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THE ECONOMICS OF CLIMATE CHANGE MITIGATION: POLICIES AND OPTIONS FOR THE FUTURE

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ABSTRACT/RÉSUMÉ

The economics of climate change mitigation: policies and options for the future

Considering the costs and risks of inaction, ambitious action to reduce greenhouse gas emissions is economically rational. However, success in abating world emissions will ultimately require a least-cost set of policy instruments that is applied as widely as possible across all emission sources (countries, sectors and greenhouse gases). The main purpose of this paper is to explore feasible ways to meet these two basic requirements for successful future climate policies. Using a range of modelling frameworks, it analyses cost-effective policy mixes to reduce emissions, the implications of incomplete coverage of policies for the costs of mitigation action and carbon leakage, the role of technology-support policies in lowering future emissions and policy costs, as well as the incentives –and possible options to enhance them – for emitting countries to take action against climate change.

JEL classification: H23; H41; O13; O3 ; Q32; Q43; Q54.

Keywords: Climate change; Climate policy; Carbon Leakage; Energy R&D; Co-benefits; Burden sharing.

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L’économie de l’atténuation du changement climatique : politiques et options futures

Eu égard aux coûts et aux risques de l’inaction, une action ambitieuse visant à réduire les émissions de gaz à effet de serre est économiquement rationnelle. Cependant, tout succès en matière de réduction des émissions nécessitera *in fine* qu’un ensemble d’instruments de politiques à moindre coût s’applique à un ensemble aussi vaste que possible de sources d’émissions (pays, secteurs et gaz à effet de serre). L’objectif principal de cet article est d’explorer les moyens concrets de satisfaire à ces deux conditions de base d’un succès des futures politiques climatiques. Sur la base d’un éventail de modèles, il analyse différents ensembles de politiques à moindre coût, l’impact d’une couverture incomplète des politiques sur les coûts de la réduction des émissions et les fuites carbone, la contribution des politiques de soutien à la technologie à la baisse des émissions futures et au coût des politiques, ainsi que les incitations – et les options possibles pour les améliorer – des pays émetteurs à agir contre le changement climatique.

Classification JEL : H23; H41; O13; O3 ; Q32; Q43; Q54.

Mots-Clés : Changement climatique ; Politique climatique ; Fuites carbone ; R&D énergétique; Bénéfices annexes ; Partage de la charge.

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THE ECONOMICS OF CLIMATE CHANGE MITIGATION: POLICIES AND OPTIONS FOR THE FUTURE

Jean-Marc Burniaux, Jean Chateau, Romain Duval and Stéphanie Jamet[1]

1. Introduction and executive summary

1. The global climate is changing, with potentially high economic and welfare costs, and the causes appear to be largely man-made. Estimates of the economic costs of climate change vary widely, with some assessments generating figures as high as a permanent 14.4% loss in average world consumption per capita (Stern, 2007a), when both market and non-market impacts are included. While there is significant uncertainty about the eventual costs of inaction with respect to climate change, there is general agreement that it has the potential to have significant implications for the world economy, especially in non-OECD countries, where reduced agricultural yields, sea level rise and the greater prevalence of some infectious diseases are likely to be particularly disruptive (OECD, 2008a). Furthermore, the risk of unpredictable, potentially large and irreversible damages worldwide would be significant.

2. Faced with this prospect, governments have reached an international consensus that global emissions will have to be cut significantly. Negotiations have started with the aim of finalising the main elements of a post-2012 international framework for addressing climate change at the 2009 United Nations Framework Convention on Climate Change Conference in Copenhagen.

3. Considering the costs and risks of inaction, ambitious action to reduce greenhouse gas (GHG) emissions is economically rational. This paper takes as given the need for such action, and aims at identifying the instruments that can cut world GHG emissions at least cost, a key criterion for assessing alternative policy mixes. Success in abating world emissions will ultimately require a cost-effective set of policy instruments that is applied as widely as possible across all emission sources (countries, sectors and gases). The main purpose of this paper is to explore feasible ways to meet these two basic requirements for successful post-2012 international climate policies.

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1.1 Future trends and uncertainties

4. A range of mitigation policies and approaches were assessed for this paper. They are discussed against the background of the world emission trends that would prevail over the next half century in the absence of new policy action (henceforth the "baseline" scenario), and their expected effects on the climate and the economy (Section 2). The main future trends that emerge under the baseline are:

- World GHG emissions have roughly doubled since the early 1970s and another doubling is projected over the period 2008-2050. As a result, CO_2 and overall GHG concentration would increase to about 525 ppm and 650 ppm CO_2 equivalent (CO_2eq) in 2050, respectively, and continue to rise thereafter. Under this baseline scenario, global temperature could increase – within a wide range of possible outcomes – by about 2°C relative to pre-industrial levels[2] by 2050, by about 4°C by 2100, and further beyond.

- Wide uncertainties surround these projections and their economic impacts, as reflected by the wide variance across available estimates of the economic damage from one additional ton of carbon. In this context, there is a case for achieving global emission pathways consistent with a "low" probability of extreme, irreversible damages from climate change. Such pathways involve a low and stable long-run GHG concentration target along with minimal overshooting.

1.2 Cost-effective policy mixes to reduce GHG emissions

5. Section 3 focuses on the choice and design of policy tools and approaches to reduce world emissions in a cost-effective way. The analysis presented here builds on the policy simulations and analysis developed for the recent *OECD Environmental Outlook to 2030* (OECD, 2008b), and takes this analysis further. The following results emerge:

- A mix of policy instruments will be required to reduce emissions at least cost, including price-based instruments, R&D policies, regulations and standards, information-based instruments, and possibly sector-wide agreements. Pricing carbon – through emission trading schemes (ETS) or taxes – is a cost-effective approach to emission control, and it should therefore feature prominently in the mix.

- Removing fossil fuel energy subsidies – an issue not explored here for lack of comprehensive data – would be a first and important step towards raising carbon externality prices from the negative levels that currently prevail *de facto* in some (mainly developing) countries. Reducing barriers to imports of climate-friendly goods would also enhance the cost-effectiveness of international climate policy.

- A scenario reflecting a global price on carbon was examined, whereby the cost of abating one ton of carbon is equalised across all countries, industries and GHGs. This provides a useful benchmark against which to assess the costs and emissions reduction potential of alternative policy options. In practice, movement towards a world carbon price might be achieved for instance through gradual expansion of the country, sector and greenhouse gas coverage of domestic emission trading schemes, combined with linking across those schemes.

- Even in such a benchmark scenario, mitigation costs vary significantly depending on the nature, horizon, and stringency of the target, as well as on the path towards it, which could involve temporarily overshooting long-term concentration targets. For instance, an illustrative scenario

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[2] Including the 0.5°C rise already observed.

involving stabilisation of long-run CO_2 concentration at about 450 ppm and overall GHG concentration at about 550 ppm CO_2 equivalent, as well as modest overshooting of the target, is found to reduce average annual world GDP growth projected over 2012-2050 by 0.13 percentage points – which results in world GDP being lower by about 4¾% in 2050, compared to the baseline scenario. A higher overshooting of the target could reduce costs in the initial periods, thus halving the projected world GDP growth impact up to 2050, but it would come at the price of higher costs after 2050 and greater risks of irreversible damages from climate change. By contrast, avoiding overshooting, for example by forcing more dramatic emission reductions before 2050, would raise the costs of action. For example, a 50% GHG emissions cut with respect to 2005 levels by 2050 is estimated to reduce average annual world GDP growth projected over 2012-2050 by ¼ percentage point from about 3½% to 3¼% compared with the baseline.

- Whatever the pathway adopted, achieving a stabilisation of overall GHG concentration in the atmosphere at 550 ppm CO_2eq will require policies that reduce emissions to about a fourth of their 2005 levels.

- The cost estimates for achieving these emission reductions could be lowered if energy subsidies were removed, as well as if barriers to imports of climate-friendly goods and services were lifted – two policy options that could not be explored here. Costs could also fall if low-cost forestry CO_2 mitigation potential, which could be large but remains uncertain, were mobilised, as well as if major new low-carbon technologies (such as carbon capture and storage) emerged as a result of mitigation policies (see below). On the other hand, the above cost estimates are optimistic in that they assume smooth adjustment to a global price-based policy approach.

- Price-based instruments are needed but they will not be enough. Various monitoring, enforcement and asymmetric information problems undermine the responsiveness of certain emitters to price signals, and achieving global carbon price coverage may not be politically feasible, at least in the near term. Therefore, there is a case for targeted use of complementary instruments at the domestic level, including standards (*e.g.* building codes, electrical appliance standards, diffusion of best practices) and information instruments (*e.g.* eco-labeling), especially insofar as the emission sources concerned are not priced.

- Insofar as a price is put on carbon, applying other policy tools such as renewable, energy efficiency or biofuel targets in addition to this price can lead to over-lap in the instruments used, and might lock in the use of specific technologies that may not be the most efficient. These policies may be motivated by other objectives, but in many OECD countries, any side benefits in the areas of innovation and/or energy security do not seem to justify the very high implicit carbon abatement prices currently embedded in renewable and biofuel subsidies and targets. As a general rule, different instruments should address different market imperfections and/or cover different emission sources.

