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A Welfare Analysis of Climate Change Mitigation Policies

Alain de Serres,

Fabrice Murtin

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A WELFARE ANALYSIS OF CLIMATE CHANGE MITIGATION POLICIES

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By Alain de Serres and Fabrice Murtin

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ABSTRACT/RÉSUMÉ

A welfare analysis of climate change mitigation policies

This paper assesses some welfare consequences of climate change mitigation policies. In the same vein as Becker, Philipson and Soares (2005), a simple index of economic progress weighs in the monetary cost induced by mitigation policies as well as the health benefits arising from the reduction in local air pollution. The shadow price of pollution is calculated indirectly through its impact on life expectancy. Taking into account the health benefits of mitigation policies significantly reduces their monetary cost in China and India, as well as in countries with large fossil-based energy-producing sectors (Australia, Canada and the United States).

JEL classification: I31; Q51; Q54.
Key words: Climate change; health; value of a statistical life; welfare measurement.

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L'impact des politiques d'atténuation du changement climatique sur le bien-être économique

Cette étude évalue certaines conséquences des politiques d'atténuation du changement climatique sur le bien-être économique. Suivant l'approche de Becker, Philipson et Soares (2005), un indice de progrès économique est proposé, combinant le coût monétaire des politiques d'abattement d'émissions de gaz à effet de serre ainsi que les bénéfices pour la santé de la réduction de la pollution de l'air qui en découle. Le prix implicite de la pollution est calculé indirectement à travers son impact sur l'espérance de vie. La prise en compte des bénéfices sur la santé des politiques d'atténuation réduit le coût monétaire de la lutte contre le changement climatique baisse de manière significative en Chine et en Inde, ainsi que dans le cas de pays à forte production d'énergie fossile (l'Australie, le Canada et les Etats-Unis).

JEL classification : I31 ; Q51 ; Q54.
Mots-clés : Changement climatique ; santé ; valeur statistique d'une vie ; mesure de bien-être.

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TABLE OF CONTENTS

Figures

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A WELFARE ANALYSIS OF CLIMATE CHANGE MITIGATION POLICIES

By Alain de Serres and Fabrice Murtin[1]

1 Introduction

1. The many shortcomings of GDP as a measurement of economic progress have been underlined in various studies, one notorious example being the Report from Commission on the measurement of economic performance and social progress (Stiglitz, Sen and Fitoussi, 2009). Most of them underscore the failure of GDP to properly account for changes in the quality of the environment or health, which limits its usefulness as a reference to assess the benefits of policies aimed at addressing environmental externalities such as climate change and the degradation of ecosystems through pollution, over-exploitation of natural resource, waste disposal or the loss of biodiversity.

2. Fully addressing these deficiencies would involve nesting the dimensions of income, environmental quality and health within a comprehensive general equilibrium welfare framework. Such a framework is difficult to develop in practice, as it requires evaluating the monetary equivalent of environmental quality (see Fleurbaey, 2009, for an extensive discussion of welfare measures). While data on green expenditures and their environmental impact would seem a natural place to start, the availability and reliability of such data are often lacking in their cross-country and longitudinal dimensions, limiting the scope for quantitative investigation. However, it is possible to assess the joint contribution of income and health to economic progress within a partial-equilibrium welfare framework. For instance, Becker, Philipson and Soares (2005) have constructed a simple measure of welfare that combines income and life expectancy, and have used this index to provide a welfare-based analysis of economic progress over the contemporary period.

3. Based on a similar approach, this paper evaluates the welfare impact of climate change mitigation policies through their effect on GDP and health (life expectancy). In this framework, the welfare cost of pollution can be assessed indirectly, first by inferring the negative impact of pollution upon health, then by valuing the associated decrease in health in monetary terms, relying on microeconomic and behavioural studies that have assessed the "willingness-to-pay" for health. More specifically, valuations of health have in the past been derived using the literature on compensating differentials for occupational mortality risks (see Murphy and Topel, 2006, and Cutler, 2004). This literature typically values a statistical year of life of an average US worker aged fifty at between USD 200 000 and USD 400 000.

4. The net economic impact of climate change mitigation policies can thus be evaluated for major countries and regions of the world by combining in the welfare framework the cost in terms of foregone GDP and the benefits in terms of gains in life expectancy. The country- or region-specific raw estimates of both the costs and benefits of mitigation actions are taken directly from an earlier study which examined the impact of a global reduction in greenhouse gas (GHG) emissions between 2005 and 2050, on the basis of an extended version of the MERGE model (Bollen *et al.,* 2009). For the purpose of this paper, the

1 The authors are both from the OECD Economics Department. They would like to thank Romina Boarini, Nils-Axel Braathen, Rob Dellink, Romain Duval, Jorgen Elmeskov, Marco Mira D'Ercole, Stéphanie Jamet, Nick Johnstone, Giuseppe Nicoletti and Jean-Luc Schneider for their comments and suggestions and Irene Sinha for editorial assistance.

estimated crude reductions in premature deaths obtained from the latter study are converted into an equivalent extension of life expectancy.[2]

5. Hence, the benefits taken into account in the calculation of the welfare impact correspond to those having a direct incidence on health through a reduction in local air pollution, which comes as a by-product of GHG emission cuts. Broader benefits associated with avoided damage caused by global warming (rising sea levels, desertification, rising frequency of extreme weather conditions, etc.), and which may take far more time to materialise in a significant way, are not taken into account. Even with respect to the health impact, the analysis in this paper is likely to underestimate the value of benefits for two reasons: first, only the gains from increased longevity are taken into account and not those accruing from reduced morbidity; second, as empirically demonstrated by Aghion, Howitt and Murtin (2009), improving environment and health will generate additional growth in per capita GDP through general equilibrium effects that are not captured in the analysis.

6. The paper is organised as follows. The next section reviews recent developments of the literature on the measurement of economic progress, especially with respect to its environmental dimension. Section 3 introduces the index of economic progress used in this paper as well as its calibration. In particular, the link between welfare and the value of a statistical life (henceforth VSL) is described. It shows that the VSL increases more than proportionally with GDP per capita, so that gains in health carry an increasing marginal benefit in the course of economic development. Section 4 analyses the trend evolution since 1960 in the resulting index among OECD countries and, based on projected growth in GDP per capita and life expectancy, extends these profiles until 2050. Section 5 assesses the welfare impact of climate change policies, more specifically the effect of a reduction in global emissions to 50% below their 2005 level by 2050. It finds that the estimated gains in life expectancy would result in significant reductions in welfare losses in China and India, as well as in advanced economies with large energy producing sectors, such as Australia, Canada and the United States. In the latter case, the gains in life expectancy would be sufficient to overcome the GDP cost of climate change mitigation and result in net welfare gains. The section is followed by concluding remarks.

2. Accounting for the economic value of pollution

7. The quest for a proper measurement of economic progress that goes beyond GDP has attracted lots of efforts in the recent past. For instance, Boarini, Johansson and d'Ercole (2006) have reviewed alternative measures of well-being. The Stiglitz, Sen and Fitoussi (2009) report has extensively discussed shortcomings of GDP as a measure of economic progress. In particular, an entire section of the report addresses environmental issues and related measures of "sustainable development", picking five of them in particular.

8. One insight from their report is that dashboards of indicators remain the simplest way to go beyond material living standards and measure the benefits from green growth policies. This approach has been undertaken by the European Commission that has produced a dashboard of "sustainable development" indicators (UNECE, 2009). Despite displaying useful information, dashboards are often heterogeneous and present a large amount of information in a non-synthetic fashion.

