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The long-term economic consequences of climate change

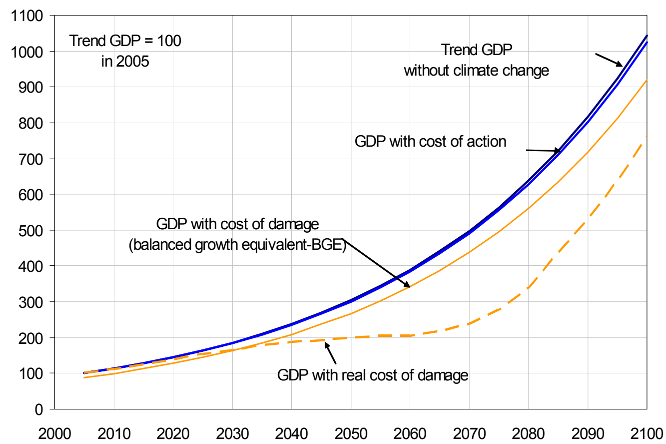
This study was prepared under the authority of the Treasury and Economic Policy General Directorate and does not necessarily reflect the position of the Ministry of the Economy, Finance and Employment.

- In 2006 the UK Treasury published a study on the economic consequences of climate change (the "Stern Review on the Economics of Climate Change"). The main novelty of the "Stern Review" was to introduce economic analysis right into the heart of the climate debate, vigorously arguing that the damage caused by global warming could be 5 to 20 times greater than the sacrifices demanded of our economies in order to fight the greenhouse effect effectively. This widely publicised message has helped forge an international consensus on the need for urgent action.

- The "Stern Review" diverges from the traditional rules of cost-benefit analysis, in that it compares the damage caused by climate warming with the costs of reducing greenhouse gas emissions. Some economists such as W. Nordhaus and R. Tol have strongly criticised some of the methodological choices underlying this analysis, notably the separation of the calculation of climate damage from the cost of action, as well as the unusually low discount rate applied (1.4%). With a more homogeneous approach to the costs and benefits of climate change prevention measures, a more orthodox discount rate and more refined treatment of the value of carbon and of uncertainty in his modelling, no doubt Stern could have headed off the objections raised without undermining his conclusions.

- The validity of these conclusions largely depends on our capacity to control the costs of attenuating the greenhouse effect. According to the Review, a 25% reduction in greenhouse gas emissions in 2050 relative to the present day ought to entail only minor adverse consequences for the world economy, on the order of 1% of global GDP in 2050. The model on which this optimistic outcome is based assumes that priority will be given to using the least-costly options for cutting carbon emissions, thanks to appropriately calibrated pricing policies. Governments therefore have a responsibility to create a system of incentives based on economic instruments designed to minimise the global cost of climate risk abatement.

Global GDP projections



Source: Hallegatte and Hourcade, for Véolia Environnement.

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DIRECTION GÉNÉRALE DU TRÉSOR ET DE LA POLITIQUE ÉCONOMIQUE

The "Stern Review on the Economics of Climate Change" is the result of nearly a year and a half of work by forty or so researchers drawn from several different nationalities (British, American, German, French, Chinese, Indian, etc.) under the leadership of Sir Nicholas Stern, then Managing Director, Budget and Public Finances at the UK Treasury, Head of the Government Economic Service and Special Adviser to the Prime Minister on the Economics of Climate Change and Development. He had previously been Chief Economist and Senior Vice President for Economic Development at the World Bank.

Under the terms of reference spelled out by the then Chancellor of the Exchequer, Gordon Brown, on 19 July 2005, Nicholas Stern's team was required first to examine, on the basis of existing studies, "the economic, social and environmental consequences of climate change in both developed and developing countries," along with "the economics of moving to a low-carbon global economy". This was to be followed by a comprehensive assessment of the economics of combating the greenhouse effect from the standpoints of both "abatement" and "adaptation".

