of GHGs emitted per unit of energy produced) and energy intensity (primary energy used per unit of GDP). The evolution of green technologies can also affect these factors. The predictions obtained must stretch over several decades, even up to a few centuries.[237] Knowing that socioeconomic projections are rarely realistic for periods of more than 10 years, such long-term projections always include a wide margin of error.[238]

Step 2. Atmospheric Concentrations of GHGs According to Different Scenarios

Once the emissions scenarios have been established, the resulting atmospheric concentrations must then be determined. These concentrations are difficult to model since "carbon sinks" like oceans, vegetation, and soils absorb a portion of emissions.[239] One reason for this difficulty is that the past absorption rates of the oceans do not allow us to determine the rates for the coming years since the oceans are finite sinks, which means that they will be saturated at some point.[240]

In its most recent report, the IPCC developed four RCP scenarios (Representative Concentration Pathways) that are representative of simulations based on two elements: the evolution of GHG emissions and the atmospheric concentrations of CO_2 that are associated with them throughout the 21st century.

The four RCPs represent GHG emissions scenarios that vary as a function of a modelling of the global level of efforts devoted to the mitigation of GHG emissions. The atmospheric concentrations of CO_2 and CO_2e associated with the different RCPs at the end of the 21st century vary according to the intensity of mitigation policies, as shown in Table A-2.

235. William D. Nordhaus, "An Optimal Transition Path for Controlling Greenhouse Gases," *Science*, Vol. 258, No. 5086, November 1998, pp. 1315-1319.
236. Elements 2 and 3 are estimated based on climate models, while elements 1, 4, 5, and 6 are based on socioeconomic models. See Robert S. Pindyck, "Climate Change Policy: What Do the Models Tell Us," *Journal of Economic Literature*, Vol. 5, No. 3, September 2013, pp. 860-872.
237. For example, the temporal horizon for the *Stern Review of the Economics of Climate Change* is 200 years. See Nicholas Stern, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, 2007, p. 202.
238. Irene Lorenzoni and W. Neil Adger, "Critique of Treatments of Adaptation Costs in PAGE and FUND Models," in Rachel Warren *et al.* (eds.), *Spotlighting Impacts Functions in Integrated Assessment Models: Research Report Prepared for the Stern Review on the Economics of Climate Change*, Tyndall Centre for Climate Change Research, Working Paper 91, 2006, p. 74; Frans Berkhout and Julia Hertin, "Socio-Economic Scenarios for Climate Impact Assessment," *Global Environmental Change*, Vol. 10, No. 3, October 2000, pp. 165-168.
239. Philippe Ciais *et al.*, "Carbon and Other Biogeochemical Cycles," in Thomas F. Stocker *et al.* (eds.), *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2013, p. 468.
240. William D. Nordhaus and Joseph Boyer, *Roll the Dice Again: Economic Models of Global Warming*, MIT Press, 1999.

Table A-1

Steps for determining the costs of proposed policies and the benefits resulting from the avoided climate change