6. Given that putting a global price on carbon may be difficult in practice, this paper assesses the additional costs, environmental consequences and competitiveness issues implied by alternative climate policy arrangements:

- Many countries currently exempt energy-intensive industries from their climate change or other environmental policies. However, analysis undertaken for this paper indicates that exempting energy-intensive industries from policy action could be costly, increasing the costs of achieving a 550 ppm CO_2eq concentration target by over half in 2050, compared to a scenario including participation by all sectors.

- Similarly, the costs of action increase significantly if policies are applied that target only CO_2 emissions, rather than all GHGs. Thus, the costs of achieving a 550 ppm CO_2eq concentration target is found to almost double globally in 2050 if it is achieved only through reductions in CO_2 emissions, compared with a scenario of reducing all gases.

- Likewise, the costs of incomplete country coverage of GHG mitigation policies appear to be large. GHG concentration targets below 750 ppm CO_2eq are found to be virtually out of reach if Annex I countries act alone, either because they would imply negative emissions in 2050 – for targets below 650 ppm – or very high costs.[3]

- While narrow country participation in mitigation action raises costs, preliminary analysis suggests that fears of carbon leakage – *i.e.* that emission cuts in a limited number of participating countries might be partly offset by increases elsewhere – may be overstated. Unless only a few countries take action against climate change, for instance the European Union acting alone, leakage rates are found to be almost negligible, below 2% for instance in the case of Annex I countries cutting their emissions by 50% by 2050. Larger country coverage not only reduces leakage but also changes its nature. The wider the country coverage, the smaller the competitiveness losses affecting energy-intensive industries, but the larger the leakage *via* lower international fossil fuel prices, which result from the fall in world demand for such fuels and lead to more fossil-fuel intensive production in countries not participating in emission reductions.

- As a result, addressing leakage through countervailing tariffs – also referred to as border tax adjustments – on (the carbon content of) imports from countries that do not take action against climate change would be a meaningful option only if the coalition of acting countries is very small. Furthermore, countervailing tariffs may not reduce the output losses incurred by energy-intensive industries in participating countries. Finally, they are estimated to entail costs for both participating and non-participating countries, could involve potentially large administrative costs and would run the risk of trade retaliation.

- International sector-wide agreements in energy-intensive industries offer a more promising approach to address incomplete coverage of broad-based action, at least insofar as they come in a stringent form such as a sectoral cap-and-trade scheme. They allow larger emissions cuts to be achieved at a lower overall cost than would be incurred by a small country coalition. However, they can have large consequences for the cross-country distribution of costs, depending on the features of sectoral and economy-wide trading schemes and whether these schemes are integrated. Apart from large energy-intensive sectors such as aluminium, cement or steel, international shipping and air transport are two industries where a sectoral approach may be useful, due to their transnational character.

1.3 Lowering the cost of achieving GHG targets through technology policies

7. The cost of *future* emission cuts can be lowered by channelling adequate resources into innovation and adoption of climate-friendly technologies. This issue is explored in Section 4, in part through the use of a global model featuring induced technological change. The main findings from this part of the analysis are as follows:

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[3] For instance, while a 750 ppm CO_2 equivalent target might *a priori* be achievable through action in Annex I countries alone, it is so large that it overstretches the limits of the OECD model used to assess mitigation costs in practice, implying a carbon price that spirals out of control by mid-century.

- To foster major technological breakthroughs, basic research and development (R&D) investments need to be raised significantly. Pricing carbon would provide some of the necessary incentives. For instance, a price path that would stabilise long-run CO_2 concentration at 450 ppm and overall GHG concentration at about 550 ppm CO_2eq is estimated to lead to a four-fold increase in energy R&D expenditures in 2050, relative to a scenario where no carbon price is set.

- Future carbon price expectations – and, therefore, climate policy credibility – are also crucial. For a given carbon price level, R&D investment is found to be much higher under more stringent long-run concentration objectives, reflecting higher expected future price increases

- However, carbon pricing alone is unlikely to spur sufficiently the basic R&D investments that could lead to major breakthroughs. It does not address the market failures undermining R&D, which are larger in climate mitigation than in most other areas, and suffers from inability to signal fully credible commitment. Therefore, there is also a case for specific R&D policies, including concerted policies at the global level.

- By contrast, despite the existence of learning spillovers in various mitigation technologies (*e.g.* renewable power generation), the case for further increases in deployment subsidies is unclear. They are already very large in many OECD countries and entail significant risks of policy failure, for example locking-in potentially inefficient technologies.

- Relying on R&D policy *alone*, however, does not appear to be an option. Simulations indicate that even under very large increases in spending and very high returns to R&D, CO_2 concentration would still rise continuously – albeit below baseline – if no price is put on carbon, reaching over 650 ppm by the end of the century, with overall GHG concentration above 750 ppm CO_2eq.

- The impact of induced technological change on mitigation costs is found to hinge crucially on the nature of R&D. Insofar as R&D leads to incremental improvements in energy efficiency, R&D and deployment of low-carbon technologies have only modest impacts on mitigation costs, especially for less stringent concentration targets that provide a lower stimulus to innovation. This reflects declining marginal returns to R&D and low-carbon technology deployment, and the availability already today or in the near future of low-carbon options in the electricity sector (nuclear and, possibly, carbon capture and storage). By contrast, if R&D leads to major technological breakthroughs – especially in transport and the non-electricity sector more broadly, where marginal abatement costs are higher, future mitigation costs could fall dramatically, by as much as 50% in 2050.

1.4 Dealing effectively with uncertainty

8. A sound international framework should be able to adjust to future scientific, economic and technological developments, but also credible and predictable enough to boost investment in low-carbon production techniques and technologies. This issue is tackled in Section 5, with the following findings:

- Political uncertainties surrounding carbon prices could have very large detrimental effects on low-carbon investments, reflecting the magnitude of irreversible fixed costs in key emitting industries such as electricity or transport. Emission trading schemes can help strengthen policy commitment and reduce political uncertainty, as they establish a political constituency – permit holders – with a strong financial interest in enforcing the policy in the future, at least if permits have a sufficiently long horizon.

- A certain degree of carbon price uncertainty is inherent in cap-and-trade systems, but large, liquid and credible schemes can facilitate the development of derivative markets and thereby – provided such markets are adequately regulated – enhance the ability of firms to hedge against short-term price volatility. Price caps and floors on permit prices, banking and borrowing provisions in permit markets, and/or linking different permit schemes can also help reduce short-term price volatility.

- In order to provide some predictability regarding longer-run policy adjustments, an international agreement might feature a mix of long-run targets and automatically renewed short-run commitment periods. Built-in mechanisms, through which less-developed countries would automatically take on more stringent commitments or actions as their income levels converge to the higher levels in developed countries, would help alleviate the need for frequent renegotiation, thereby contributing to reduce policy uncertainty worldwide.

1.5 Building political support for action

9. The cost of incomplete country coverage of mitigation policies underlines the need for wide policy action across the main emitting countries. Against this background, Section 6 of the paper discusses existing incentives for countries to take action and sketches out possible ways to enhance them. The main findings from this section are:

- The relatively distant direct benefits from avoided climate change may not provide sufficient incentives for strong mitigation action in large developing countries, given the relatively high carbon intensity of their economic activity and their steady income growth prospects. For instance, a global emission trading scheme with full auctioning of emission rights (or a world carbon tax) would entail higher costs (as a share of income) for China and India than for most OECD countries.

- The co-benefits from action in terms of reduced outdoor local air pollution and/or improved energy security are found to be large and may significantly offset mitigation costs. The overall co-benefits would be expected to be even greater if other co-benefits, *e.g.* in terms of reduced water pollution or avoided biodiversity losses, had also been assessed. Local air pollution benefits alone, however, may not provide sufficient participation incentives to large developing countries. This is partly because direct local air pollution control policies are typically cheaper than indirect action *via* GHG mitigation. Furthermore, over the medium run and/or for less stringent long-run emission-reduction objectives, these co-benefits may be lower in developing countries than in the OECD area, as the cheapest GHG abatement opportunities in developing countries are initially found in the electricity – rather than the transport – sector, where the human health benefits from emission cuts appear to be smaller.

- As regards energy security gains, incomplete evidence suggests that mitigation action would merely increase the magnitude of the decline in economies' fossil fuel intensity as already projected in the baseline scenario. Also, oil intensity – with its associated dependency on a small number of producer and transit countries in sometimes politically unstable regions, may not decline much, and large coal producers – including China and India – might enjoy lower energy security gains than other countries, *ceteris paribus*.

- Efficiency calls for mitigation actions to take place wherever they are least cost, and therefore for the costs of global mitigation action to be distributed in a way that secures action by all key emitters. Where emission reductions take place may be a separate consideration from who pays for that action. This could be achieved *via* the allocation of emission rights or, equivalently, reduction commitments, under a global emissions trading architecture. For instance, looking at the 2050 horizon, a rule based on population size or GDP per capita – so-called per capita and "ability to pay" allocation rules – would boost the participation incentives of most developing countries. By contrast, a grandfathering rule, where emission objectives would be assigned on the basis of each country's contribution to current emissions, would benefit primarily large emitters on a per-capita basis (Russia and, to a lesser extent, most OECD countries and China). No simple rule is likely to address all incentive problems.