The results of this study were published in October 2006 as a document of more than 700 pages. The "Stern Review" represents in condensed form the best available scientific and economic expertise on climate change. **This paper takes a critical look at the approach and the economic reasoning deployed by Nicholas Stern concerning the central point in the Review namely the comparison between cost of the damage caused by climate change and the sacrifices required in order to limit greenhouse gas emissions and rising temperatures.**

Stern discards the conventional cost-benefit analysis format, in which all investment costs and resulting gains are aggregated and discounted to yield the net present value of a project. In this Review, the gains associated with combating climate change are treated as the cost of the damage that would occur in the absence of government action; these are then compared with current per capita consumption. On the other hand, the costs of action are assessed separately and expressed as a percentage of GDP in 2050. Similarly, the emissions abatement scenario for which Stern calculates the cost is calibrated to limit warming to less than 3°C relative to the pre-industrial era; consequently this would only serve to avoid damage resulting from temperature rises of between 3°C and +3.9–4.3°C[1]. The heterogeneity of the method of calculation precludes a rigorous comparison of the costs of action and inaction, but this methodological limitation leaves the Review's political and economic message intact. In fact, Stern's decision to estimate the cost of action in relation to GDP in 2050 leads to higher results than with a conventional discounting method: when we relate the discounted figure[2] for the total cost of emissions abatement between 2005 and 2050 to cumulative discounted GDP over the same period, the cost of action works out to 0.6%, versus 1% in Stern's central scenario.

Whatever the case, the message of the Stern Review remains economically sound: in environmental matters, *laissez-faire* would have a far greater cost to human wealth than the preventive measures required to curb, and then reduce, greenhouse gas emissions, provided these measures are designed so as to minimise their economic cost. Stern effectively mobilises the existing literature in support of this analysis, carrying out a very richly documented qualitative evaluation of the effects of warming, distancing himself from certain well established rules of economic calculation to quantify its impact on GDP. **The Review's biggest success is to have brought the debate into the economic sphere, both by stating the economic usefulness of action in objective terms and by spotlighting effective public policy on climate change as a central issue.**

1. The Review states that the total cost of climate change over the next two centuries would equate to an average decline in per capita consumption of at least 5% "now and forever"

This 5% cost, corresponding to one of the scenarios envisaged, is calculated excluding non-market impacts relative to a central scenario in which the planet experiences no climate change. If the non-market impacts of climate change (environmental quality, human health, political and social stability) are taken into account, the amplification effects associated with hard-to-predict feedback loop effects between climate and biosphere, together with the concentration of damage in the poorest regions of the planet, would raise the **total cost to around 20% of per capita consumption.**

These estimates are higher than the previous ones[3], whose shortcomings N. Stern points out, namely: underestimation of possible temperature rises, insufficient weight given to extreme climate events (droughts, floods and storms) resulting from rising average temperatures, and "surprises" (a slowdown in thermohaline circulation--*i.e.* the circulation of temperatures and salt--in the Atlantic, faster melting of the Antarctic ice shelf), compartmentalisation of analyses by sectors, imperfect modelling of depressive impacts on investment, and so forth.

(1) The 3.9°C and 4.3°C figures correspond to the two central scenarios (baseline climate and high climate) used by Stern to calculate the costs of inaction.

(2) With the same discount rate as the one used by Stern to assess damage, i.e. 1.4%.

(3) The studies by Mendelssohn (1998), Nordhaus and Boyer (2000) and Tol (2002) generally find losses on the order of 1% to 2%.

1.1 The model is based on a series of scenarios regarding temperature change and the occurrence of unpredictable events

The "Stern Review" draws on the progress made in scientific knowledge and overhauls the framework for economic analysis by incorporating the specific features of climate change, namely very long-term damage, which is unevenly spread between regions, and whose real extent cannot be determined with certainty. The PAGES[4] 2002 "integrated assessment model" used by Stern is based on a stochastic matrix articulated around three key parameters, namely: the possible existence of climate "feedback loops" aggravating the initial temperature rises (for instance through the release of methane trapped in permafrost, a weakening of the absorption capacity of ocean and forest carbon sinks; and, secondly, the nature of the impacts of climate change (market/non-market) and the speed at which they appear (progressive/non-linear). Altogether the model includes two groups of three damage scenarios (see charts 1 and 2) looking to 2200, each of the groups corresponding to different temperature increase profiles (+2.4 to 5.8°C in 2100 relative to pre-industrial levels for the baseline-climate-change scenario, +2.6 to 6.5°C for the high-climate-change scenario), the scenarios within each group being distinguished from each other by whether or not they take non-market damage and large-scale unpredictable events into account. Each of the scenarios presents the damage until 2200 arising from greenhouse gas emissions over the period from now until 2100.