LOGICAL STEPS	HYPOTHESES TO BE MADE	FACTORS OF UNCERTAINTY
1 **Projections of GHG emissions**	**• How much economic growth will there be?** **• How much demographic growth will there be?** **• How will the energy intensity of economic activity evolve?** **• How will carbon intensity evolve?**	**• Projection of the global economy over the very long run** **• Possible changes in demographic trends** **• Multiplicity of factors affecting carbon intensity and energy intensity** **• Hard-to-predict evolution of green energy sources**
2 **Atmospheric concentrations of GHGs according to different scenarios**	**• What is the absorption rate of carbon sinks (vegetation, oceans, soils)?** **• Does the relative saturation of the oceans slow down their absorption of GHGs?** **• What will be the level of global efforts to reduce emissions (in connection with the first step)?**	**• The preceding hypotheses** **• Saturation of finite carbon sinks (oceans)** **• Absorption capacity of other carbon sinks (vegetation, soils)** **• The IPCC's RCP scenarios**
3 **Temperature changes resulting from an increase in the atmospheric concentration of CO_2**	**• What is the equilibrium climate sensitivity, namely its reaction to GHGs, including the doubling of CO_2?** **• What are the feedback effects?** **• Are they positive overall (reinforcing warming)?** **• What is the magnitude of each of these effects?** **• How will global warming affect each region?**	**• The preceding hypotheses** **• Sensitivity between 1.5 and 4.5** **• Growing uncertainty since the 4th assessment report** **• Inconsistencies between the empirical data and climate models** **• The effect of water vapour and clouds, the albedo effect of ice and other surfaces, etc.** **• Regional effects, ocean currents, etc.**
4 **Socioeconomic damage associated with a temperature increase**	**Enumerative method:** **• Which effects should be included?** **• Which estimates for each effect?** **• Does adaptation change the results?** **Statistical method:** **• Are climate effects well reflected by the level of well-being (income and consumption)?** **• Is adaptation well integrated?** **• What value should be placed on biodiversity and other hard-to-quantify effects?** **• Probability of extreme catastrophes?**	**• The preceding hypotheses** **• Sea level elevation** **• Melting of ice sheets** **• Net effects on agriculture (climate variation and fertilizing effect of CO_2)** **• Effects on other industries** **• The adaptive capacities of societies** **• Future technologies** **• Presence of hard-to-quantify effects** **• Non-zero chance of extreme climate catastrophes**
5 **The economic costs resulting from GHG reduction policies**	**• What replacement options will companies and individuals choose?** **• What new technologies will emerge in response to reduction policies?**	**• The preceding hypotheses** **• Reactions of economic agents** **• New technologies (renewable energy)**
6 **The discount rate used to compare the damage avoided with the costs of GHG mitigation policies**	**• What discount rate should be chosen (and what intertemporal preference rate)?**	**• The preceding hypotheses** **• Choice of discount rate (including the intertemporal preference rate)** **• Sensitivity of models to the choice of discount rate**

Note: This table summarizes this Annex. See the corresponding sources at each of the steps.

Table A-2

Characteristics of the different RCPs

RCP NAME	GHG REDUCTION EFFORTS	ATMOSPHERIC CONCENTRATION OF CO_2 IN 2100 (PARTS PER MILLION)	ATMOSPHERIC CONCENTRATION OF CO_{2E} IN 2100 (PARTS PER MILLION)
RCP2.6	**Rigorous**	**421**	**475**
RCP4.5	**Intermediate**	**538**	**630**
RCP6.0	**Intermediate**	**670**	**800**
RCP8.5	**None**	**936**	**1,313**

Source: Lisa V. Alexander *et al.*, "Summary for Policymakers," in Thomas F. Stocker *et al.* (eds.), *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2013, p. 29.

Step 3. Temperature Changes Resulting from an Increase in the Atmospheric Concentration of CO_2

The increasing temperature of the Earth's atmosphere following an increase in the atmospheric concentration of CO_2 is estimated by the equilibrium climate sensitivity. This is "a measure of the climate system response to sustained radiative forcing" and represents "the equilibrium global average surface warming following a doubling of CO_2 concentration."[241] The equilibrium climate sensitivity is therefore a central element when it comes to the development of public policies concerning climate change, since temperature variations determine the future harm to humans and to biodiversity.

The level of sensitivity is a variable whose exact value always remains unknown, and whose level of uncertainty has climbed over the past decade. The uncertainty regarding the sensitivity level to be used is illustrated by the differences between the two most recent IPCC reports, from 2007 and 2013. The fourth IPCC report, released in 2007, estimated that this sensitivity was between 2°C and 4.5°C, with a more likely estimate of 3°C (which is to say that an atmospheric concentration of CO_2 that is twice as high entails a 3°C temperature increase).[242] The fifth IPCC report, released in 2013, proposes a larger interval, from 1.5°C to 4.5°C, but without providing a most likely estimate.[243]

The IPCC is not in a position to provide a most likely estimate because of "a lack of agreement on values across assessed lines of evidence and studies."[244] This lack of agreement is explained by the divergence between the estimates of empirical data and those of climate models. Indeed, these last overestimated the temperature increases of the past twenty years, marked by a pause in global warming. For the 1998-2012 period, the average of a sample of 117 simulations from 37 models overestimated the observed temperature increase by a factor of more than four.[245] According to the IPCC, 111 of the 114 available models overestimated the temperature trend over the same period.[246] This does not mean that the average temperature is not trending upward, but is an indication of an overestimation of the equilibrium climate sensitivity by the models, which still remains to be confirmed.