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2 The extended MERGE model includes a social global welfare function which allows to determine the path of GHG local air pollution emission reductions that will maximise welfare, However, the impacts of mitigation policies in terms of GDP costs and health benefits (*i.e.* reductions in crude premature deaths) used for illustrative purposes in this paper are taken from a scenario where the path of emission reductions is set exogenously and the model solved to produce the least-cost policy mix to meet such path.

9. For that reason, composite indices have been proposed as an alternative approach allowing for the relevant information to be summarised into a single index (see Afsa *et al.*, 2008, Osberg and Sharpe, 2002). For instance, Osberg and Sharpe's (2002) "index of economic well-being" aggregates indices of current consumption, of inequality and social protection, the costs of CO2 emissions per capita and so on. Estes *et al.*, (2005) focus more strictly on environmental issues and aggregate 76 variables related to environmental systems (air, land, water, biodiversity), reductions in environmental stress (air pollution, waste pressure), human vulnerability (exposition of inhabitants to environmental disturbances) as well as cooperation with other countries on environmental issues. Recurrent criticisms to this approach underscore the ad hoc selection of underlying variables as well as problems linked to their rescaling and weighting in the final composite index.

10. A third approach has focused on a modified definition of GDP called "Green GDP". Nordhaus and Tobin (1973) and later Cobb and Cobb (1994) have proposed "Measures of Economic Welfare" that adjust GDP for the costs of pollution, losses of primary forests, CO2-related damages and ozone depletion (see Alfsen *et al.*, 2006, for a survey). The main strength of this methodology, which is to take a forward-looking approach to the environmental impact of current activities, is also its main weakness since it is much more sensitive to assumptions about future developments.

11. In the same vein, an approach undertaken by the World Bank consists in adjusting the macroeconomic savings rate for the decline in asset values caused by the depletion of natural resources. In practice, rents from natural resources are calculated as the difference between world prices and the average unit extraction or harvest cost, and global pollution damages from CO2 emissions are deducted. Several criticisms have been made, including the use of the market price to valuate rents from natural resources, as well as the incomplete coverage of environmental issues (underground water depletion, unsustainable fisheries, and soil degradation).

12. Lastly, the "Ecological Footprint" initially proposed by Wackernagel and Rees (1995) and further refined by Arrow *et al.*, (2004, 2008) and Ewing *et al.*, (2008) aims at measuring "how much of the regenerative capacity of the biosphere is used by human activities". The index is constructed such that the regenerative capacity is compromised when the value exceeds unity. According to this index, humanity's footprint has exceeded Earth's biocapacity since the mid-1980s. Despite its appealing conceptual framework, the index has been criticised for ignoring the opportunities offered by technological progress, and also because biocapacity is obtained from real yields, thus neglecting soil erosion.

13. Most of the former measures have a common drawback, which is that they do not reflect the economic value (cost) of pollution. For instance, adjusted savings rates or the ecological footprint provide some indication on whether the environmental capital increases or decreases. However, they are unable to assess the relative variation of this stock, namely the variation of environmental capital with respect to its current level, as obviously the latter quantity is unobserved, multi-dimensional and difficult to define. Yet, strictly speaking, it is the relative variation of the environmental capital that determines the cost of pollution. Applying Hotelling rule, if the initial stock of environmental capital is scarce, the cost of pollution will tend towards infinity. If the initial stock is available in a very large quantity, then the cost of pollution will tend towards zero. Such information is not available with the former statistical tools, which rather fulfil a descriptive, albeit necessary, task.

14. In contrast, this paper presents a measure of economic progress that takes into account the economic value of pollution. In welfare economics, one way to reflect the shadow price of non-classical goods (such as environmental quality) is to rely on the assessment of the willingness-to-pay to have more of those goods. As such, this approach uses revealed preferences to determine the equivalent income corresponding to a given quantity of those goods. In the environmental literature, many studies have looked at the willingness-to-pay for air quality (Afroz *et al.*, 2005; Carlsson and Johansson-Stenman,

2000), water quality (Hite, Hudson and Intarapapong, 2002; Whitehead, 2003) and so on. However, these results are too disparate to be aggregated into a single measure of the cost of pollution. In addition, there is crucial lack of panel data on both environmental quality and public expenditures that would allow for an assessment of the income gradient of environmental quality, that is, the willingness-to-pay of governments to protect environmental quality.

15. Consequently, an indirect approach to providing an economic value to pollution has been selected for this paper. It focuses on an essential side-effect of pollution upon human health, which is then conveyed in monetary terms. A definition of welfare that rests upon both the level of income and the quality of health is proposed in the next section.

3 Measuring welfare

16. This section describes a simple theoretical framework based on Becker, Philipson and Soares (2005) (henceforth BPS). It lays down the main ingredients of the model, and then derives the welfare function that values both the quantity of life (life expectancy) and its quality (GDP per capita).

3.1 A welfare function for the quantity and quality of life

17. The key issue to be addressed is the monetary valuation of improvements in health. Following the seminal studies by Arthur (1981) and Rosen (1988), the willingness-to-pay of agents for better health is determined by the expected discounted present value of lifetime utility. Let Y and S be respectively lifetime income and the survival function. The indirect lifetime utility V(Y,S) derived from consumption c(t) is

$$V(Y,S) = \max \int \exp(-\rho\, t)\, S(t)\, u(c(t))\, dt \qquad (1)$$

$$\text{subject to } Y = \int \exp(-r\, t)\, S(t)\, y(t)\, dt = \int \exp(-r\, t)\, S(t)\, c(t)\, dt$$

where ρ is the rate of time preference, r the interest rate and y(t) income. The budget constraint stipulates that at any date the lifetime expected discounted value of future consumption equals expected lifetime wealth, implying the assumption of perfect annuity markets.

18. As do BPS, one considers a hypothetical life-cycle individual who receives the same income per capita in all years of her lifetime and faces throughout life the country's cross-sectional survival function. Assuming that the interest rate r equals the actualisation rate ρ, the solution of the maximisation programme specifies that consumption remains constant throughout the life cycle, and that for all t, c(t) = y(t) = y. The programme is simplified as

$$V(y,S) = u(y)\, A(S) \qquad (2)$$

where $A(S) = \int \exp(-r\, t)\, S(t)\, dt$ is the actualised value of one annuity based on the survival function S. Indirect utility is therefore translated into a yearly, rather than lifetime, basis.

19. In addition, the survival process is assumed to follow an exponential process that guarantees a constant instantaneous mortality rate π over the life cycle. Formally,

$$\frac{dS}{S} = -\pi .dt \qquad (3)$$

It follows that life expectancy LE – calculated as the integral of the survival function – and the value of one annuity are respectively equal to

$$LE = \frac{1}{\pi} \qquad (4)$$

$$A(S) = \frac{1}{r+\pi} \qquad (5)$$

20. Equations (2), (4) and (5) yield the welfare function of a hypothetical life-cycle individual

$$\mathrm{V(y, LE)} = \frac{\mathrm{u(y)}}{\mathrm{r + 1/LE}} \qquad (6)$$

21. As a last step, the utility function is specified as the sum of a constant relative risk aversion utility function and a constant, which captures the value of being alive relatively to being dead

$$\begin{aligned} \mathrm{u(c)} &= \frac{1}{1-1/\gamma}\mathrm{c}^{1-1/\gamma} - \alpha \quad \text{if } \gamma \neq 1 \\ \mathrm{u(c)} &= \log(\mathrm{c}) - \alpha \qquad\quad \text{if } \gamma = 1 \end{aligned} \qquad (7)$$

As a normalisation, utility of death is equal to zero. If the inter-temporal elasticity of substitution γ is equal to one or above, then α is positive and the (minimal) level of annual consumption c_0 at which the individual is indifferent between being alive or dead is given by

$$\begin{aligned} \mathrm{c0} &= \exp(\alpha) \qquad\qquad\quad \text{if } \gamma = 1 \\ &= [\,\alpha\,(1-1/\gamma)\,]^{1/(1-1/\gamma)} \quad \text{otherwise} \end{aligned} \qquad (8)$$

3.2 Beyond GDP: a simple index of economic progress

22. Following technological progress in medical science and equipment, extended healthcare and public health infrastructure as well as the enhanced knowledge and education of the population, life expectancy has increased in most regions of the world since 1960, with a few exceptions such as Russia and some sub-Saharan African countries in the wake of the HIV/AIDS epidemics (see Dormont *et al.*, 2009, and Joumard *et al.*, 2008, for an analysis of determinants of health among OECD countries). As improvements in health raise lifetime utility, they can be evaluated in monetary terms with the help of the above framework.