The model's results show per capita income losses of between 5.3% and 13.8% in 2200 relative to a "no-climate-change" scenario, the distribution of the range of damage (with a 90% confidence interval) stretching between 1% and 35% depending on the value of the parameters. These estimations in fact reflect an overweighting of the most pessimistic and least probable scenarios[5]: this explains why the results are more "alarmist" than in Nordhaus, for example, where the damage is calculated on the basis of "medium" scenarios. The difference stems from the fact that Stern does not wish to eliminate or minimise the importance of the most extreme situations on the grounds that they have only a minute chance of occurring. On the contrary, Stern takes these as a benchmark to help shape public choices (assuming the worst). This approach may be justified in the presence of uncertainties, as explained by Weitzman just after the Review's publication[6].

On the market side, these losses are modelled with the aid of three-factor production functions (capital, labour, environmental quality); physical phenomena associated with rising temperatures affect the quantity, and indeed the productivity of factors of production and ultimately, in an aggregated and hence necessarily simplified view[7], they lead to declines in GDP[8]: e.g. falling agricultural output due to its extreme sensitivity to climate conditions (water availability, drought, etc.), the destruction of infrastructures and assets and reduced trade flows caused by flooding and storms, or a reduction in the abundance and productivity of labour factors due to higher mortality and impaired population health. Stern is nevertheless careful to point out that this is more a case of reduced final consumption than of lower GDP: the potentially stimulating effects of climate change on the productive environment and economic activity (such as adaptive measures and repairs to damage through, for example the building of infrastructures to protect coastal areas, or large scale purchases of air conditioners, etc.) are indeed counted as opportunity costs insofar as these additional and unforeseen expenditures divert resources that would otherwise have been available for other investments.

Stern employs the notion of "Balanced Growth Equivalent" (BGE) to express these losses of GDP over time in terms of their present value. For each of the 6 aforementioned scenarios, the change in per capita GDP is first converted into an equivalent measure of social welfare. The following step consists in determining what is the present level of per capita consumption that would lead to the same level of welfare in the absence of climate warming (this being the BGE). For each scenario, the discounted cost of climate warming is defined as the difference between the BGE calculated with impacts of climate change and the BGE excluding climate change or, which is equivalent, as the impact of the "depressive" shock produced by climate damage over the next two centuries in relation to the present level of per capita consumption.

(4) Policy Analysis of the Greenhouse Effect.

(5) Hourcade and Hallegatte: "*Le Rapport Stern sur l'économie du changement climatique : de la controverse scientifique aux enjeux pour la décision publique et privée*" (The Stern Review on the economics of climate change: from scientific ontroversy to public and private decision making issues), study conducted for *Veolia Environnement*.

(6) Weitzman (2007): "The role of uncertainty in the economics of catastrophic climate change", June 2007.

(7) The approach taken by Stern is purely enumerative: GDP losses are calculated for each sector and each geographic zone taken in isolation, without taking interactions into account.

(8) The relationship between the intensity of climate warming and impacts can take very different forms. For example, damage to infrastructure increases in a non-linear fashion with the peak wind speed (via a $y = x^3$ type cubic response function); crop yields too follow a curve whose trend is not necessarily monotonous, which can take the form of an "inverted U", evidence of a possible, transitory and localised increase in production with a moderate rise in temperature, followed by a fall in production after certain thresholds are crossed.