241. IPCC, *IPCC Fourth Assessment Report: Climate Change* 2007, 2.3: Climate sensitivity and feedbacks.

242. *Ibid.*

243. Mark C. Freeman *et al.*, "Climate Sensitivity Uncertainty: When Is Good News Bad?" National Bureau of Economic Research Working Paper 20900, January 2015.

244. Lisa V. Alexander *et al.*, "Summary for Policymakers," in Thomas F. Stocker et al. (eds.), *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2013, p. 16.

245. John C. Fyfe *et al.*, "Overestimated Global Warming over the Past 20 Years," *Nature Climate Change*, Vol. 3, No. 9, September 2013.

246. IPCC, "Observed Changes and Their Causes," in Rajendra K. Pachauri *et al.* (eds.), *Climate Change 2014: Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014, p. 43.

The difficulty of establishing an estimate of sensitivity comes from feedback effects. It is recognized that the doubling of the atmospheric concentration of CO_2 entails a direct temperature increase of around 1.2°C.[247] The sensitivity estimates are located in an interval that is higher than 1.2°C (from 1.5°C to 4.5°C). Scientists therefore estimate that following an increase in the atmospheric concentration of CO_2, certain effects will amplify the direct initial warming. This is what is called a positive feedback effect.

Changes in the quantity of water vapour stemming from higher concentrations of CO_2 represent the most well-known positive feedback effect, whereas the feedback effect of clouds represents the largest source of uncertainty.[248] This uncertainty is well illustrated by a study presented as part of the fourth IPCC report, which arrives at different equilibrium climate sensitivity, ranging from 1.9°C to 5.4°C, solely by altering the radiative properties of clouds.[249]

Step 4. Socioeconomic Damage Associated with a Temperature Increase[250]

Once the equilibrium climate sensitivity has been determined, it is possible to estimate the warming associated with different scenarios of atmospheric concentrations of GHGs. The next step is to estimate the corresponding socioeconomic damage. This last is measured in losses of GDP or of consumption for future generations.

Two methods are generally employed to quantify this damage, namely the enumerative method and the statistical method. The enumerative method is based on the estimates of the research in various fields of the natural sciences measuring the impacts of temperature variations on the environment. An economic value is then attributed to the environmental impact in question. For example, an increase in the sea level will entail the loss of livable and arable land, and will necessitate the construction of additional dikes, which are variables with market values. The value of the resources used for the protection of coasts and of land lost because of rising sea levels will be added to the impacts on the other economic sectors, such as energy, agriculture, forestry, tourism, etc. A value must then be assigned to certain effects that do not have market values, like human health or the disappearance of animal and plant species.

The statistical method quantifies socioeconomic damage, but without referring to the natural sciences literature. This method is based solely on the observed relation between climate variations and well-being, which presupposes that the evolution of the climate is entirely reflected in the evolution of incomes and consumption.

Neither of these two methods is perfect. One variable in the evaluation of the damage caused by climate change, but which is not entirely integrated in the integrated assessment models, is the capacity of populations to adapt to climate variations, which varies positively with economic and technological development. The models based on the enumerative method neglect the fact that different economic agents will react and adapt to the physical changes caused by climate variations, and thereby mitigate the magnitude of the potential harm. On the contrary, those based on the statistical method implicitly take into account adaptive capacity. However, the adaptation taken into account is often conditioned by the technologies existing today, which considerably overestimates the socioeconomic damage caused by climate change.[251]

On the other hand, the models do not take into account certain hard-to-quantify impacts, although these remain relatively small compared to total damage. According to most experts, these omissions underestimate total harm only a little in the models.[252]