23. Following BPS, the monetary value of gains in life expectancy equals the additional income that would provide the same level of lifetime utility everything else equal. More formally, consider a given

country at two points in time, with GDP per capita and life expectancy denoted by (y, LE) and (y', LE') respectively. At the final stage, the equivalent income w(LE,LE') of the gain in life expectancy (LE'-LE) would give a person the same utility with income y' and life expectancy LE' than with income y'+w(LE,LE') and initial life expectancy LE. Recalling from (2) the definition of lifetime utility, this condition can be written as

$$u(y'+w(LE,LE'))A(LE) = u(y')\, A(LE') \qquad (9)$$

24. Put differently, w(LE,LE') equals the marginal willingness-to-pay for an increase in life expectancy from LE to LE'. An explicit solution for w(LE,LE') can be derived, inverting the utility function and using equations (4), (5) and (7):

$$\begin{aligned} w(LE,LE') &= u^{-1}\left[u(y')\frac{A(LE')}{A(LE)}\right] - y' \\ &= \exp\left[\log(y')\frac{r+1/LE}{r+1/LE'} - \alpha\left(\frac{r+1/LE}{r+1/LE'} - 1\right)\right] - y' \qquad \text{if } \gamma = 1 \quad (10) \\ &= \left[y'^{1-1/\gamma}\frac{r+1/LE}{r+1/LE'} - \alpha(1-1/\gamma)\left(\frac{r+1/LE}{r+1/LE'} - 1\right)\right]^{\frac{\gamma}{\gamma-1}} - y' \quad \text{otherwise} \end{aligned}$$

25. The calculation of the monetary value of improvements in health allows for the extension of the measure of economic progress beyond growth in GDP. Indeed, using the above framework, it is possible to look at growth in "full-income", as defined below:

$$g = \frac{[y'+w(LE,LE')] - y}{y} \qquad (11)$$

26. This full-income index of economic progress encompasses both growth in GDP per capita and the equivalent income that the population of a given country has received from improved health and higher expected lifetime utility. How the above measure compares with growth in GDP per capita will be investigated in a further section. To make the index operational, the parameters of the model are calibrated using the concept of the value of a statistical life.

3.3. The link between welfare measurement and the value of a statistical life

27. In order to provide estimates of the change in economic progress or full income arising from improvements in life expectancy, the latter must be given a monetary value. A large number of microeconomic studies assess the willingness-to-pay of workers for reductions in risks of accidental death. These studies use wage differences across jobs with different occupational mortality risks to identify the marginal willingness-to-pay of agents to reduce these risks. Once aggregated on a statistical population, marginal willingness-to-pay yields the value of a statistical life (henceforth VSL), namely the aggregate monetary value that compensates the loss of one life among a given population. For instance, consider a population of 1 000 workers who require a USD 5 000 premium to accept a 1 in 1 000 increase in the annual probability of accidental death. Then, expected death would rise by 1 each year and would be

compensated by 5 000x1 000 = USD 5 million, the value of one statistical life.[3] In this framework, the willingness-to-pay and the VSL depend on the age and consumption level of the reference population.

28. Estimates of the VSL are used for public policy analysis, for instance by governmental agencies such as the US Environmental protection Agency (EPA). However, the use of a particular value of VSL is controversial as it depends on the context. As surveyed by Viscusi (1993) and Viscusi and Aldy (2003), studies focusing on the labour market offer a range of values roughly comprised between 4 and 9 million in 2004 USD. The EPA uses a default value of 6.3 million in 2004 USD. As shown by Murphy-Topel (2005), the latter amount corresponds to the value of a life-year of about USD 200 000 at the beginning of active life, then peaking at USD 350 000 around age 50 and flattening around USD 100 000 after age 90. In some specific cases, the retained VSL might fall in a lower range of values. For instance, studies focusing on air quality programmes generally retain a lower value because these programmes benefit the elderly to a larger extent, implying a lower average life expectancy for the relevant population (recall that the VSL can be expressed as the discounted present value of a stream of value of life-year over the remaining lifetime and therefore diminishes with age). In this context, Bollen *et al.,* (2009) adopt a reference VSL of 1.2 million in 2004 USD, which is in the median range of values recommended by Holland *et al.,* (2004) for the Clean Air for Europe Programme at the European Commission.

29. The theoretical framework described above offers a simple expression for the VSL implied by the transition between two risky environments where life expectancy amounts to LE and LE’ respectively. Consider a population of N workers who pay each year a premium w(LE, LE’) to observe a decrease $\Delta\pi = \pi' - \pi$ in the instantaneous mortality rate π. Each year, the number of saved life is N $\Delta\pi$ and the amount invested for health improvement is N w(LE, LE’). It follows that

$$\text{VSL}\,(\text{LE}, \text{LE}') = -\frac{\text{w}(\text{LE}, \text{LE}')}{\Delta\pi} \qquad (12)$$

Recalling from (4) that $\pi = 1/\text{LE}$ and identifying the premium paid each year as the willingness-to-pay given by equation (10), the VSL becomes

$$\text{VSL}\,(\text{LE}, \text{LE}') = \frac{\text{w}(\text{LE}, \text{LE}')}{1/\text{LE} - 1/\text{LE}'} \qquad (13)$$

3.4 Calibration of parameters

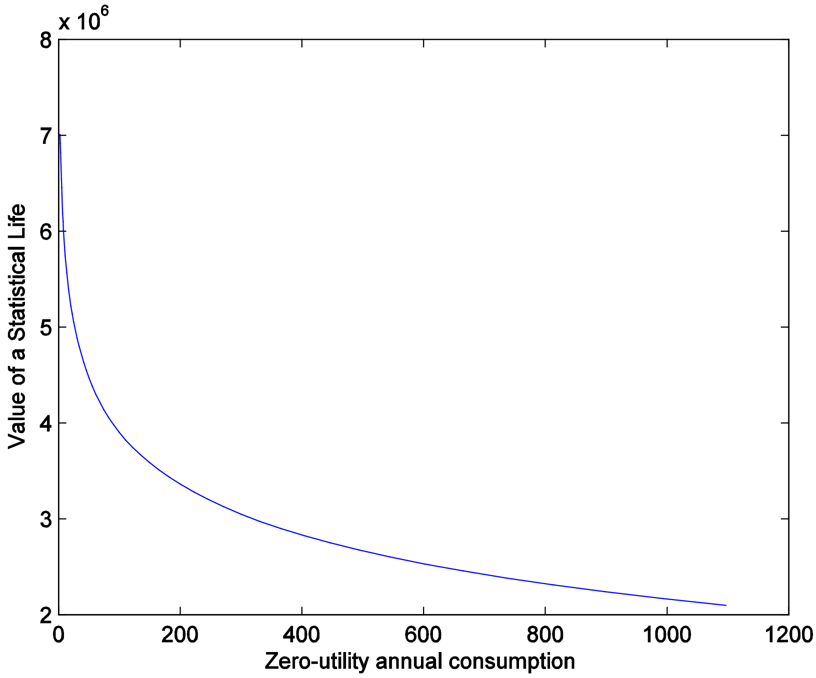
30. Parameters (γ , α, r) are calibrated as follows. The annual real interest rate is assumed to be 0.03. The inter-temporal elasticity of substitution is set equal to 1 so that a log utility function is considered in the rest of the analysis. This choice is dictated by the following two considerations. First, BPS choose γ = 1.25 following Browning *et al.,* (1999) who argue that inter-temporal elasticity of substitution is likely to be a bit larger than one, while Murphy-Topel (2005) consider a range of values comprised between 0.7 and 1.2 in their calibration analysis and select γ = 0.8. Thus, an elasticity equal to unity seems to be a median value with respect to the two main studies in the existing literature. A second reason for choosing γ = 1 is