Chart 1: per capita GDP growth paths between now and 2200

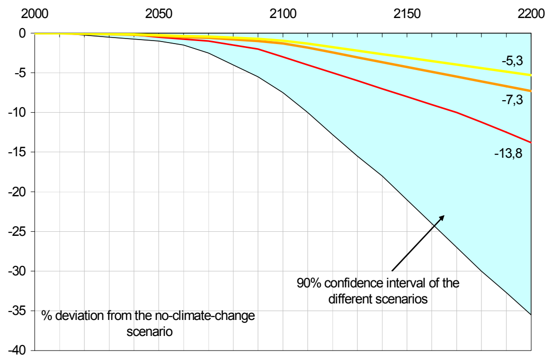
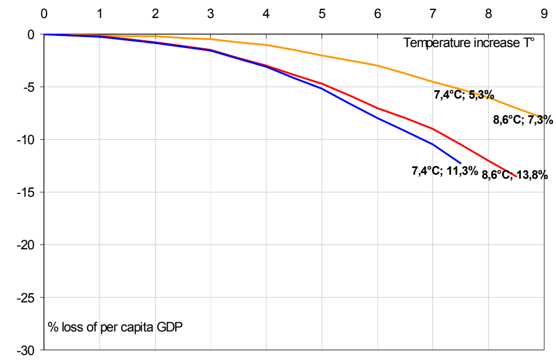


Chart 2: change in loss of per capita GDP depending on temperature increase



Source: Stern Review.

In chart 1, the red line corresponds to a high climate scenario that includes both market and non-market impacts and the risk of catastrophes; the orange line designates the same scenario, but this time with no assessment of non-market impacts; the yellow line represents a baseline climate trajectory that does not take into account non-market impacts in the estimation of GDP losses. In chart 2, the red and orange lines respectively have the same properties as on the previous chart; the blue line is analogous to the yellow line in chart 1, except that it takes non-market damage into account. It will be noted that only the two high climate scenarios (red and orange) allow us to chart the effects of warming at very high temperatures (>+7°).

1.2 Stern uses discounting to assess intertemporal losses of welfare

Assessing intertemporal losses of welfare consists in determining the value one attaches today to damage that will occur in the future. In its traditional form, the economic calculation applicable to public investments consists in constructing the discount rate[9] in the form of three components, which also occur in Stern:

- **pure preference for the present** (or the "price of time"), which reflects both the preference given to immediate welfare rather than future welfare (the impatience effect) and the probability that the individual or group will not exist in the future;
- **the wealth effect**, which depends on the expected growth rate and the elasticity of the marginal utility of consumption. The expectation of a future surplus of wealth encourages economic agents to want to consume more today, especially when the marginal utility associated with a future increase in wealth is low. To offset the low incentive to save, then, the capital market balance (between saving and investment) would lead to high interest rates. To simplify, the combination of sustained growth and a sharply declining marginal utility thus goes hand in hand with a high propensity to satisfy immediate consumption needs;
- **the precautionary effect**: expectations of the future growth path can be fraught with uncertainty. Consequently, there is a powerful incentive to build up precautionary savings. Agents forgo consumption today in order to attenuate losses of utility associated with the most pessimistic scenarios. Consequently, prudence attenuates the wealth effect and reduces the discount rate. The issue of uncertainty lies precisely at the heart of economic thinking on climate change, with respect to changes in the determinants of future temperature rises and the extent of damage and its impact on GDP growth paths.

2. Stern's method calls for three types of comment, insofar as it introduces biases into the final calculation

2.1 The final discount rate adopted by Stern (1.4%) is far lower than conventional standards

According to Stern, there is no reason to downplay the losses future generations may have to suffer. Considering that a high discount rate would tend to "wipe out" the loss of welfare suffered by future generations as a result of climate warming, especially since these rise exponentially over time, Stern does not think it illegitimate to ease the rules of economic calculation in order to account for the specific nature of the problem of climate change.