Furthermore, most models do not take into account the non-zero chance of a substantial loss of global well-being following extreme climate catastrophes. This once again underestimates the damage due to climate change. The few models that account for such risks probably assign too low a probability to their occurrence.[253]

247. David A. Randall *et al.*, "Climate Models and Their Evaluation," in Susan Solomon *et al.* (eds.), *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2007, p. 631.
248. IPCC, *op. cit.*, footnote 241.
249. Hervé Le Treut *et al.*, "Historical Overview of Climate Change," in Susan Solomon *et al.* (eds.), *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2007, p. 114.
250. The ideas in this section are drawn primarily from Richard S. J. Tol., "The Economic Effects of Climate Change," *Journal of Economic Perspectives*, Vol. 23, No. 2, 2009.
251. Indur M. Goklany, "What to Do about Climate Change," Policy Analysis No. 609, Cato Institute, February 5, 2008, p. 6.
252. Douglas J. Arent *et al.*, "Key Economic Sectors and Services," in Christopher B. Field et al. (eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2014, p. 690.
253. Martin Weitzman, *Some Basic Economics of Climate Change*, in Jean-Philippe Touffut (ed.), *Changing Climate, Changing Economy*, Edward Elgar, 2009.

Step 5. The Economic Costs Resulting from GHG Reduction Policies

GHG reduction policies will inevitably entail economic costs. Companies will have to resort to more expensive alternatives in order to limit their GHG emissions. The reduction in economic activity and higher prices that result will have an impact on GDP and consumption. Technological progress, however, allows us to reduce the cost of transitioning toward less carbon-intensive energy sources, as illustrated by the reductions in the cost of renewable energy sources over the past decade.[254]

Hypotheses regarding technological change have an impact not only on emissions scenarios, and therefore on atmospheric concentrations of GHGs, but also on the economic costs of an accelerated transition toward a carbon-free economy.

As we can see, this step in the calculation involves less uncertainty that the others.

Step 6. The Discount Rate Used to Compare the Damage Avoided with the Costs of GHG Mitigation Policies

In order to be in a position to adopt the most appropriate public policies for limiting the harm caused by climate change, it is essential to compare the costs of mitigation policies with the benefits to be had from the reduction of GHG emissions, in order to ensure that the costs do not exceed the benefits. Ideally, we should adopt mitigation policies up until the point at which the marginal cost of reducing one tonne of GHGs is equal to the marginal benefit of the tonne of GHGs avoided.

The difficulty of this exercise stems from the fact that the benefits associated with the reduction of GHGs will accrue to the citizens of future generations, whereas the costs of mitigation policies will be borne by the citizens of current generations. Taking into account the fact that present consumption is always more highly valued than future consumption, we use a positive discount rate. However, comparing the consumption of current generations to that of generations that have not yet been born raises ethical considerations, which are widely used to justify a lower discount rate than for relatively shorter horizons. Indeed, economist Martin Weitzman of Harvard University characterized the discounting of the distant future as the most critical problem in economics.[255]

The importance of the discount rate used is well illustrated by the calculation of the social cost of carbon which represents the marginal impact of GHG emissions. Knowledge of this cost makes it possible to adopt policies allowing for the internalization of negative externalities associated with activities that emit carbon.

The different estimates of the social cost of carbon are extremely divergent and rest essentially on the discount rate used, a controversial problem for which there is still no solution, according to William Nordhaus, an economist at Yale University.[256] In order to determine which environmental regulations have positive effects, the American government mandated a working group made up of several experts to calculate this cost. In 2007, using a 3% discount rate, they arrived at a result of $24 per tonne of CO_2 for the year 2015. When the study was updated, this cost was revised upward to $37. Indeed, this update illustrates the influence of the discount rate used. In calculating the social cost of carbon for the year 2050, the authors obtain an estimate of $26 with a 5% discount rate, but an estimate of $97 with a 2.5% discount rate.[257]

The degree of sensitivity of the social cost of carbon to the discount rate used is also well illustrated by a review of the 311 estimates in the literature. The average cost is $5 per tonne of CO_2 for an intertemporal preference rate[258] of 3%, compared to $75 for a rate of 0%.[259] It is therefore very difficult to determine which of all of these estimates is the most appropriate.