[3] Furthermore, if one is prepared to assume that each year of life has the same value (Aldy and Viscusi, 2007), it is possible to derive from the VSL the value of a statistical “life-year” for a given discount rate and average life expectancy of the population. This amounts to expressing the VSL as the present discounted value of stream of values of statistical life-year over the remaining life. For example, using a 3 per cent discount rate and assuming an average life expectancy over the population of 30 years (corresponding to an average age of around 50), then a VSL of USD 5 million as calculated earlier would correspond to a value of a life-year of USD 255 000. However, assuming a constant value for each year of life is not uncontroversial (Lindhjem and Navrud, 2011).

that VSL is excessively sensitive to the value of γ if it is close but different from 1. The issue of discontinuity is avoided when a logarithmic utility function is considered.

31. Last, the parameter α is calibrated with the help of an estimate of the VSL, as there is a direct relationship between the two (Murphy and Topel, 2006).[4] Figure 1 uses equations (13) and (10) to plot the VSL as a function of c_0, the consumption level with zero utility that depends directly on α through equation (8). Life expectancy and GDP per capita are taken as the OECD average across countries in 1960 and 2005, using y'= 26 415 USD 2000, LE=68.5 and LE'= 78.7. The VSL comes out as a decreasing function of the minimal threshold of consumption. Indeed, at c_0 agents are indifferent between being alive and being dead, so that the higher this threshold, the lower the value of a statistical life. In practice, the retained VSL is USD 3 million, leading to α=5.9915 and a minimal consumption of c_0 = USD 400. The retained value of VSL is intermediate between the high one obtained from labour market studies and the lower VSL retained in Bollen *et al.*, (2009). The findings presented below are qualitatively unchanged within the range of possible values for the VSL.

Figure 1. The value of a statistical life with respect to parameter c_0



Source: Authors' calculations

4 As explained by Murphy and Topel (2006), the parameter α is linked to the elasticity of instantaneous utility ε=u(c)/[u'(c)c], which determines the value of a life-year as well as the VSL. BPS choose the same value for ε as Murphy-Topel (2006), namely ε = 0.346. In their setting, this corresponds to a VSL comprised between USD 1.5 and 2 million for developed countries, and a minimal consumption c_0 equal to USD 353.

3.5 Characteristics of the welfare function

32. This sub-section shortly describes some characteristics of the welfare function as defined by equation (6) under the above calibration. Figure 2 maps life expectancy and GDP per capita on welfare iso-curves, which correspond to a given level of expected lifetime utility. Each iso-curve shows different combinations of income and life expectancies that would yield identical utility as measured by equation (6) and (7) under the assumption of $\gamma=1$. Consider for instance an average US citizen whose annual income is around USD 44 000 for an 80 years life expectancy. He would enjoy equivalent welfare if he were receiving instead an annual income USD 37 000, but for a 90 years life expectancy. The two situations would generate the same level of expected lifetime utility (equal to 110), implying a marginal rate of substitution of around 1.4. By comparison, consider a country (say, South Africa) where the average income is around USD 10 000 and life expectancy around 60 years.[5] The income that an average citizen from that country would be willing to give up in return for a 10 years gain in life expectancy (to 70 years) would be significantly less (USD 2000 instead of 7000), implying a marginal rate of substitution of five (*i.e*. over three times larger). Put differently, the average US citizen would value the gain of an extra day of life at nearly USD 2, while it would be valued at around USD 0.55 by the average-income earner of a country whose welfare level would be roughly 35 per cent lower on average.[6]

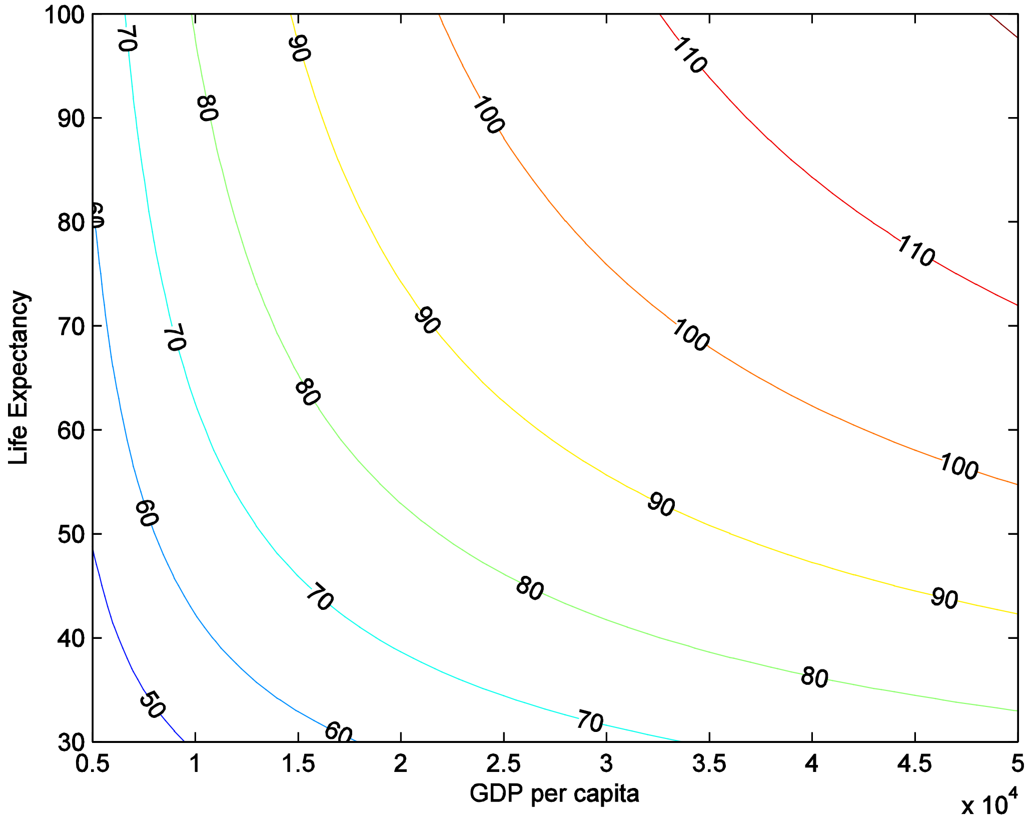
33. The marginal contributions of life expectancy and GDP per capita to welfare vary with the stage of development. As follows from the normalisation of welfare to zero when one approaches the zero-utility consumption level, growth in GDP per capita entails large gains in welfare when GDP per capita is still at a low level by current OECD standards, say below USD 10 000. In that case, even large gains in life expectancy have small effect on lifetime utility relative to the gain entailed by one extra unit of GDP per capita. In other words, the marginal rate of substitution of life expectancy relative to GDP per capita is very low. In contrast, at higher stages of development the marginal increase in welfare is a decreasing function of GDP per capita as follows from the concave shape of the utility function. Then, growth in welfare becomes relatively more sensitive to gains in life expectancy.