Some authors such as William Nordhaus see an "upward" artifice in the assessment of damage. This is because for each of the discounting parameters Stern adopts lower values than those commonly accepted in economic analysis[10]:

(9) "*Révision du taux d'actualisation public des investissements publics*" (Revision of the public discount rate on public investments), *Commissariat général au Plan, 21 January 2005.*

- **the pure preference for the present is set at 0.1%**, which is lower than the majority of existing estimations of the rate for pure preference for the present.
- **the annual per capita growth rate of 1.3%** is derived from one of the scenarios contained in the IPCC Synthesis Report to simulate the scale of climate warming (Special Report on Emission Scenarios, SRES 2000), characterised by an assumption of rapid global population growth (0.6% per year) and slow real GDP growth (+1.9% to +2.3% per year) relative to the IPCC's other scenarios. Stern thus picks as his reference the least favourable of the IPCC's scenarios in terms of per capita income growth (+1.1% to +1.3% per year), compared with 2.8% in the most optimistic SRES 2000 scenario;
- **Stern treats the elasticity of the marginal utility of consumption as equal to 1**. This represents the lower bound of the estimations supplied by the existing literature (the parameter ranges between 1 and 3). By choosing a low elasticity Stern neglects the prudence aspect (the square of the elasticity). Agents' aversion to risk is all the lower when the elasticity of marginal utility of consumption is low[11].

2.2 Conversely, certain of the choices made in the Review lead to underestimation of the present value of future damage caused by climate warming

Stern does not spell out the weighting he attaches to the uncertainty of risks whose probability is hard to assess: while the probability of a certain number of phenomena occurring is well defined (rising sea level, shifting crop-growing zones, rising rainfall in rainy regions, etc.), other events with potentially catastrophic consequences are liable to occur even though their probability cannot be determined *ex ante* (e.g. the Gulf Stream could stop flowing in the North Atlantic, carbon sinks could become saturated, etc.). **If uncertainty as to the extent of the damage is taken into account, this would argue in favour of a lower discount rate**. It is possible, however, that Stern may be using this precautionary effect implicitly, as a general argument for lowering the other discounting parameters.

The question of the relative weighting to be assigned to the losses of wealth affecting the poorest countries no doubt warrants further discussion, as Stern himself acknowledges. Climate change could be expected to affect Africa, the Middle East, India and Southeast Asia worst, the latter two regions being expected to experience a larger-than-average decline in their per capita GDP due to their special vulnerability (–6% in 2100 versus –2.6% for world GDP over the same time frame[12]). Although he does not do so in his study, Stern calls for application of a different utility function to each region of the world in order to reflect the greater sacrifice a given loss entails for a poor country by comparison with an industrialised one. Indeed, the simple aggregation of GDP losses in absolute value terms for the different regions of the world, by means of a single utility function (based on the conventional assumption of a single representative agent), appears to minimise the impact of climate change on the developing countries' well-being, and hence global damage.

2.3 Generally speaking, Stern appears to use the discount rate as a single, exclusive adjustment variable capable of performing several functions

Following on from the *Rapport Lebègue* (2005), Stern would no doubt have arrived at a similar result in estimating damage using a discount rate closer to the standard ones. At the same time he would probably have better accounted for changes in the relative price of environmental goods[13]. The price associated with climate stability could rise over time relative to the price of traditional private consumption goods.

(10) To arrive at a socio-economic assessment of public investments, the former French *Commissariat Général au Plan* (General Planning Commission) recommends a 4% discount rate, excluding the risk premium and the opportunity cost of public funds, this rate declining after 30 years to a floor of 2%. In its 2003 Green Paper, the UK Treasury recommends 3.5% for 30–year assessments, declining to 1% beyond 300 years. As the *Rapport Lebègue* explains, it may be justifiable to reduce the rate after a certain length of time due to the uncertainty of the wealth effect: the absence of reliable projections of economic growth over the (very) long term heightens the importance of the "precautionary" effect and encourages the present generation to make an even greater effort the further away the future generation is. See Delattre & Véron (2005): "*Taux d'actualisation public et calcul économique*" (Public discounting rate and economic calculation), *DPAE no. 84*.

(11) The elasticity of the marginal utility of consumption and risk aversion are two sides of a single coin determining the utility function. To illustrate the point, take two opposing ends of the distribution of utility: in the first case an individual has a 50% chance of obtaining a monetary gain of 95 and a 50% chance of obtaining 105; in the second, the same individual is sure of obtaining a gain of 100. In a situation of perfect information, the rational agent will be all the less inclined to agree to incur a risk in order to obtain a higher gain (105, which is greater than the average risk-free gain of 100) if his marginal utility declines sharply with his consumption: the higher the elasticity, the greater the aversion to risk.