A High Degree of Uncertainty

As we can see, the different approaches of climate economists for determining the social cost of carbon are characterized by a high degree of uncertainty. This is all the more so given that the margins of error at each step

254. International Energy Agency, *Tracking Clean Energy Progress 2015*, 2015, p. 20.

255. Moritz Drupp *et al.*, *Discounting Disentangled: An Expert Survey on the Determinants of the Long-Term Social Discount Rate*, Centre for Climate Change Economics and Policy, Working Paper No. 195, June 2015.

256. William Nordhaus, *Estimates of the Social Cost of Carbon: Background and Results from the Rice-2011 Model*, Cowles Foundation for Research in Economics, Discussion Paper No. 1826, Yale University, October 2011.

257. In 2007 US dollars. Interagency Working Group on Social Cost of Carbon, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis*, Executive Order 12866, February 2010, p. 1; Interagency Working Group on Social Cost of Carbon, *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis*, Executive Order 12866, May 2013, p. 3.

258. The intertemporal preference rate is a component of the discount rate.

259. Richard S. J. Tol, "The Social Cost of Carbon," *The Annual Review of Resource Economics*, Vol. 3, October 2011, p. 432. The values found by the author are $19 and $276 per tonne of carbon. We obtain the equivalent in tonnes of CO_2 by multiplying these numbers by 0.2727.

of the calculation increase the uncertainty associated with each of the other steps. For example, in the calculation of the damage caused by climate change, the standard deviation of the economic impact in terms of loss of GDP does not include all of the uncertainty associated with the preceding steps.[260]

Economist Robert Pindyck from MIT is highly critical of integrated assessment models. He states that they "create a perception of knowledge and precision that is illusory," and that the hypotheses associating climate change with economic losses are arbitrary. Thus, the models are close to useless in determining the social cost of carbon and the policies that should be adopted, according to him.[261] Martin Weitzman, for his part, declares that the uncertainty associated with climate change means that the cost-benefit analyses derived from the models are far from achieving the degree of precision of traditional cost-benefit analyses.[262]

The Results of the Cost-Benefit Analyses

Although the effects associated with climate change derived from the integrated assessment models are highly uncertain, they represent the best available estimates and should, at the very least, serve as guidelines in the adoption of public policies.

The most recent IPCC report compiles the results of integrated assessment models from different studies having quantified the socioeconomic damage associated with climate change. Unfortunately, very few studies quantify the damage associated with increases of more than 3°C above today's temperatures. Most of the studies measure the impact of a temperature increase of from 2.2°C to 3°C. For example, for studies estimating warming of 2.5°C, the average of the estimates of the damage caused is 1.1% in terms of loss of GDP.[263] While there is no timeframe associated with these temperature increases, it is generally accepted that these studies measure the economic impacts from now until the end of the 21st century.[264] For its part, the OECD estimates that GDP will be from 0.7% to 2.5% lower in 2060, and from 1.5% to 4.8% lower by the end of the century.[265]

The economic cost associated with a stabilization of atmospheric concentrations of GHGs at 430-480 parts per million of CO_2e—necessary in order to have a greater than 66% chance of respecting the 2°C limit—is equivalent to a loss of consumption of 4.8% in 2100, according to the IPCC.[266]

Based on these figures, we could be tempted to conclude that the economic cost of mitigation policies will be as high as the benefits that we think will result from a lower global temperature. However, the IPCC's estimates of the costs of mitigation policies are based on the least expensive scenario, namely that of a single carbon price imposed on a global scale. Given the difficulties of reconciling the interests of rich countries with those of developing countries (see Chapter 1), it is unlikely that this will be the case. Indeed, William Nordhaus calculated that if only 50% of countries participate, the economic costs associated with the tax would be 250% higher than an optimal tax.[267] Moreover, the IPCC bases its estimate on very strong hypotheses regarding the widespread availability of certain technologies, like carbon capture and storage. The IPCC recognizes, though, that without this technology, the cost of mitigating GHGs could increase by 138%.[268]

These strong hypotheses, combined with the high adaptive capacity of human beings, suggests that GHG reduction efforts to limit the temperature increase to 2°C will in all likelihood cost more than the benefits. Nonetheless, this does not constitute a reason not to act. The lack of studies measuring the impact of an increase greater than 3°C—which surely underestimates the weight accorded to the possibility of irreversible catastrophes—can justify the adoption of mitigation policies.