- In the absence of a global carbon price mechanism, one option to engage large emitters from developing countries would be to scale up the clean development mechanism (CDM) by moving away from the current project-by-project method towards a sectoral and/or policy-based approach. However, this may not fully address fundamental concerns regarding the environmental integrity of the scheme. In this regard, binding international sector-wide agreements might be a useful alternative, although these may need to be accompanied by arrangements to provide financing or technology support to mitigation actions in developing countries.

- A cost-effective international climate policy package should also improve incentives to take action against deforestation and degradation in developing countries. An efficient mechanism would be to compensate forest owners for any action to curb deforestation and degradation relative to a baseline scenario, or alternatively for the rate of utilisation of their overall *potential* capacity to grow forest, either *via* free allocation of emission rights or through direct income transfers. A pre-condition is to improve urgently the measurement, monitoring and baseline projections of emissions from deforestation and degradation.

- Finally, addressing domestic political economy obstacles to mitigation action could facilitate wide participation in an international agreement. Stringent international sector-wide agreements could help curb domestic opposition in developed countries by energy-intensive industries exposed to foreign competition. Grandfathering emission permits to domestic firms is a costlier option and, if pursued, would need to be phased out quickly. The adverse household income distribution effects of carbon pricing and subsidy elimination seem small in most developing countries, as richer households are often more affected than their poorer counterparts, but concerns could still be alleviated through more general social programmes. In developed countries, existing social transfer schemes would mitigate such concerns. By contrast, targeted exemptions to GHG pricing can be costly and should be avoided.

2. Projected emissions and their consequences: trends and uncertainties

2.1 Past emission trends

10. World GHG emissions have roughly doubled since the early 1970s, reaching about 47 Gigatons CO_2 equivalent (Gt CO_2eq) in 2005 (Figure 2.1). Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) together account for over 99% of all current anthropogenic GHG emissions, with Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6) accounting for the remaining 1%.[4] While the bulk of CO_2 emissions are energy-related, a substantial share – about 16% – results from land use changes, including deforestation.[5] After two decades of slowing, which culminated in

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4. Non-CO_2 emissions result inter alia from agriculture (rice cultivation, livestock, fertiliser use), coal and gas extraction, landfills and various chemical processes involved in the production of steel and chemical products.

5. Cement production is another significant source of non energy-related CO_2 emissions.

a temporary stabilisation in the early 1990s as GDP fell in transition economies, emissions have accelerated sharply since 1995, growing at about 2.5% a year on average over 1995-2005.

[Figure 2.1. World emission trends by gas]

11. Non-OECD countries have accounted for most of the growth in world emissions over the past four decades, including the recent acceleration (Figure 2.2). As a result of this trend, OECD countries now contribute to just over 35% of world GHGs emissions, down from 55% in 1970. Power generation and transport contributed most to the recent pick-up in world emissions growth, reflecting fast output increases in these sectors in developing countries (Figure 2.3).

[Figure 2.2. World emission trends by country/region]

[Figure 2.3. World energy-related CO_2 emission trends by sector]

12. Despite the fall in their share of world emissions, OECD countries still emit much more in per capita terms than most other world regions (Figure 2.4). Compared with China, India, the Middle East and the rest of the world, emissions per capita remain almost twice as high in Japan and the European Union, three times as high in Russia and four to six times as high in New Zealand, Canada, United States and Australia. Almost the reverse picture emerges when countries and regions are ranked according to CO_2 intensity of output, reflecting the greater energy efficiency and/or less carbon-intensive energy mix of more developed economies (Figure 2.5). Lower energy efficiency in emerging countries, combined with their rising contribution to world GDP growth, has contributed to the moderation in energy – and CO_2 – efficiency gains observed at the world level in recent years.

[Figure 2.4. GHG emissions per capita, by country/region, 2005]

[Figure 2.5. GHG emissions per unit of GDP, by region, 2005]

2.2 Projected emission trends

13. A pre-requisite in assessing the costs and effects of mitigation policies is to project future world emissions at unchanged policies. This "baseline" projection, which assumes no further action is taken to limit emissions beyond what has been done or planned so far, is obtained here by running the OECD ENV-Linkages model over the period 2005-2050 (For details about the OECD ENV-Linkages computational general equilibrium model, see Burniaux and Chateau, 2008). Underlying the baseline projection is an economic convergence assumption under which income levels in developing countries converge towards those in developed countries over the coming decades (Box 1). In this new scenario, which has been developed for the present paper, average annual world GDP growth in 2005 constant PPP $US would be about 3¾% over 2006-2050 (Table 2.1), roughly in line with the 2000-2006 average as well as with recent OECD projections up to 2025 (Hervé *et al.* 2007). Overall, average world GDP per capita in constant PPP $US is expected to rise more than three-fold over the 2006-2050. When expressed in constant 2005 $US at market exchange rates, baseline world GDP per capita growth up to 2030 falls roughly in the middle of the range provided in the IPCC's Special Report on Emission Scenarios (Nakicenovic *et al.* 2000).

[Table 2.1. Baseline economic scenario: main features]

14. Other critical drivers of projected emissions include assumptions about future fossil fuel prices and energy efficiency gains (for details, see Burniaux and Chateau, 2008). The baseline scenario incorporates the recent surge of the international crude oil price, assuming that it culminates at $US100 per barrel (in real 2007 prices) in 2008, stays constant in real terms up to 2020 and increases gradually later on up to $US122 per barrel in 2030. Beyond that horizon, oil exporters' crude oil supply is projected to

decelerate gradually, capturing in a rough way the continued influence of reserve constraints, and resulting in a sustained rise in the real crude oil price beyond 2030 at a 1% annual rate over 2030-2050 (Figure 2.6). The international price of natural gas is assumed to follow the international crude oil price up to 2030, but this link then weakens somewhat, reflecting a higher assumed long-term supply elasticity for natural gas than for oil. Coal prices are projected to rise only modestly (in real terms) beyond their recent levels – with the price of steam coal being assumed to reach $US100 per ton in 2008-, in line with the assumption of a high long-term supply elasticity. These projected fossil fuel price trends are broadly in line with IEA projections up to 2030, as available at the time of drafting this paper. Future energy efficiency gains are calibrated based on IEA energy demand projections, and imply a gradual weakening of the relationship between economic growth and energy demand growth, especially after 2030. Finally, in the baseline projection the EU Emissions Trading Scheme (EU-ETS) is assumed to be sustained in the future, with a gradual convergence in the carbon price to $US25 per ton of CO_2 and a stabilisation at this level (in real terms) beyond 2012.

[Figure 2.6. International fossil fuel price trends in the baseline scenario]

Box 1. Methodology of construction of the baseline economic scenario

Baseline economic scenarios underlying climate change projections – such as those developed for the IPCC (*e.g.* Nakicenovic *et al.* 2000) – typically assume gradual, and at least partial, convergence of income levels towards those of most developed economies. The approach followed in this paper is comparable in spirit, but special emphasis is put on setting up a framework that integrates some of the current theoretical and empirical knowledge regarding long-run economic growth, and allows transparent assumptions concerning the drivers of GDP growth over the projection period (for discussion of assumptions, detailed results and data sources, see Duval and de la Maisonneuve, 2009).

Concretely, in line with previous OECD work (OECD, 2004), a “conditional convergence” hypothesis is incorporated into the projections. Following recent research (*e.g.* Hall and Jones, 1999; Easterly and Levine, 2001), and based on a standard aggregate Cobb-Douglas production function with physical capital, human capital, labour and labour-augmenting technological progress, GDP per capita is first decomposed as follows for the year 2005:

$$Y_t \;/ Pop_t = (K_t \;/ Y_t\;)^{\alpha/(1-\alpha)} A_t\, h_t\, (L_t \;/ Pop_t\;)$$

where Y_t/Pop_t, K_t/Y_t, A_t, h_t, and L_t/Pop_t denote the level of GDP per capita (using PPP exchange rates to convert national GDPs into a common currency), the capital/output ratio, total factor productivity (TFP), human capital per worker and the employment rate, respectively. α is the capital share in aggregate output.

With this initial decomposition of current cross-country differences in income levels at hand, long-run projections are then made for each of the four components so as to project the future path of GDP per capita:

- Long-run annual TFP growth at the “frontier”, defined as the average of “high-TFP” OECD countries, is 1.5%. The annual speed at which other countries converge to that frontier is assumed to tend gradually towards 2% annually from its rate in the recent past.
- The human capital of the 25-29 age group is assumed to level off where it is currently highest, consistent with past experience. The speed at which other countries converge to that “frontier” is assumed to tend gradually towards that of the average world country over 1960-2000, and starting from its rate in the recent past. The human capital of the working-age population is then projected by cohorts.
- Capital/output ratios in all countries gradually converge to current levels observed in the United States, which is implicitly assumed to be on a balanced growth path. In other words, marginal returns to capital converge across countries over the very long run, in a world where international capital is mobile.
- Employment projections combine population, participation and unemployment scenarios. The baseline United Nations population scenario is used. In those OECD countries where participation is currently highest, future retirement ages are partially indexed to life expectancy. Elsewhere, it gradually converges to the average observed in “frontier” countries. Unemployment rates converge to 5%.