(12) These figures are necessarily approximations insofar as they take no account of macroeconomic loop effects connected with trade in goods and movements of people (trade and migratory flows) between the different regions concerned.

(13) On two-factor analytical models and the notion of orthodox ecological discount rates, see Guesnerie (1996).

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The Stern Review has the merit of employing economics in order to legitimise public policies aimed at combating climate change. According to Stern, the general principle of prudence in the face of the future volatility of growth[14] and the risk of hard-to-predict catastrophes, together with the ethical considerations surrounding the welfare of future generations, justify *ex ante*, and in general, the use of a low discount rate, even if this entails a downward adjustment in each individual parameter.

The Review's central message seems to be robust. To be sure, explicit modelling of the rising social cost of carbon as part of an integrated approach to the costs of fighting climate change and the associated benefits (in terms of damage avoided) would surely have yielded comparable results, only more convincingly so. From a theoretical standpoint, a conventional cost-benefit analysis with a single present value would have been preferable. But its practical application would have raised serious difficulties, regarding for example assessment of the "marginal" costs and benefits of policies aimed at preventing the greenhouse effect.

3. The costs of reducing greenhouse gas emissions turn out to be lower than those of the damage caused

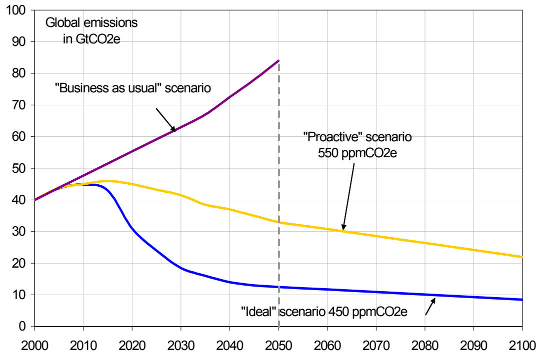
The Stern Review contrasts the discounted value of the damage caused by global warming (5–20% of global GDP in 2005) with the more modest cost of combating climate change: **implementing policies and measures to cut greenhouse gases would cost only 1% of global GDP on average in 2050**. Some economists claim that this favourable outcome is a reflection of particularly optimistic assumptions regarding technological progress and the deployment of relatively inexpensive emissions reduction techniques[15].

3.1 The costs of cutting greenhouse gas emissions are based on a number of assumptions

3.1.1 The level of stabilisation of atmospheric greenhouse gas concentrations and the requisite volume of emissions reductions

Stern takes as his baseline scenario a pathway in which atmospheric greenhouse gas concentrations are stabilised at 550 ppmCO_2e[16] at the end of the 21st century. The current stock is 430 ppmCO_2e and is rising at an annual rate of 2.5 ppm at the current rate of emissions. At this rate, the level of greenhouse gas concentration could rise to 550 ppm by 2035 and more than 700 ppm in 2100. To stabilise this at 550 (450) ppmCO_2e in 2100, emissions would have to be 25% lower (70%) in 2050 relative to current levels, in order to bring them down to 27 GtCO_2e (13.5 GtCO_2e), i.e. 50 to 70 gigatons less than in the trend scenario. These different scenarios are illustrated in chart 3 and in table 1 on the following page.

Chart 3: change in emissions in the different scenarios



Source: Stern Review.

The emissions pathways illustrated above are indicative only, since in theory there is an infinity of "roads" to achieve the objective. Note, however, that the range of possibilities narrows as the objective becomes harder to achieve. It is now widely accepted that the profile of the stabilisation curves will split into three phases: a continuation or perhaps even amplification of present emissions growth trends over the next 5 to 10 years; a plateau around 2015-2020; then a steady decline until 2050 and beyond. Any other pathway would be either unrealistic or unduly costly (entailing a massive and brutal adjustment effort) or, given the inertia of the climate system, would result in breaching the "carbon budget" (aggregate emissions throughout the 21st century) available to humanity if the climate constraint is to be respected.

(14) Stern stresses on several occasions that climate warming has the capacity to cause major changes in growth paths. This implies revisiting the terms of classical economic analysis, which focuses on assessing marginal "disturbances" around an unchanged linear growth path.