From this perspective, it is appropriate to bear the cost of mitigation policies, just as it is logical to insure oneself in one's daily life against events whose probability is low, but whose occurrence would entail considerable damage, like a fire in one's home.[269] This is an entirely separate discussion, however.

It would be very sensible, though, for the political debate to take into consideration all of the costs and benefits associated with climate change, and integrate

260. *Ibid.*, p. 425.
261. Robert S. Pindyck, "The Use and Misuse of Models for Climate Policy," NBER Working Paper No. 20900, April 2015.
262. Martin Weitzman, *op. cit.*, footnote 253.
263. Richard S. J. Tol *et al.*, "Key Economic Sectors and Services: Supplementary Material," in Field, C.B. *et al.* (eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part A: Global and Sectoral Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2013, p. SM10-4.
264. Richard S. J. Tol, *op. cit.*, footnote 250, p. 44.
265. Rob Dellink *et al.*, "Consequences of Climate Change Damages for Economic Growth: A Dynamic Quantitative Assessment," OECD Economics Department Working Papers No. 1135, 2014, p. 3.
266. Ottmar Edenhofer *et al.*, "Summary for Policymakers," in Ottmar Edenhofer *et al.* (dir.), *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2014, p. 15.
267. William D. Nordhaus, *A Question of Balance: Weighing the Options on Global Warming Policies*, Yale University Press, 2008, p. 19.
268. Ottmar Edenhofer, *op. cit.*, footnote 266.
269. Martin Weitzman, *op. cit.*, footnote 253; Robert S. Pindyck, *op. cit.*, footnote 236, p. 16.

the latest developments in economics. The *Stern Review*, heavily criticized for its overestimation of the harm caused by climate change and its choice of a zero discount rate (see Chapter 2), arrives at the conclusion that we must stabilize the atmospheric concentration of GHGs at 500-550 parts per million of CO_2e.[270] Since then, estimates of the harm due to climate change have fallen as the economic research on this question has improved.[271]

In sum, the optimal level of atmospheric concentrations of GHGs—still based on a carbon tax imposed at the planetary level—would be around 550 parts per million of CO_2e for an intertemporal preference rate of 1%, and of 625 for an intertemporal preference rate of 3%.[272] The United Nations Framework Convention on Climate Change, during the Conference of the Parties in Copenhagen in 2009, instead retained the 2°C target and an atmospheric concentration of around 450 parts per million of CO_2e.

Bibliography

ALEXANDER Lisa V. *et al.*, "Summary for Policymakers," in Thomas F. Stocker *et al.* (eds.), *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2013.

ARENT Douglas J. *et al.*, "Key Economic Sectors and Services," in Christopher B. Field *et al.* (eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2014.

BERKHOUT Frans and HERTIN Julia, "Socio-Economic Scenarios for Climate Impact Assessment," *Global Environmental Change*, Vol. 10, No. 3, October 2000.

CIAIS Philippe *et al.*, "Carbon and Other Biogeochemical Cycles," in Thomas F. Stocker *et al.* (eds.), *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2013.

DELLINK Rob *et al.*, "Consequences of Climate Change Damages for Economic Growth: A Dynamic Quantitative Assessment," OECD Economics Department Working Papers No. 1135, 2014.

DRUPP Moritz *et al.*, *Discounting Disentangled: An Expert Survey on the Determinants of the Long-Term Social Discount Rate*, Centre for Climate Change Economics and Policy, Working Paper No. 195, June 2015.