This framework is applied to 76 countries covering 90% of world GDP and population in 2005. For all other countries, the productivity convergence scenario is applied to labour productivity or GDP per capita instead of TFP.

The approach followed here addresses the criticisms made recently towards economic projections using market exchange rates, which constitute the vast majority of scenarios published in the literature (Castles and Henderson, 2003a, 2003b; Henderson, 2005). This is for two reasons. First, purchasing power parities (PPPs), not market exchange rates, are used to compare initial income per capita levels. Second, future productivity growth is assumed to be faster in tradable than in non-tradable industries, in line with historical patterns. Reflecting this "Baumol-Balassa-Samuelson" effect, the real exchange rate of fast-growing countries typically appreciates. Therefore, the GDP PPP per worker path produced by the ENV-Linkages model combines both a volume effect (GDP growth in constant national currency) and a relative price effect (the real exchange rate appreciation), with the former being the main driver of emissions.

15. According to the baseline projection, annual world GHG emissions – including non-CO_2 gases[6] but, importantly, excluding CO_2 from land use changes[7] – would almost double over the period 2005-2050, rising from 39 Gt CO_2eq to about 72 Gt CO_2eq **(**Figure 2.7**)**. This would occur despite sizeable assumed energy efficiency gains, which would result in a sharp slowdown in annual emissions growth to about 0.8% over 2030-2050, down 1.7 percentage point from the 1995-2005 average (Table 2.2). In line with past trends, Brazil, China and India and other developing countries would account for most of the rise in world emissions, with yearly emission growth rates typically exceeding 2% in many of these countries. In Russia, by contrast, emissions growth would be slowing gradually with demographic decline. Emissions growth would also be low in OECD regions, even staying flat or slightly declining in Japan and the European Union. As a result, the contribution of OECD countries to annual world emissions would shrink further to about 25% in 2050. Overall, projected world emissions growth from fossil fuel combustion stands above the average, but falls well within the range, of similar exercises reported by the IPCC (Figure 2.8). It is also slightly higher than in recent OECD and International Energy Agency (IEA) projections (OECD, 2008b; IEA, 2007a), mainly reflecting faster baseline economic growth in non-OECD regions, especially over the next two decades.

[Figure 2.7. Projected GHG emissions by country/region]

[Table 2.2. Projected emission growth rates by country/region]

[Figure 2.8. Comparison of the baseline projection of CO_2 emissions with other studies]

2.3 The consequences of climate change

16. The projected increase in emissions over the coming decades is expected to have major effects on atmospheric concentrations of GHGs and thereby the global climate. According to the baseline scenario CO_2 concentration would rise to about 520 ppm in 2050, and overall GHG concentration to about 690 ppm CO_2eq, which is not far from a doubling of concentration relative to the preindustrial level.[8] This scenario falls roughly in the middle of the range of previous studies (Figure 2.9). The resulting rise in global mean temperature could be over 2°C by 2050, including the 0.5°C increase already observed (Figure 2.10).[9] The

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[6] The current version of the ENV-Linkages model incorporates six GHGs: CO2, CH4, N2O, HFCs, PFCs and SF6.

[7] The current version of the ENV-Linkages model does not incorporate GHG emissions from land use changes. Emissions from land use changes are not featured in Figure 2.7 but are taken exogenously from the median scenario reported in the IPCC's Special Report on Emission Scenarios (Nakicenovic *et al.* 2000), which assumes a gradual decline in these emissions throughout this century.

[8] CO_2 concentration in the pre-industrial area is estimated at 270 ppm. Concentration and temperature dynamics are projected here using a simplified climate module named MAGICC (version 5.3 available at http://www.cgd.ucar.edu/cas/wigley/magicc/index.html; Wigley, 2008).

[9] The projected temperature increases mentioned in this section represent instantaneous effects at a given date. Long-term equilibrium temperature increases are larger, due to the inertia of the earth system.

long-run rise in temperatures would depend on the level at which the GHG concentration stabilises. However, without any further policy action and major technological breakthroughs, concentration would rise continuously and global mean temperature could increase by about 4°C by 2100 – within a wide range of possible outcomes[10] – and further beyond.

[Figure 2.9. Projected trends in GHG concentration across a range of previous studies]

[Figure 2.10. Projected temperature increase in the baseline scenario (relative to pre-industrial levels)]

17. Even abstracting from uncertainty and potential catastrophic events (see below), the impacts of temperature increases by 2°C or more would affect a wide range of human activities. “Market” impacts on agriculture production, energy consumption, or water resources would directly affect GDP, while “non market” impacts on health, biodiversity or migration would reduce human welfare more broadly (for details, see Jamet and Corfee-Morlot, 2009). In the current state of knowledge, the impact on GDP would be limited for a moderate rise in temperatures (below -3% of GDP for a +2.5°C increase), but could be much larger for the higher temperature increases projected beyond the 2050 horizon (Figure 2.11). Also, the impacts of climate change are projected to be unevenly distributed across countries. As a general rule, larger damages are expected in developing countries (see Section 6).

[Figure 2.11. Global impacts of climate change from various studies]

2.4 Risks and uncertainties

18. Wide economic and environmental uncertainties surround the expected damages from a business-as-usual scenario, with non-negligible risks of very large losses as a result. In fact, uncertainties compound at many levels including:

- *Future GHG emissions*, which in the baseline projection are driven by a number of hard-to-predict factors (*e.g.* demographic growth, productivity gains, fossil fuel prices and energy efficiency gains). In particular, labour productivity growth matters, considering both its historical variability and its important contribution to emissions growth (OECD, 2006a).[11] Other influential factors include assumptions made about current and future crude oil and natural gas reserves.[12]

- *The links between emissions, GHG concentration and global temperature*. In particular, the so-called climate sensitivity parameter, which measures the impact on temperature of a doubling of concentration, is very uncertain. A best estimate is 3°C (IPCC, 2007), but its 66% confidence interval is [2°C-4.5°C], and values above 5°C cannot be excluded (Meinshausen, 2006).

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[10] The 66% confidence intervals for global mean temperature increases are [1.3-3°C] and [2.2–5.8°C] in 2050 and 2100, respectively.

[11] The respective contributions of labour and capital to future economic growth are another, related influence on projected emissions. Insofar as capital and energy are complements rather substitutes in the production process, a larger contribution of capital would boost the growth of energy-intensive sectors and thereby increase emissions, ceteris paribus.

[12] This is because the exhaustion of these reserves is expected to induce a shift towards more carbon-intensive coal. However, crude oil and natural gas reserves are not yet explicitly modelled in the current version of the ENV-Linkages model. A reserve constraint is approximated through exogenous assumptions regarding crude oil supply in the oil-producing region of the model.

- *The physical impacts from a given rise in global temperature, especially for a large increase*. Existing estimates are likely to understate the effects of any global temperature increase, because they do not fully cover the non-market impacts, which are increasingly seen as likely to dominate (Watkiss and Downing, 2008, and Yohe, 2006). One offsetting factor is that damage estimates may not fully account for adaptation possibilities – *i.e.* defensive actions to lower the damages from climate change as it occurs, although these would also be costly. Furthermore, the severity of the effects is likely to become non linear as the increase in temperature crosses thresholds beyond which the melting of the Greenland and West Antarctic ice sheets becomes more likely, thereby leading to large sea level rise, and possibly altering global thermohaline circulation (*e.g.* the Gulf Stream). Such "extreme", largely irreversible events are seldom, if ever, explicitly factored into climate change damage cost estimates.

- *The valuation of physical impacts from climate change*. There are several methodological challenges facing economic analysis itself, regarding the valuation of physical impacts, the aggregation of regional effects into global impact estimates, and the valuation of distant damages (Jamet and Corfee-Morlot, 2009). In particular, the choice of a social discount rate is contentious and is a major influence on (the present value of) damage estimates (Table 2.3).[13]

[Table 2.3. The influence of the social discount rate on the estimated impacts of climate change]

19. In principle, the probability distribution of the social cost of carbon (SCC) – which measures the marginal impact of emissions, and is computed as the net present value over the life span of the impacts of one additional ton of carbon emitted in the atmosphere today – should reflect the overall uncertainty around the impacts of climate change, both environmental and economic. This is not exactly the case in practice because the vast majority of studies do not cover the risk of extreme events, but despite this downward bias, observed variance across existing SCC estimates is already quite large, and high values cannot be excluded (Figure 2.12).[14]

[Figure 2.12. Distribution of the social cost of carbon across a range of existing studies]

20. The magnitude of risks and uncertainties suggests that strong early action against climate change may partly be justified as an insurance policy against large unforeseen adverse climate developments. From this perspective, a tractable global climate policy objective may not be to balance (marginal) damages and costs, as standard economic theory would suggest, but rather to follow a risk-based approach and set a GHG concentration objective and a timing of action consistent with a "low" probability of "dangerous" climate change (see *e.g.* Stern, 2008). Such objectives are hard to determine, reflecting the limits of cost-benefit analysis in the presence of a low and unknown probability of "extreme" and irreversible events.[15]

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[13] See *e.g.* the recent controversy surrounding the assumption made in the Stern Review, where the social discount rate used was lower than in many other studies (Dasgupta, 2007; Nordhaus, 2007; Stern, 2007). Some have put forward this choice as an attempt at capturing indirectly extreme events (Weitzman, 2007a).