34. In order to better illustrate the relationship between the VSL and the level of economic development, Figure 3 plots the ratio of the VSL to GDP per capita (as calculated from equation 13 for given levels of life expectancy) for different values of GDP per capita. As can be seen, the monetary value of health increases more than proportionally with the level of GDP per capita, albeit to a falling extent as the latter gets bigger. Put differently, the VSL is a convex function of the level of development. This non-linear effect can be important in practice. For instance, applying the value of the ratio of the VSL and GDP per capita in 2000 to the level of GDP per capita in 2050 would entail an underestimation of about 20% of the VSL if GDP per capita were to reach an average level of USD 60 000 (see below).

5 According to official statistics, life expectancy in South Africa has actually fallen to closer to 50 years since the mid-1990s.

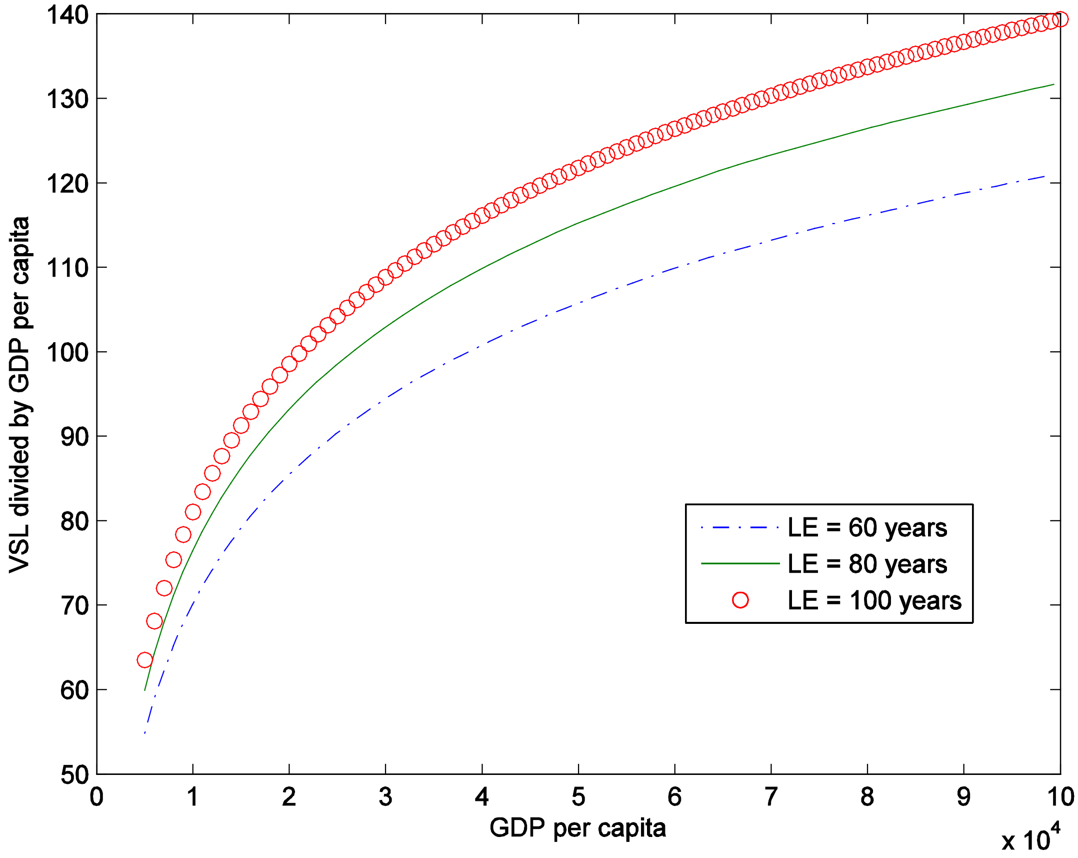
6 Not surprisingly, the difference is much smaller in percentage terms. While the richer-country citizen would be willing to accept an income reduction of 1.3 per cent to raise life expectancy by one per cent, the corresponding figure for the poorer-country citizen would be 1.1 per cent.

Figure 2 Welfare indifference curves



Source: Authors' calculations based on equations (6) and (7).

Figure 3 The value of a statistical life as a ratio of GDP per capita



Source: Authors' calculations

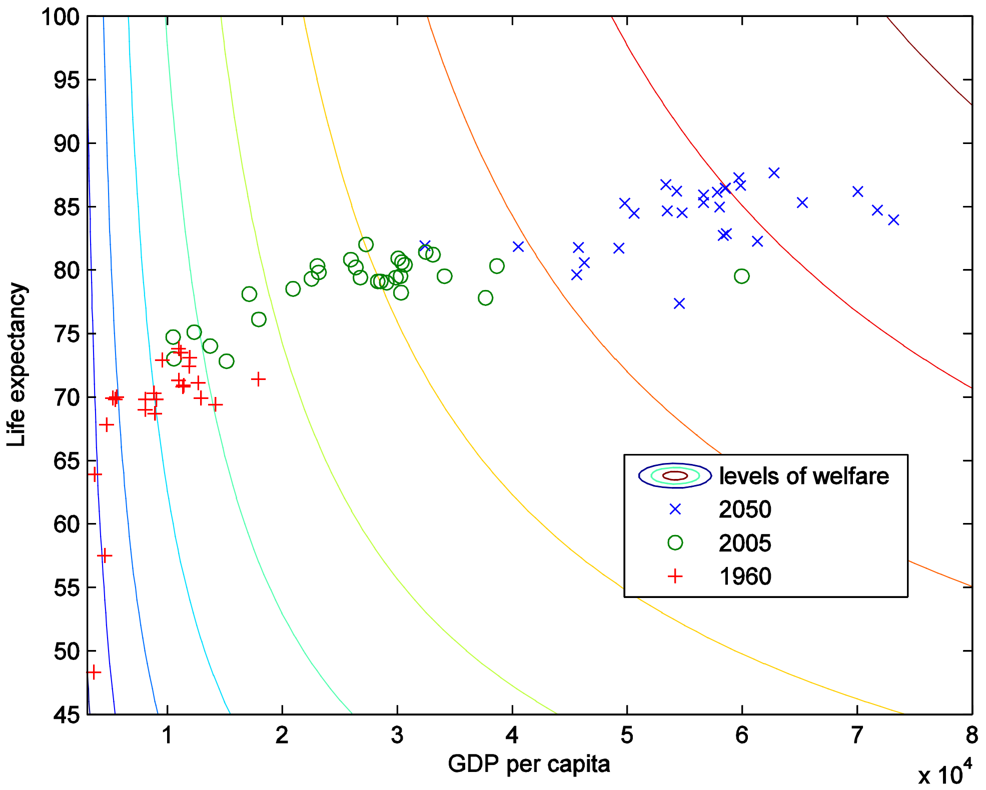
4 Trends in welfare among OECD countries

35. This section describes how OECD countries have fared in terms of the constructed welfare index during the 1960-2005 period. In addition, projected life expectancy and GDP per capita for the period 2005-2050 are considered. An important assumption underlying the construction of the welfare index is that changes in GDP per capita be independent from increases in life expectancy. This requires that the working life of individuals be extended in proportion to life expectancy. For the purpose of this exercise, projections of life expectancy are based on national estimates, while projected GDP per capita corresponds to the baseline economic scenario developed in Duval and de la Maisonneuve (2010). This scenario excludes any impact of climate change and is constructed around a conditional convergence hypothesis.