(15) See for example Richard S.J. Tol (2006): "The Stern review of the economics of climate change: a comment", 30 October 2006.

(16) Greenhouse gas concentrations are expressed in parts per million or ppm. 1 ppm designates 1 cubic centimetre of gas per cubic metre of air. The notion of CO_2 equivalent (CO_2e) serves to reduce greenhouse gases to a common standard irrespective of differences in the lifespan and radiation absorption capacities of the various greenhouse gases.

Table 1: link between greenhouse gas emissions and temperature increases in the different scenarios

	Greenhouse gas emissions in2050	Greenhouse gas emissions concentra-tions in 2100	Tempe-rature increase in 2100	Range of proba-bilities
Stern Revieuw scenarios	45 $GtCO_2e$ = emissions in 2005	>700 $ppmCO_2e$	> 3°	52–96%
Stern Revieuw scenarios	*business as usual* 77-85 $GtCO_2e$ +85% relative to 2005	>750-800 $ppmCO_2e$	>4°	40–90%
Stern Revieuw scenarios	*Proactive* 33,8$GtCO_2e$ −25% relative to 2005	550 $ppmCO_2e$	> 2°	63–99%
Stern Revieuw scenarios	*Ideal* 13,5$GtCO_2e$ −70% relative to2005	450 $ppmCO_2e$	<2°	26–78%
UE	*Two-factor global* 19 $GtCO_2e$ −60% relative to 2005	450 $ppmCO_2e$	<2°	26–78%

Source: Stern Review and European Commission.

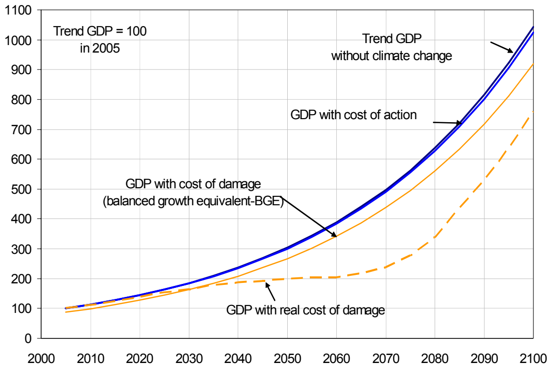
NB: In the first scenario, greenhouse gas emissions in 2050 are identical to those in 2005 and greenhouse gas concentrations in 2100 exceed 700 $ppmCO_2e$. The temperature in 2100 rises by more than 3°C. This temperature increase scenario has a 52%-96% probability of materialising.

Based on a synthesis by Meinshausen of 11 studies (2006), the Review establishes a correspondence between atmospheric greenhouse gas concentrations and temperature increase. In particular, a stabilisation at 550 $ppmCO_2e$ leaves us with a 1–37% chance of remaining below +2°C relative to pre-industrial levels (respectively 31–79% for 3°C and 47–94% for 4°C). Stabilising concentrations at 550 ppm would thus protect us against only part of the effects of a very sharp rise in temperatures, on the order of the one the Review utilises to model the cost of climate change impacts (+3.9° in 2100). The EU's proposed target for the international community, *i.e.* to limit global warming to a maximum of +2°C, would imply a still greater effort (stabilisation below 450 $ppmCO_2e$). At this threshold, according to the IPCC Fourth Assessment Report, the temperature would be expected to rise by 2.1°C. Subject to the many uncertainties still surrounding the relationship between greenhouse gas concentrations in the atmosphere and temperature increase, in practice the aim of limiting the average temperature increase to a maximum of 2°C will in all likelihood be hard to achieve; and humanity will in any case have to contend with the consequences, with no alternative but to try to attenuate them.

3.1.2 The nature of public policies and the portfolio of technologies employed

The "Stern Review"[17] identifies a combination of measures that would cut fossil fuel CO_2 emissions by 25% between 2002 and 2050 (through improved energy efficiency, curbing energy demand and substituting low carbon-emitting fuels). It calculates changes in the average cost of emissions reduction based on various technologies' penetration rates[18] and the marginal cost of abatement associated with them ($/ton of carbon)[19]: in 2050, the total cost of cutting CO_2 emissions with a view to achieving 550 ppm would come to 930 billion dollars, or around 1% of GDP in 2050. Estimations in fact range between −1% (a net gain for the economy) and 3% of GDP, depending on the assumptions used regarding oil and gas prices, growth in energy demand, and technological innovation.