[14] This finding is consistent with the wide variance found by Weitzman (2001) in a survey of economists' opinions on the appropriate level of the social discount rate for public policy decisions.

[15] Climate irreversibilities and their uncertainty justify early action and stringent targets, so as to retain the possibility to cope with future climate change and its consequences (Arrow and Fisher, 1974; Henry, 1974). The unknown probability of "extreme" events further reinforces this "catastrophe insurance" motive for strong early action (Weitzman, 2007b). On the other hand, abatement costs are also widely uncertain, especially over longer horizons, and many of the investments made also entail irreversibilities (see

3. Cost-effective policy mixes to reduce GHG emissions

3.1 Mitigation policy assessment criteria

21. An ideal set of mitigation policy instrument(s) to minimise the overall economic cost of achieving any *given* emission reduction objective would meet four broad criteria:

- Equalise marginal abatement costs across all emission sources in order to fully exploit *existing* opportunities for low-cost GHG emission reductions. This requires the set of instruments to be cost-effective *per se* but also to be applied as widely as possible across countries, sectors and GHGs.

- Cope effectively with risks and uncertainties, *i.e.* the set of instruments should be responsive to risks and uncertainties surrounding both climate change and abatement costs.

- Foster an efficient level of innovation and deployment of emissions-reducing technologies in order to lower *future* marginal abatement costs.[16] For an environmental problem which is of great magnitude (in terms of mitigation costs) and has a long time horizon, such as climate change, this criterion plays an important role in assessing alternative policy instruments.

- Provide sufficient political incentives for adoption and compliance both across and within countries, which is needed for any of the above criteria to be met.

This section deals mainly with the first two criteria. The other two criteria will be addressed in Sections 4 and 6, respectively. The focus of the analysis is on identifying the range of instruments that will ultimately have to be featured in a least-cost mitigation policy mix.

3.2 The importance of wide use of price-based instruments

22. Abstracting from market failures other than the GHG externality, from policy distortions and from considerations of political feasibility, instruments that put a price on carbon would be expected to equalise marginal abatement costs across all individual emitters, thereby minimising the overall cost of achieving any emissions reduction objective. Emissions trading schemes (ETS) and taxes both meet this “static efficiency” property, although they differ in a number of respects, some of which will be discussed in the course of this paper (see also OECD, 2007a, and Duval, 2008).

Removing fossil fuel subsidies

23. Removing fossil fuel energy subsidies would be a first step towards raising carbon prices from the negative levels that currently prevail *de facto* in some countries, and would lower emission reduction costs more broadly. Such subsidies are also costly to public finances, distort resource allocation throughout the economy, and suffer from poor targeting where they are used as social policy devices, as in many non-OECD countries. They are estimated to be large and on the rise, even if recent policy action in some countries has offset some of the run-up in subsidisation caused by higher oil prices, but their exact magnitude is uncertain. According to the IEA (IEA, 2006a), consumer subsidies – mostly through price controls – reached about $US250 billion (or about 0.5% of world GDP) in 2005 (Figure 3.1), and rose

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Section 5). This would argue for postponing action so as to retain the option to take better informed and cheaper measures in the future, ceteris paribus (see Pindyck, 2007).

[16] Innovation could also help reduce the cost of adaptation.

further between 2005 and 2008.[17] Taking a broader definition, including producer subsidies (*e.g.* subsidies to energy-producing capital, tax incentives etc.) which are found both in OECD and non-OECD countries, (highly) preliminary work carried out under the auspices of the Global Subsidies Initiative suggests world fossil fuel subsidies might have been in the order of $US600 billion (or about 1.2% of world GDP) in 2006 (Global Subsidies Initiative, 2008).

[Figure 3.1. Energy subsidies in selected developing and middle-income countries, 2005]

Cost-effective scenarios with full coverage of GHG emission sources

24. Partly reflecting their cost-effectiveness, price-based instruments are spreading rapidly across the OECD. In particular, ETS are already in place or are about to be implemented in the European Union, Australia, Canada, New Zealand, Norway and some North-Eastern US States. They are under serious consideration in a growing number of geographical areas, including some Western and mid-Western US States, Japan and South Korea. Wide international use of price-based instruments was also implicitly promoted by the 1997 Kyoto Protocol, which allowed international mitigation commitments by a group of countries – referred to as Annex I countries[18] – to be met through international permit trading, and made provision for an instrument – the Clean Development Mechanism (CDM) – that could potentially expand the country coverage of the protocol worldwide.

25. Although highly stylised, scenarios in which a world price is put on GHG emissions are useful benchmarks, as they provide lower bound estimates of aggregate emission reduction costs.[19] Illustrative simulations are thus run with the ENV-Linkages model assuming that a world tax (or a set of harmonised domestic taxes) is implemented covering all countries, industries and GHGs. Ignoring transaction costs and uncertainties, such a world carbon tax policy is equivalent to an ETS with full permit auctioning. Concretely, four such cost-effective scenarios are considered (Figure 3.2):[20]

- Scenario A: Long-run CO_2 concentration is stabilised at 450 ppm, and overall GHG concentration at about 550 ppm CO_2eq, with modest overshooting of the target before 2050. The emission pathway associated with a target are expressed in terms of future concentrations may vary in terms of the peak year of emissions, the degree of temporary overshooting (if any) allowed relative to the concentration target, and the year and level at which concentrations are stabilised. Therefore, a concentration target gives more leeway to choose a pathway of emission

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[17] Although no comprehensive up-to-date data on energy subsidies are available, existing evidence points to large increases in recent years. For instance, oil subsidies in China, India and the Middle East have increased from about $US50 billion overall in 2005 to $US85 billion in 2007, and possibly up to $US100 billion in 2008 (IEA, 2008a).

[18] Annex I countries include most OECD member states and some countries from central and eastern Europe and the Commonwealth of Independent States that are undergoing the process of transition to a market economy (EITs).

[19] These scenarios are not exactly cost-effective since they do not include a removal of energy subsidies, the use of R&D policy instruments, or policies to reduce emissions from land use changes, all of which should be part of a cost-effective policy mix. Furthermore, given that the current version of ENV-Linkages does not incorporate GHG emissions from land use changes, this mitigation option is omitted in all policy scenarios.

[20] In all CO_2 concentration scenarios, the percentage reduction in CO_2 emissions with respect to baseline at any given date is also assumed to apply to non-CO_2 gases, expressed in CO_2 equivalent based on their global warming potential (GWP) over 100 years. Nonetheless, CO_2 and non-CO_2 gas concentrations are reported separately in what follows, partly because of the methodological issues surrounding the GWP of each gas, which can differ significantly depending on the length of the period considered.

reductions that softens the disruptive impact of mitigation on the economy, although it may introduce some confusion in the international policy debate since the link between emissions and concentrations entails uncertainties. Stabilisation of overall GHG concentration at about 550 ppm would be consistent with a temperature increase (relative to pre-industrial levels) not exceeding 3°C over the longer run (Figure 3.3).

- Scenario B: Long-run CO_2 concentration is stabilised at 450 ppm, and overall GHG concentration at about 550 ppm CO_2eq, allowing for significantly higher overshooting of the target. In order to reach the same long-term target as in scenario A, this scenario will require greater emission reductions after 2050. While scenarios A and B, as well as other emission pathways for the next decades, can be compatible with overall GHG concentration stabilisation at about 550 ppm CO_2eq sufficiently far in the future, GHG emissions will ultimately have to fall to about a fourth of their 2005 level if such a target is to be met.

- Scenario C: A 50% cut in total world GHG emissions (expressed in CO_2eq) in 2050 relative to 2005 levels, starting in 2013 and phased in gradually so that world emissions peak in 2020. This illustrative scenario may be seen as one possible version of the 50% cut in emissions in 2050 recently advocated or discussed by EU countries and the G8. It would be consistent with stabilisation of CO_2 concentration in the atmosphere below 450 ppm in the long run, and stabilisation of overall GHG concentration below 550 ppm CO_2eq, without any overshooting.[21]

- Scenario D: Long-run CO_2 concentration is stabilised at 550 ppm, and overall GHG concentration slightly above 650 ppm CO_2eq.