36. Figure 4 situates OECD countries on the mapping of life expectancy and GDP per capita in 1960, 2005 and 2050. As discussed above, there was a difference of about 40 units of welfare between the two extreme countries in 1960, and differences in GDP per capita can account for more than three quarters of the welfare gap. Then, convergence in life expectancy has reduced the welfare gap across OECD countries but large absolute differences in GDP per capita still generated substantial inequality in welfare in 2005. Looking ahead, absolute differences in welfare are expected to narrow to less than 20 units by 2050. Two factors are expected to reduce the welfare gap by 2050: First, absolute convergence in both GDP per capita

and life expectancy is expected to take place; second, decreasing marginal utility should mechanically homogenise the distribution of welfare among OECD countries.

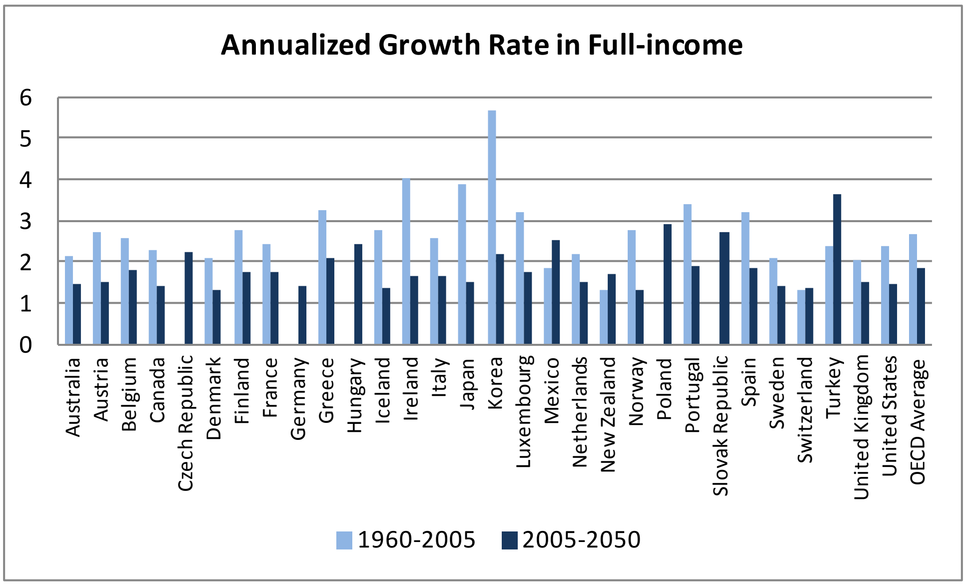
Figure 4 Historical and projected levels of welfare among OECD countries



Source: Authors' calculations based on Economic Outlook 88, Duval and de la Maisonneuve (2010) and United Nations (2008)

37. Using equation (11), the two dimensions of welfare can be combined to yield a measure of growth in full-income equivalent. Based on this measure, which captures both growth in life expectancy and GDP per capita, weaker growth in welfare is projected over the next four decades relative to what has been observed over the last fifty years, with average annual growth (un-weighted across OECD countries) projected to decline from 2.7% over the period 1960-2005 to 1.8% over 2005-2050 (Figure 5). The growth differential between the two periods is partly explained by the fast catching up in GDP per capita observed in some countries (*e.g.*, Ireland, Japan and Korea) over the period 1960-2005.

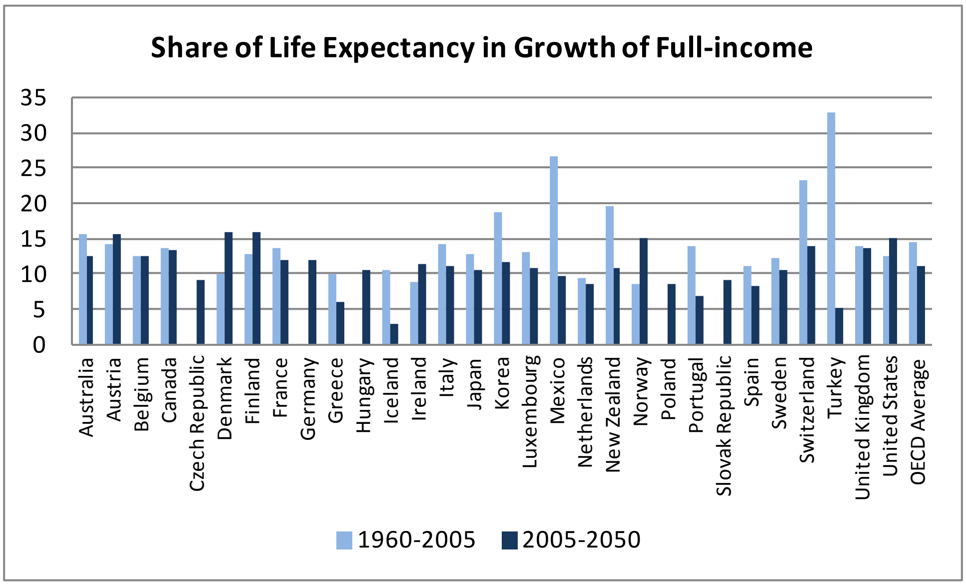
Figure 5 Historical and projected economic progress among OECD countries, 1960-2050



Source: Authors' calculations based on Economic Outlook 88, Duval and de la Maisonneuve (2010) and United Nations (2008)

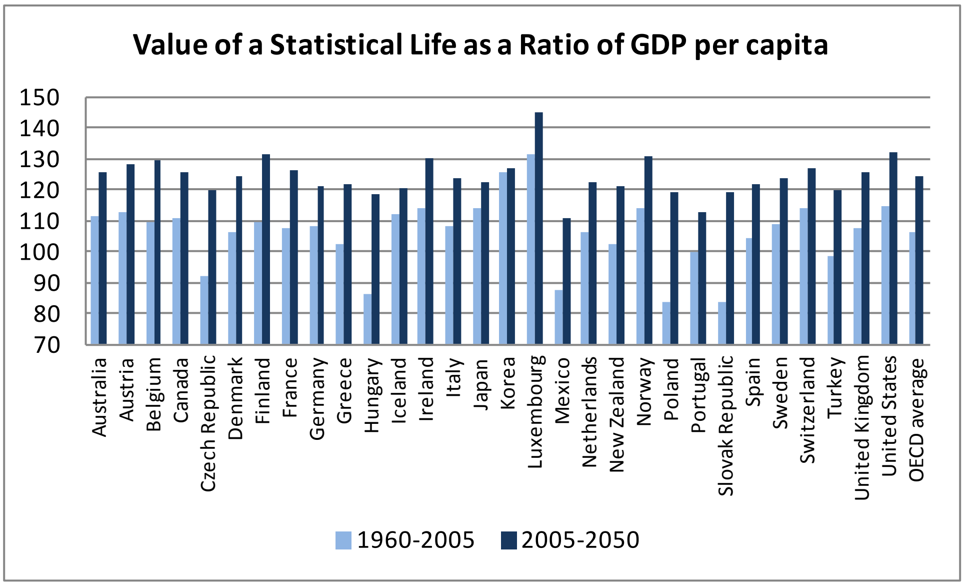
38. Over both periods, growth in GDP per capita represents the bulk of growth in welfare. As shown in Figure 6, life expectancy explains on average about 15% and 11% of the growth in welfare over 1960-2005 and 2005-2050 respectively. Mexico and Turkey have experienced exceptional catch-up in life expectancy and as a result the latter share represents respectively 26% and 33% of welfare growth achieved during the 1960-2005 period. The share of life expectancy is affected by two contradictory effects: first, the growth rate of life expectancy is generally projected to slow down in the future as a consequence of the natural limitation of human life; on the other hand, growth in life expectancy will increasingly contribute to growth in welfare at the margin because of the increase in the VSL. As mirrored by Figure 7, the VSL will increase more rapidly than GDP per capita in all countries.