270. Nicholas Stern, *op. cit.*, footnote 237, "Summary of conclusions."
271. Robert Mendelsohn, "Climate Change and Economic Growth," Commission on Growth and Development, Working Paper No. 60, 2009, pp. 10-11.
272. Richard S. J. Tol, "Targets for Global Policy: An Overview," *Journal of Economic Dynamic and Control*, Vol. 37, No. 5, 2013, p. 918.

EDENHOFER Ottmar *et al.*, "Summary for Policymakers," in Ottmar Edenhofer *et al.* (dir.), *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2014.

FREEMAN Mark C. *et al.*, "Climate Sensitivity Uncertainty: When Is Good News Bad?" National Bureau of Economic Research Working Paper 20900, January 2015.

FYFE John C. *et al.*, "Overestimated Global Warming over the Past 20 Years," *Nature Climate Change*, Vol. 3, No. 9, September 2013.

GOKLANY Indur M., "What to Do about Climate Change," Policy Analysis No. 609, Cato Institute, February 5, 2008.

INTERAGENCY WORKING GROUP ON SOCIAL COST OF CARBON, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis*, Executive Order 12866, February 2010.

INTERAGENCY WORKING GROUP ON SOCIAL COST OF CARBON, *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis*, Executive Order 12866, May 2013.

INTERNATIONAL ENERGY AGENCY, *Tracking Clean Energy Progress 2015*, 2015.

IPCC, "Observed Changes and Their Causes," in Rajendra K. Pachauri *et al.* (eds.), *Climate Change 2014: Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014.

IPCC, *IPCC Fourth Assessment Report: Climate Change* 2007, 2.3: Climate sensitivity and feedbacks.

LE TREUT Hervé *et al.*, "Historical Overview of Climate Change," in Susan Solomon *et al.* (eds.), *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2007.

LORENZONI Irene and ADGER W. Neil, "Critique of Treatments of Adaptation Costs in PAGE and FUND Models," in Rachel Warren *et al.* (eds.), *Spotlighting Impacts Functions in Integrated Assessment Models: Research Report Prepared for the Stern Review on the Economics of Climate Change*, Tyndall Centre for Climate Change Research, Working Paper 91, 2006.

MENDELSOHN Robert, "Climate Change and Economic Growth," Commission on Growth and Development, Working Paper No. 60, 2009.

NORDHAUS William D., "An Optimal Transition Path for Controlling Greenhouse Gases," *Science*, Vol. 258, No. 5086, November 1998.

NORDHAUS William D., *A Question of Balance: Weighing the Options on Global Warming Policies*, Yale University Press, 2008.

NORDHAUS William D., *Estimates of the Social Cost of Carbon: Background and Results from the Rice-2011 Model*, Cowles Foundation for Research in Economics, Discussion Paper No. 1826, Yale University, October 2011.

NORDHAUS William D. and BOYER Joseph, *Roll the Dice Again: Economic Models of Global Warming*, MIT Press, 1999.

PINDYCK Robert S., "Climate Change Policy: What Do the Models Tell Us," *Journal of Economic Literature*, Vol. 5, No. 3, September 2013.

PINDYCK Robert S., "The Use and Misuse of Models for Climate Policy," NBER Working Paper No. 20900, April 2015.

RANDALL David A. *et al*., "Climate Models and Their Evaluation," in Susan Solomon *et al.* (eds.), *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2007.

STERN Nicholas, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, 2007.

TOL Richard S. J., "Targets for Global Policy: An Overview," *Journal of Economic Dynamic and Control*, Vol. 37, No. 5, 2013.

TOL Richard S. J., "The Economic Effects of Climate Change," *Journal of Economic Perspectives*, Vol. 23, No. 2, 2009.

TOL Richard S. J., "The Social Cost of Carbon," *The Annual Review of Resource Economics*, Vol. 3, October 2011.

TOL Richard S. J. *et al*., "Key Economic Sectors and Services: Supplementary Material," in Field, C.B. *et al*. (eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part A: Global and Sectoral Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2013.

WEITZMAN Martin, *Some Basic Economics of Climate Change*, in Jean-Philippe Touffut (ed.), *Changing Climate, Changing Economy*, Edward Elgar, 2009.