[Figure 3.2. GHG emissions in alternative cost-effective policy scenarios]

[Figure 3.3. Link between long-run GHG concentration and global temperature]

26. The economic costs of stabilising long-run CO_2 concentration at 450 ppm, and overall GHG concentration at about 550 ppm, with modest overshooting of the target are estimated to amount to 4 ¾ % of world GDP in 2050 (Table 3.1, "550 ppm-base" Scenario A).[22] Only small costs would be incurred as long as emission cuts with respect to baseline and marginal emission abatement costs remain modest, *i.e.* before 2025 in practice (Figure 3.4). However, GDP costs would rise exponentially over time, reflecting the combination of higher emission reductions with respect to baseline and rising marginal abatement costs. A higher degree of overshooting would reduce costs by postponing more of the emission cuts required until after 2050 (Table 3.1, Scenario B). However, this would come at the price of higher emission cuts and thereby higher costs after 2050, and the projected temperature increase would be both larger and faster, with increased risks of irreversible events.[23] By contrast, avoiding overshooting would reduce environmental risks but would raise the cost of action. For example, a 50% emission cut by 2050 with respect to 2005 levels (Scenario C) is found to reduce world GDP by about 9% in 2050 –lowering average

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[21] Stabilising concentration around this level beyond 2050 implies emission reductions of about 1% a year after 2050.

[22] While abatement also obviously generates benefits in terms of avoided climate change, such benefits are not captured in the conventional GDP estimates reported in this section.

[23] According to simulations using the MAGICC climate module, global temperature would rise by 1.9°C by 2070 in the "high" overshooting Scenario B, versus 1.6°C in the "modest" overshooting Scenario A.

annual world GDP growth projected over 2012-2050 from about 3½% to 3¼%, compared with the baseline scenario.[24]

[Table 3.1. Economic costs and environmental impacts of alternative cost-effective policy scenarios]

[Figure 3.4 Time profile of economic costs and GHG emissions price under the "550 ppm-base" GHG concentration scenario (Scenario A)]

27. Emission reduction costs are also estimated to vary disproportionately with the stringency of the target. Relatively modest mitigation objectives can be achieved at a low economic cost by taking advantage of the flexibility provided by substitutions across GHGs, fuels and industries, as illustrated by the decomposition of emission reductions in Table 3.2. For instance, the costs of stabilising CO_2 concentration at 550 ppm, and overall GHG concentration at about 650 ppm CO_2eq, without overshooting are estimated to be just 0.7 percentage point of GDP in 2050 (Table 3.1, Scenario D). As cheaper abatement opportunities are exhausted, the world economy faces sharply rising marginal abatement costs and any further abatement is achieved by reducing overall energy intensity, as in the "550 ppm-base" GHG concentration Scenario A (Table 3.2). The obvious counterpart to the smaller costs of less stringent targets is a higher environmental impact and risk (see Figure 3.3).

[Table 3.2. Decomposition of world GHG emission trends under alternative scenarios]

28. The above cost estimates are broadly in line with other studies (Box 2). Estimates also abstract from the potential cost savings from recycling revenues from GHG taxes or permit sales. Revenues are assumed to be redistributed to households through lump-sum transfers, while they could in fact be used to reduce other distortive taxes on labour or capital. Large fiscal revenues are expected in the more stringent emission reduction scenarios, reaching for instance 3% of GDP for the OECD and 6% of GDP for the world as a whole in 2050 in the "550 ppm base" scenario. Insofar as these revenues are used to lower taxes whose distortive effects on the supply of labour and/or capital *are greater* than those from GHG taxes or permit sales – not all of which are captured here since labour supply is fixed in ENV-Linkages, mitigation costs could fall below the above estimates.[25] By contrast, under a cap-and-trade scheme with grandfathered permits, costs could exceed the above estimates, as the latter do not factor in the possible detrimental effects of higher consumption prices – equivalent to those of a consumption tax hike – on labour supply.[26] These considerations underline the importance of using policy instruments which raise revenues when addressing climate change.

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[24] According to simulations using the MAGICC climate module, global temperature would rise by 1.5°C by 2070 in this scenario, versus 1.6°C in the "modest" overshooting Scenario A.

[25] See *e.g.* De Mooij (1999), Goulder (1995), Goulder *et al.* (1999), Pezzy and Park (1998). However, it might be argued that major tax distortions could still be at least partly eliminated independently from carbon tax revenues, *e.g.* by changing the tax structure (see Johanson *et al.* 2008).

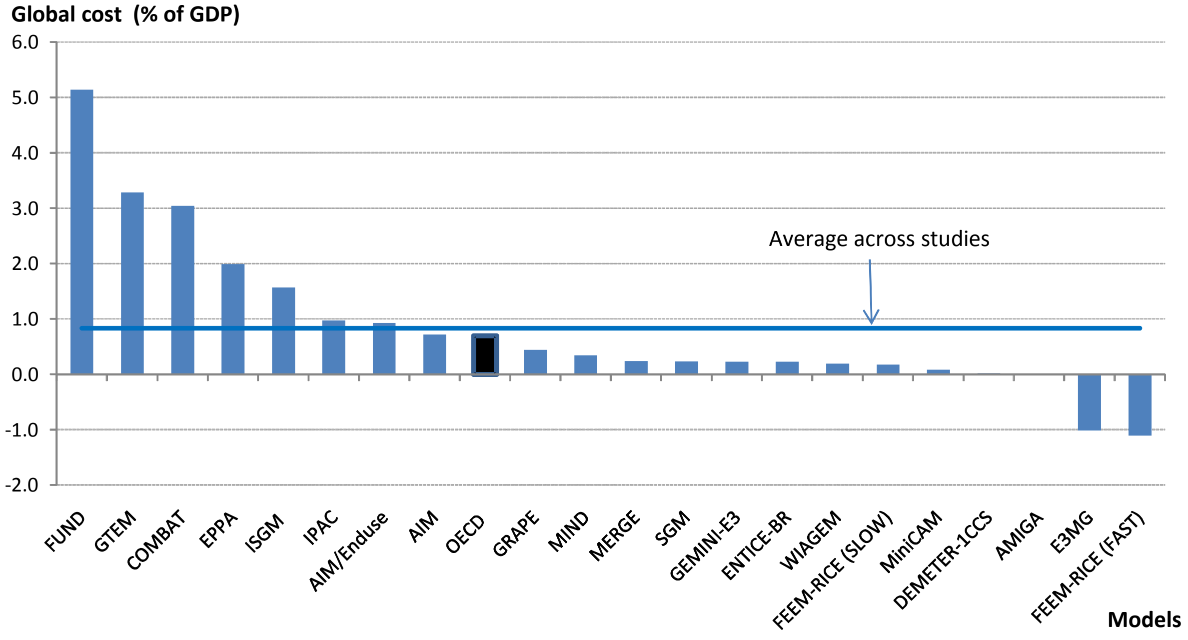
[26] In fact, based on recent OECD analysis of the employment effects of tax wedges (Bassanini and Duval, 2006), and assuming that carbon pricing would affect labour supply just like any other component of the labour tax wedge, a back-of-envelope calculation suggests the additional cost of carbon pricing – not captured here – in terms of reduced labour supply could reach as much as 1 percentage point of GDP for OECD countries in 2050. Raising and recycling revenues from carbon pricing could bring down this cost to zero or even possibly – if accompanied by an appropriate change in the tax structure – turn it into a gain.

Box 2. Comparison of ENV-Linkages estimates with other recent studies

Among the key parameter values and modelling assumptions that drive mitigation cost estimates, emissions growth in the baseline scenario is critical. For instance, achieving a 50% cut in all GHG emissions in 2050 with respect to 2005 levels is in fact equivalent to a reduction relative to baseline 2050 levels by over 70% (Figure 3.2). Such a large cut puts the world economy on the steeper part of the "global" marginal abatement cost curve, thereby raising average costs. Due to a number of recent developments, as well as changes in modeling framework and assumptions, some of the cost estimates of the more stringent mitigation scenarios reported in this paper are higher than those noted in the *OECD Environmental Outlook* (OECD, 2008b). This reflects a variety of factors, including *inter alia* higher projected world GDP and thereby higher underlying energy demand growth, upward revisions to fossil fuel price assumptions,[1] and delayed action – assumed to start in 2013 instead of 2008. Overall, however, these cost estimates fall approximately in the middle of the range of recent estimates. A comparison across 21 models of long-run 550 ppm CO_2 only concentration stabilisation scenarios yields average world GDP costs and marginal abatement costs (*i.e.* carbon prices) of about 1.4% and 43 (2 000 $US) in 2050, respectively (De la Chesnaye and Weyant, 2006).[2] This is roughly in line with the 0.7% of GDP and $US48 (2005 $US) reported in Table 3.1 for the 550 ppm CO_2 – corresponding to about 650 ppm CO_2eq all gases included – stabilisation scenario (Scenario D). All these and other (Edenhofer *et al.* 2006) cost estimates are presented in Figure 1 below. Furthermore, a comparison of the responsiveness of emissions to carbon prices points to slightly stronger sensitivity in ENV-Linkages than in other models, implying slightly lower marginal abatement costs (Hoogwijk *et al.* 2008). Finally, estimates of the cost of bringing world emissions down to their 2005 level by 2040 are in line with recent IMF simulations of such a scenario (IMF, 2008).[3]

Figure 1. Comparison across different models (and their corresponding baselines) of the cost of stabilising long-run CO_2 concentration at 550 ppm[1]

(2050, per cent of world GDP)



1. More precisely, the model comparison focuses on stabilising the radiative forcing of GHG emissions below an increase of 4.5 W/square-meter relative to pre-industrial level, which according to simulations with the MAGICC model roughly corresponds to a stabilisation of CO_2 concentration at 550ppm by 2150. Estimates (based on 12 studies) assume that least-cost policies are implemented. Negative numbers correspond to GDP gains from mitigation action. Such gains reflect the strong impact of mitigation policies on technological change – and thereby on GDP growth – embedded in some models. Differences between estimates arise from two sources, model properties and the baseline scenario.