Figure 6 The contribution of growth in life expectancy to economic progress



Source: Authors' calculations based on Economic Outlook 88, Duval and de la Maisonneuve (2010) and United Nations (2008)

Figure 7 The value of a statistical life as a share of GDP per capita



Source: Authors' calculations based on Economic Outlook 88, Duval and de la Maisonneuve (2010) and United Nations (2008)

5. The impact of climate change mitigation on life expectancy, GDP per capita and welfare

39. This section provides an illustrative application of the index of economic progress through a welfare analysis of climate change mitigation policies. It focuses on two effects of the reduction in GHG emissions with opposite consequences on welfare, namely the negative impact on GDP growth and the positive one on life expectancy.

40. As described thoroughly in Bollen *et al.* (2009), a substantial reduction in GHG emissions would be accompanied by an improvement in air quality with further improvements in health that would result from lower emissions of particulate matter, sulphur and nitrogen pollutants.[7] As a consequence, premature mortality would fall dramatically especially in the United States and in Eastern Europe. In a scenario corresponding to a 50% cut in GHG emission (relative to 2005) by 2050, the authors show that air pollutants such as primary particles, NOx and SO_2 would also be reduced by about 50% at a global level. In turn, premature mortality would start to decline within the first few years of reductions in emission and overall stand at 42% below baseline values in 2050.[8]

41. The massive reduction in premature mortality rates described by Bollen *et al.*, (2009) is first conveyed into the corresponding decline in crude total mortality rates. Crude mortality is the sum of premature and non-premature mortality rates.[9] For the sake of simplicity, non-premature mortality is assumed to be unaffected by GHG reduction policies. Hence, non-premature mortality rates are calculated as the difference between United Nations (2008) projected crude death rates and Bollen *et al.*, (2009) premature mortality rates under the business-as-usual policy scenario.

42. Then, variations in crude mortality rates calculated under various policy scenarios are converted into their equivalent changes in life expectancy. Such a calculation is not straightforward as crude mortality rates depend on two unknown factors, namely mortality rates by age and the shape of the age pyramid. Hence, a proper calculation would necessitate the treatment of a large amount of data. However, it is possible to deliver shortcut estimates based on an assumption on the age-profile of mortality rates.

43. To this end, the following calculations assume that mortality occurs according to a Weibull distribution with unknown parameters k and λ. Such a functional form is motivated by the fact that the implied age-profile of the mortality rate p(a) can fit the data.[10] The mortality rate varies with age "a" according to

$$p(a) = \frac{k}{\lambda}\left(\frac{a}{\lambda}\right)^{k-1} \qquad (14)$$

Using the characteristics of the US Census (2011) survival tables allows for a calibration of parameter k. After age 30, mortality is found to increase exponentially with age at a rate of about $k = 5$. As life

7 It is also reminded in Bollen *et al*. (2009) that reduced air pollution may result in higher temperature increases in the short run since several of the air pollutants have a cooling effect.

8 Even though the differences from the baseline scenario in 2050 vary across regions, similar reductions would be observed in China, India and the United States (at around 40 per cent), while Europe would see smaller declines (closer to 25 per cent). Also, the time profile of the reductions would differ across regions, with a more rapid decline observed earlier on in advanced economies but a flattening out after 2030, whereas premature deaths would still be falling (relative to baseline) in 2050 in developing countries. As mentioned earlier, this does not take into account the (hard-to-quantify) broader effects of GHG emission reductions through avoided climate damage.

9 Premature mortality is defined as the number of deaths to persons aged 0-74 divided by the population age 0-74. It represents roughly 10% of total mortality in developed economies and is two or three times larger in China and India.

10 Admittedly, this choice is not consistent with the theoretical section where an exponential form is being used as it displays a simple closed-form relationship between mortality rates and life expectancy. Here the objective is not simplicity but the derivation of a realistic rule to transform crude deaths rates into life expectancy measures.

expectancy is simply the integral of the survival function, simple calculations show that life expectancy is proportional to λ[11]. The mortality rates can thus be rewritten as

$$p(a) = m(k)\,LE^{-k}\ a^{k-1} \qquad (15)$$

where m(k) is a given function of k. Summing over all ages yields the crude death rate

$$p = m(k)\,LE^{-k} \int a^{k-1} f(a)\,da \quad (16)$$

where f(.) is the distribution of population.

44. Consider now two health environments characterised by the same distribution of population, a similar shape of the mortality function but a different parameter of scale λ (*i.e.* mortality rates can be uniformly rescaled across the two environments). Then the ratio of crude mortality rates is given by

$$p_1 / p_2 = (LE_2 / LE_1)^{k} \qquad (17)$$

45. Equivalent levels of life expectancy under various scenarios of GHG emission cuts can therefore be calculated. The first part of Table 1 and Figure 8 describe the projected levels of life expectancy in 2050 by geographical area. The business-as-usual (BAU) scenario retains the UN (2008) baseline. It also assumes that GHG emissions continue to rise unabated to reach, in 2050, nearly twice the emission level of 2005.

Table 1. Life expectancy, GDP per capita and welfare projections, 2005-2050

	2005		2050 BAU scenario			2050 50% GhG reduction			Full-income growth BAU scenario	Full-income growth 50% GhG reduction
	LE	GDP per cap.	LE	GDP per cap.	Growth of GDP per cap.	LE	GDP per cap.	Growth of GDP per cap.		
USA	78.3	41410	83.3	80437	1.48	84.1	79688	1.45	1.69	1.70
OECD EUROPE	77.4	30930	83.6	56158	1.33	83.9	54961	1.28	1.58	1.54
JAPAN	82.1	30056	87.2	58811	1.49	87.4	58584	1.48	1.68	1.68
AUS-CAN-NZL	79.9	34566	85.6	65211	1.41	86.3	64283	1.38	1.64	1.63
NON-EU EASTERN COUNTRIES	67.3	10697	75.9	42808	3.08	76.5	39382	2.90	3.49	3.32
OPEC+MEXICO	72.3	11254	79.5	34785	2.51	79.7	32611	2.36	2.80	2.66
CHINA	72.0	4062	79.3	30286	4.46	80.2	28344	4.32	4.75	4.63
INDIA	62.0	2144	73.3	22025	5.18	74.1	21223	5.09	5.68	5.63

Note: *OECD Europe* includes all European countries that are members of the OECD, and *non-EU eastern countries* regroup countries that were members of the former Soviet Union.

Source: Authors'calculations based on Bollen *et al.* (2009)

11 This follows from the shape of the survival function $S(t) = \exp(-(t/\lambda)^{k})$. Actually, one has LE = λ Gamma(1+1/k).

46. As a result, a 50% GHG emission cut would lead to substantial extensions in life expectancy, especially in China (0.9 year), India (0.8 year) and the United States (0.8 year). In the latter case, the gain would come on top of an expected 5 years gain between 2005 and 2050 embedded in the BAU scenario. The results are also consistent with the notion of a threshold level beyond which pollution level has much less incidence on health. In many advanced countries or regions, emission cuts beyond 25% yield relatively little marginal gains, whereas cuts well above 25% are needed in China and India to generate most substantial gains as shown by Figure 8.