Chart 4: transaction costs on Euronext and integration phases



Source: Hallegatte and Hourcade[20].

NB: the gap in 2005 GDP between the blue and the orange lines stems from the method chosen by Stern, see definition of Balanced Growth Equivalent in 1.1.

As shown in chart 4 above, combating climate change is unlikely to have a material effect on the world economy's growth potential: the global "shock", which is expected to be weak, would be comparable to a 1% rise in the price index, assuming no change in nominal incomes. The economic system as a whole should have no difficulty absorbing this.

(17) Study titled "Costs and Finance of Abating Carbon emissions in the energy sector" (October 2006) carried out by Dennis Anderson, Professor emeritus at Imperial College, London University, and formerly Chief Economist at Shell, appended to the Stern Review.

(18) Dennis Anderson (10) obtains the distribution of market shares of the various technologies for electricity generation, road transport and total primary energy production in 2025 and 2050 from among 20,000 different distributions weighted by their probability.

(19) The relative costs of the different technologies per unit of energy produced are determined in relation to those of the benchmark energy technologies or sources, i.e. coal and gas for electricity generation, petrol and diesel fuel for transport, and gas for industrial and residential heating. The baseline prices of fuels are $50 per barrel of crude oil and $6 per GJ of natural gas. These assumptions are compatible with IEA projections. If oil were to remain durably at $100 a barrel, this would make alternative technologies more rapidly profitable and bring down the cost of action to combat climate warming. Dennis Anderson factors in the uncertainties surrounding fuel price trends and the capital cost of low-carbon-content technologies by simulating several cost distributions weighted by their probability, using the Monte Carlo method to aggregate all of the foregoing.

(20) Previous page: Hourcade and Hallegatte: op. cit.

The meta-analysis performed by Terry Barker for the "Stern Review" based on 11 existing models corroborates these findings, but with a wider range of variations (between a GDP loss of 3.4% and a net gain of 3.9% in 2050).

3.2 The Stern Review emphasises two key parameters to minimise the total cost of greenhouse gas emissions reduction

1) **Mobilising the potential for low-cost abatement measures in certain sectors** (1–\$2/tCO_2 for deforestation avoided, negative costs for energy efficiency and landfills), for certain gases (less than \$3/teCO_2 for emissions associated with the production of nitric and adipic acid, \$0.2/tCO_2 for HFC) and in certain countries, having regard to comparative advantages (solar energy and biofuels in Brazil) and capital stock renewal rates (investment in progress in energy infrastructures in China and India).

2) **The effectiveness of public policies,** *i.e.* the capacity of governments to implement appropriate economic incentives for agents rapidly and progressively. The Review stresses that the longer action is delayed, the more "brutal" and hence costly the efforts will be. In a 550 ppm scenario, greenhouse gas emissions will have to decline by 1% a year between now and 2050 if the peak occurs in 2015, and by 3–4.5% a year if the peak is not reached until 2040. Stern argues that public policies should be implemented gradually to allow the different sectors time to adapt to the "carbon constraint". Indeed the Review signals its preference for a combination of instruments designed to introduce the price of carbon into agents' cost structures, either explicitly (*via* permits trading or taxation) or implicitly (through regulation).

He further considers that, due to market imperfections (externalities associated with the dissemination of knowledge, rents derived from existing installations, in the design of networks, incomplete markets, etc.), the carbon price signal alone is unlikely to be sufficient to guarantee an optimal level of innovation, research and development, nor the deployment of already profitable technologies. Stern calls for a quadrupling of public incentives for private R&D (currently \$34 billion for biofuels, renewables, and nuclear power) and for a significant increase in public R&D spending, notably in the energy sector (from \$10 billion to \$20 billion, which was the level prevailing at the beginning of the 1980s).

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