Source: Energy Modelling Forum (EMF-21), Innovation Modelling Comparison Project and US Climate Change Science Program.

1. Compared with the *OECD Environmental Outlook*, higher projected fossil fuel prices have only limited effects on projected emissions growth in the baseline scenario. This is because the negative impact of higher fuel prices on energy demand is largely offset by the positive impact on emissions of the energy mix shift away from oil towards (more carbon-intensive) coal, reflecting the projected increase in the relative price of oil. However, higher fossil fuel prices imply that larger energy efficiency gains and larger changes in the energy mix are embedded in the baseline scenario of this paper, *i.e.* more of the cheap emission abatement opportunities are projected to be exploited by firms and households. This increases the marginal cost of emission cuts under policy action scenarios.
2. More precisely, the model comparison focuses on stabilising the radiative forcing of GHGs emissions below an increase of 4.5 W/square-meter relative to pre-industrial level, which according to simulations with the MAGICC model roughly corresponds to a stabilisation of CO_2 concentration at 550 ppm by 2150.
3. IMF estimates are derived from simulations using the G-Cubed model (McKibbin and Wilcoxen, 1998).

29. Estimated mitigation costs would be reduced by taking account of: *i)* the possible removal of energy subsidies, which for lack of comprehensive data could not be explored here (for past OECD quantitative analysis focusing on Annex I countries only, see OECD, 1999); *ii)* the possible emergence of major new low-carbon (so-called “backstop”) technologies in the future, such as carbon capture and storage on a large scale, which are not featured in ENV-Linkages but are discussed extensively in Section 4; *iii)* the existence of forestry mitigation options, as emissions and sequestration in this area are not covered by the modelling, and thereby are not subject to carbon pricing in the policy simulations. In line with most other comparable exercises, the baseline and policy scenarios considered here all assume that forest stocks will deplete gradually in developing regions but continue to rise in industrialised countries over this century, leading to a drop of net emissions from deforestation to zero by 2080. There is some consensus that forestry could significantly contribute to a low-cost global mitigation portfolio, although there is large uncertainty about its mitigation potential from avoided deforestation, forest management and afforestation (Nabuurs *et al.* 2007).[27]

The implications of incomplete coverage for the cost of mitigation policies

30. While the previous discussion suggests that standard model simulations may over-estimate the mitigation costs associated with cost-effective policies, post-2012 policies could also turn out to be much costlier than the estimates considered thus far. General equilibrium model cost estimates typically underestimate the transaction and resource reallocation costs that are likely to be incurred in practice. More importantly, it is unclear whether all countries, industries, diffuse emission sources and gases could be covered by carbon pricing, at least initially. By restricting the range of low-cost abatement options, incomplete coverage increases the overall cost of achieving any given world emission reduction, and could make it impossible to reach the most stringent emission or concentration targets.

31. The losses from limited country coverage can be illustrated through two simple exercises. First, it appears that even moderately stringent concentration targets would be impossible to meet if Annex I countries acted alone. For instance, stabilising overall GHG concentration at about 650 ppm CO_2eq would require a reduction in world GHG emissions by over 23 Gt by 2050. Such a reduction could not be achieved by Annex I countries alone since their emissions would have to become negative. Second, GHG concentration targets below 750 ppm CO_2eq are also found to be virtually out of reach if Annex I countries act alone, as they would imply very high costs. For instance, while a 750 ppm CO_2eq target might *a priori* be achievable, it is so large that it overstretches the limits of the ENV-Linkages model in practice, implying a carbon price that spirals out of control by mid-century. An emissions pathway consistent with a lax 800 ppm CO_2eq target is found to be achievable through action in Annex I countries alone – at least up to 2050 – at a cost of about 2% of their combined GDP in 2050.

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[27] Emissions from land uses and land use changes may currently account for about 16% of world GHG emissions. Estimates of the world mitigation potential at carbon prices less than $US100 per ton of CO_2 in 2030 range from 0.7 Gt of CO_2 annually in some integrated assessment models to 13.8 Gt. (or about 22% of projected GHG emissions in the baseline scenario) in some forest sector models (Nabuurs et al. 2007).

32. Likewise, reaching a given target by restricting emission reductions to CO_2 only (without covering non-CO_2 gases), or exempting energy-intensive industries from policy action would raise costs relative to the cost-effective scenarios. For instance, achieving the same amount of GHG emission reductions (in CO_2eq terms) as in the "550 ppm-base" scenario through CO_2 emission cuts only is estimated to raise costs in 2050 from 5% to 9% of world GDP (Table 3.3). This illustrates the large low-cost mitigation potential of non-CO_2 gases, especially for less stringent mitigation objectives.[28] Similarly, exempting energy-intensive industries (chemicals, metallurgic, other metal, iron and steel industry, paper, and mining products) increases the cost of the "550 ppm-base" scenario from 5% to 7½% of world GDP.

[Table 3.3. Economic costs from stabilising overall GHG concentration below 550 ppm with incomplete coverage of industries or GHGs]

Carbon leakage and competitiveness

33. Smaller country coalitions entail larger mitigation costs in part because they are ineffective from an environmental perspective, as emission cuts in participating countries may be partly offset by increases elsewhere, a phenomenon often referred to as "carbon leakage". Carbon leakage may arise though two main channels: *i)* the competitiveness channel, as carbon-intensive industries in participating countries lose market shares to their foreign competitors and/or relocate capital in non-participating countries; *ii)* the fossil fuel price channel, as emission reduction efforts in participating countries lower world demand for fossil fuels, thereby inducing a price decline that triggers greater fossil fuel use and higher GHG emissions in non-participating countries.

34. Simulation analysis to illustrate the issue related to leakage is undertaken by means of examples where, in many cases, the European Union is acting alone. The purpose is not to judge the merits of individual action *per se* – which may bring important political impetus to wider action – but only to illustrate general issues through concrete examples. In an illustrative scenario where the European Union cuts emissions unilaterally by 50% in 2050 (relative to 2005 emission levels), leakage is found to be sizeable, amounting to 20% of the reduction achieved by the European Union in 2050 (Table 3.4).[29] However, if a similar emission reduction (2.9 Gt, or about 3.9% of projected 2050 world emissions) is spread across all Annex I countries, carbon leakage becomes negligible, falling to less than 2%.[30] This reflects both the larger country coverage and the fall in marginal abatement costs in participating countries. Moreover, it is not only the magnitude but also the nature of leakage that changes with the size of the coalition. The wider the country coverage, the smaller the market share losses affecting energy-intensive industries in participating countries (the first leakage channel), but the larger the impact of policy action on international fossil fuel prices (the second leakage channel). Finally, the leakage rate also declines substantially when non-CO_2 gases are covered. For instance, if the European Union were to cut only CO_2 rather than all GHG emissions by 50% in 2050, the leakage rate is estimated to rise from about 20% to 29%.[31] This reflects both lower marginal abatement costs when all GHGs are included, and the fact that

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[28] In the current state of technology, the marginal abatement costs of non-CO_2 gases are initially lower than those of CO_2, but their marginal abatement cost curve ultimately becomes steeper. As a result, their mitigation potential is exhausted more rapidly, and the bulk of any further emission reductions is achieved by cutting CO_2 emissions.

[29] This means that for each Gt cut by the European Union in this illustrative scenario, emissions in the rest of the world rise by 0.2 Gt, so that the net decline in world emissions is 0.8 Gt.

[30] In fact leakage would already fall to a very low level (below 2.5%) if the emissions reduction was spread across Annex I countries excluding the United States.

[31] This actually understates the "true" increase in leakage, since a 50% CO_2 emission cut scenario is in fact less stringent than a 50% GHG emission cut scenario.

incorporating non-CO_2 gases shifts some of the burden of emission reductions onto sectors, such as agriculture, that have only marginal influence on world fossil fuels markets.

[Table 3.4. Impact of country and GHGs coverage on carbon leakage rates]

35. The magnitude of carbon leakage is driven by a number of factors, not least the degree of product differentiation across the energy-intensive goods produced by different countries (as measured by the value of international trade substitution elasticities) and, even more importantly, the elasticity of carbon supply at the world level (Burniaux and Oliveira Martins, 2000). Intuitively, the less elastic the supply of carbon, the more difficult it is to reduce emissions, and the larger the amount of leakage in case of unilateral action. The relative values of supply elasticities for different fossil fuels also matter, as they imply different evolutions of their relative prices in response to a carbon constraint, which may amplify or instead mitigate leakage.[32] Thus the behaviour of carbon producers at the world level – an issue tackled in Section 6 – is critical in determining the amount of leakage.