47. The gains in life expectancy are found to partly compensate for the loss in welfare induced by the GDP cost of climate change mitigation (and that is ignoring the direct economic benefit from mitigation, *i.e.* the avoided climate-related damages). As an illustration, Table 1 and Figure 9 reproduce, for each region, the average annualised loss in GDP growth as well as the growth rate of full-income, resulting from the 50% reduction in GHG emissions over the period 2005-2050.[12] The full-income variable takes into account additional gains in life expectancy from GHG emission cuts. As shown on Figure 9, emission cuts would result in average GDP growth being reduced by around 0.15 percentage points in non-EU Eastern countries, China and oil-exporting countries (OPEC+Mexico), while the growth reduction would be less than 0.05 percentage points in most other regions. In all regions, the impact of the GDP slowdown on welfare is partly offset by gains in life expectancy. Not surprisingly, the offset is largest in countries where the gains in life expectancy are strongest (*i.e.*, China, India and the United States) though it is also substantial in commodities-rich, energy-producing countries such as Australia and Canada. In the case of the United States, even though only one source of benefits is taken into account, welfare is found to increase following the emission cuts, reflecting the combination of a relatively low cost in terms of foregone GDP growth combined with large gains in life expectancy.

6. Concluding remarks

48. This paper has proposed a framework for analysing potential welfare implications of green growth policies. A simple index of economic progress that takes into account both per capita GDP growth and gains in life expectancy is constructed in the vein of Becker, Phillipson and Soares (2005), that is, defining welfare through the value of a statistical life. It is shown that the latter increases more than proportionally with GDP per capita, making gains in health an increasing marginal benefit in the course of economic development.

49. In practice, this welfare index helps assess one important side benefit of climate change mitigation policies, namely the reduction in local air pollution. As a result, taking into account the gains in life expectancy arising from lower levels of air pollution can substantially reduce the welfare losses corresponding to GDP cost of mitigation policies. The fact that the health-related benefits only partly offset the costs of mitigation action in this stylised exercise should not come as a surprise given that the broader benefits in the form of climate-related damage avoidance are not taken into account. Indeed, if the objective was primarily to reduce air pollution, this could be achieved in a more cost-effective way than through broad GHG emission abatement policies, as emphasised in Bollen *et al.,* (2009).

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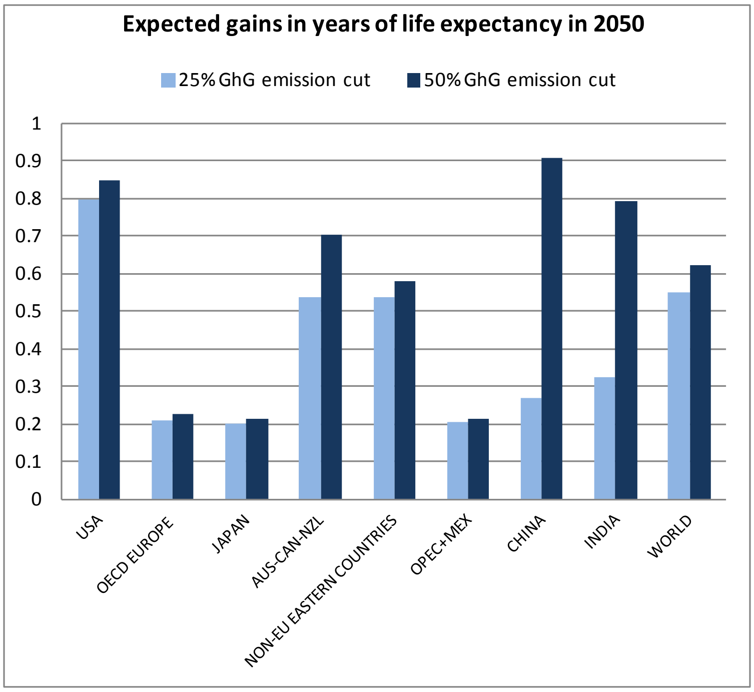
12 The comparison is made on the basis growth rates since the full-income measure is not defined in level terms.

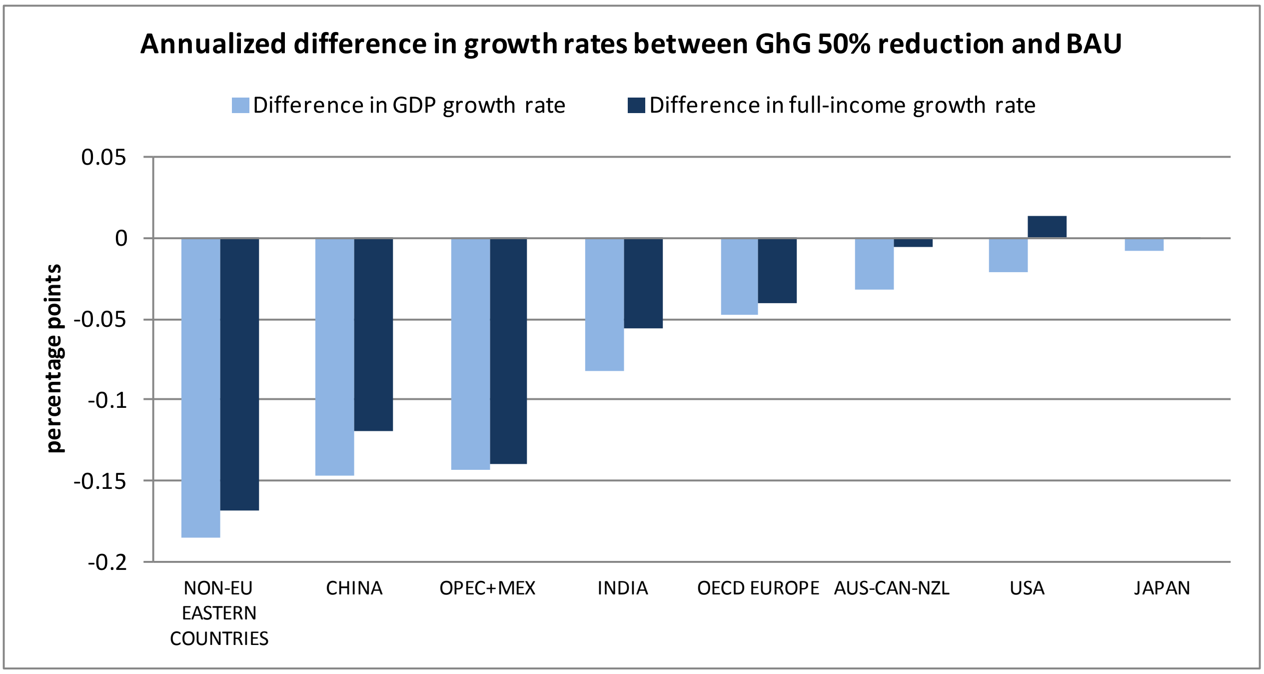
Figure 8 Projected gains in life expectancy



Note: *OECD Europe* includes all European countries that are members of the OECD, and *non-EU eastern countries* regroup countries that were members of the former Soviet Union.

Source: Authors'calculations based on Bollen *et al.* (2009)

Figure 9 Variations in annualised growth rates in GDP and economic progress due to climate change mitigation



Note: *OECD Europe* includes all European countries that are members of the OECD, and *non-EU eastern countries* regroup countries that were members of the former Soviet Union.

Source: Authors'calculations based on Bollen et al. (2009)

50. Even in terms of health-related benefits, several other externalities could be considered, such as the impact of climate change on water quality and shortage, on ozone depletion and malaria diffusion, all of which could potentially cause major health risks in the future as described extensively in WHO (2004). In addition, this study has focused on mortality risks, but the adverse effects on morbidity could also be taken into account, leading to larger welfare gains from mitigation action (Hunt, 2011). Furthermore, the definition of the welfare function adopted here could be seen as too restrictive and income-biased, as it confounds with lifetime income. It could well be argued that health enters directly the utility function (*i.e.* it is valued *per se*). Finally, dynamic effects stemming from health improvements could be beneficial to long-term growth as shown by Aghion, Howitt and Murtin (2010). These questions are left open for future research.

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