36. The fact that carbon leakage may become very small in a large coalition does not imply that output effects for energy-intensive industries in domestic and international markets are negligible. For instance, in a global carbon price scenario where world emissions are reduced by 50% relative to the 2005 level by 2050, the output of energy-intensive industries is projected to drop by 14% at the world level relative to the baseline, even though there is by definition no leakage. Furthermore, this world output loss would be unequally distributed across regions. In particular, European energy-intensive industries would be less affected than their less energy-efficient foreign competitors, not least from developing countries (Table 3.5, Panel A). The overall size and unequal distribution of the output loss of energy-intensive industries hint at possible political obstacles to including them in a wide international agreement.

[Table 3.5. Impact of alternative policy scenarios on the output of energy-intensive industries in 2050]

Policy responses to incomplete coverage and competitiveness concerns

Countervailing duties

37. One policy response to leakage that has received growing attention lately is to impose countervailing tariffs on imports from non-participating countries, based on their carbon content (see *e.g.* Stiglitz, 2006). In principle, countries that take action against climate change could apply to each ton of carbon used (directly, and ideally indirectly *via* inputs) in the production of imported goods a border-tax adjustment equal to the local carbon price, so as to “level the playing field” in their goods and services markets.[33] Model simulations suggest that countervailing tariffs would indeed reduce the risk of carbon leakage for small coalitions of acting countries. For instance, they are estimated to reduce leakage significantly in a scenario where the European Union unilaterally cuts GHG emissions by 50% (Table 3.6).[34] This confirms the importance of the competitiveness channel when only few of the main

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[32] For instance, if the supply of coal is assumed to be more elastic than that of crude oil, coal becomes relatively more expensive in world international markets if a carbon constraint is imposed. This induces a substitution away from more carbon-intensive coal in non-participating countries, and therefore a decline in emissions that amounts to negative carbon leakage, ceteris paribus.

[33] In principle, the import tariff per ton of carbon could be set above the local carbon price and even at a level high enough to reduce leakage drastically. However, such a tariff would come closer to an outright import tariff than to a countervailing duty. Therefore, this possibility is not explored here.

[34] Model simulations in Table 3.6 assume countervailing tariffs apply fully to the direct but only partly – *i.e.* to the electricity input only – to the indirect carbon content of imports.

emitters take action.[35] While addressing leakage, countervailing tariffs may not curb the output losses incurred by energy-intensive industries located in the European Union, which are found here to be slightly increased (relative to the baseline scenario) from 6% to 7% (Table 3.5, Panel B). Several factors contribute to offset the positive output effects of the market share gains associated with countervailing tariffs, including *inter alia* the impact of costlier (energy-intensive) imported inputs on the production costs of EU energy-intensive industries – which is somewhat larger than for other sectors - a slight increase in the carbon price required to meet the EU emission target, and the fact that energy-intensive industries still face some competitiveness losses as a result of the indirect impact of the European carbon price on the price of their non-energy inputs.

38. The need for, and the effectiveness of, countervailing duties declines rapidly with the size of the coalition, as leakage rates are much lower and tariffs address a smaller share of remaining leakage. For instance, when border tax adjustments are applied at the level of Annex I countries – assuming a targeted reduction in their emissions by 50% in 2050 (about 14 Gt, or 19% of projected 2050 world emissions), the leakage rate only falls from 9% to 5%. This reflects the greater importance of the fossil fuel price channel – which countervailing duties do not address – when country participation is larger.

39. Despite some effectiveness under small coalitions, countervailing import tariffs raise a number of important concerns. They are found to raise the costs of mitigation in participating countries,[36] but they also entail economic losses for non-participating countries, compared with a situation where no such tariffs are imposed. For instance, in a scenario where Annex I countries cut their emissions unilaterally by 50% by 2050, imposing a countervailing duty achieves a small additional world emissions reduction of about 0.6 Gt (or about 0.8% of projected 2050 world emissions) at a cost of about 1% of world GDP (1.7% instead of 0.8%, see Table 3.6). Partly reflecting the losses incurred by affected trade partners, countervailing tariffs might also trigger retaliation rather than greater participation in mitigation action. Furthermore, the practical difficulties in calculating a tariff based on the carbon content of imports from different origins would likely entail large administrative costs. At a minimum, it seems little plausible that the indirect carbon content of imported goods could be taken into account. Also, it is not certain that the current World Trade Organisation (WTO) legal framework provides grounds for such measures (OECD, 2006b; Perez, 2007). In order to partly meet some of these concerns, a generalised system of predictable, permanently applied environmental tariffs has been advocated (Perez, 2007). While such a system might prevent some escalation of trade barriers, it would still entail significant economic and administrative costs to both participating and non-participating countries, however.

[Table 3.6. Effects of countervailing import tariffs on carbon leakage and mitigation costs]

Sector-wide approaches

40. International sector-wide approaches offer another, more collaborative option to reduce carbon leakage and address competitiveness concerns. In their strongest form, they would consist of emission-reduction commitments covering all major world emitters in a given industry, along with permit trading among participants.[37] Insofar as leakage risks are concentrated in a few large energy-intensive sectors dominated by a small number of participants (*e.g.* some types of ceramic, aluminium, iron and steel, pulp

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[35] Another, less important factor is the existence of negative leakages (see above).

[36] This finding is not entirely obvious in theory. On the one hand, a countervailing duty raises the price of imported goods, which comes at a cost to local consumers. On the other hand, it reduces the distortion arising from the indirect impact of the carbon price on domestic goods production and consumption when no countervailing tariff is applied.

[37] Alternatively, a sectoral carbon tax could be applied at the world level.

and paper), international sector-wide agreements could be a useful complement to an agreement on national emission targets involving only some countries. Measures may be needed to provide financial and/or technological support to developing countries to ensure sufficient incentives for their participation in such sectoral emission reductions. Apart from large energy-intensive sectors, international shipping and air transport are two industries where a sectoral approach may be useful, due to their transnational character. However, like countervailing tariffs or any other type of partial (as opposed to global) mitigation measure, international sector-wide agreements fail to address the fossil-fuel price channel of leakage, at least if they cover only a few selected energy-intensive industries. Also, they can become costly if sector-level and economy-wide permit markets are not linked through fungible permits, as cheap abatement opportunities through trading *across* sectors are then lost. Finally, sectoral approaches can come in many different forms, most of which might be significantly less effective than sectoral permit trading, as they do not involve binding sectoral emission caps (see *e.g.* Box 1 in Duval, 2008).

41. As an illustration of the effects of international sector-wide agreements on emissions and mitigation costs, a model simulation is run where an EU-ETS achieving a 50% reduction in EU emissions by 2050 is supplemented with a worldwide ETS specific to energy-intensive industries also implying a 50% emissions cut by 2050 (Table 3.7). To avoid double taxation, the two systems are assumed to be either segmented – with different permit prices on each market – or integrated, in which case permit fungibility ensures there is only one single carbon price. Compared with a scenario where the European Union acts alone, the total emissions reduction achieved at the world level is found to be much higher. In this illustrative example, permit prices are higher in the sector-wide scheme than in the EU-ETS under segmented markets, reflecting *inter alia* the particular combination of emission reduction targets and the higher baseline growth in GHG emissions outside the European Union. As a result, the sector-wide scheme increases the costs incurred by the European Union, as their energy-intensive industries become subject to the tighter international emissions constraint. This is particularly the case if both markets are fully integrated, although such integration is beneficial overall as it reduces *aggregate* costs. The reverse holds for non-EU countries, as their energy-intensive industries gain from lower permit prices in the integrated market. However, despite higher EU costs in this particular example, the much larger reduction in world emissions is delivered at a significantly lower cost than if the European Union tried to achieve it alone. This can be inferred from the elasticity of the world GDP loss to the reduction in world emissions, which is significantly lower in scenarios featuring international sector-wide agreements than when the European Union is assumed to act alone. Finally, compared with a scenario where the European Union acts alone, the international sector-wide agreement spreads the output losses incurred by energy-intensive industries more evenly between the European Union and the rest of the world (Table 3.5, Panel B).

[Table 3.7. Effects of international sector-wide agreements on emissions and mitigation costs]

Domestic permit allocation rules

42. Finally, permit allocation rules have also been used to address international competitiveness concerns, *e.g.* by grandfathering permits to energy-intensive industries exposed to international competition. However, this approach does little to alleviate deterioration in international price competitiveness, since marginal emission abatement costs are ultimately passed onto consumers – at least in reasonably competitive markets – irrespective of permit allocation rules. Nonetheless, insofar as firms have to maintain their activity in order to be eligible to free permits, grandfathering may still soften the output and employment effects of mitigation policies by implicitly subsidising the continuation of otherwise unprofitable activities.[38] This comes at a cost to society, however, due both to the financing of the implicit output subsidy itself, and the fact that larger and costlier cuts then have to be imposed on other parts of the economy in order to reach a given emissions reduction objective. Finally, expectations that

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[38] This may be the case insofar as the continuation of such activities is required for eligibility to free permits.

permits will continue to be grandfathered in the future might undermine recipients' incentives to lower their own emissions, as such cuts reduce their future expected entitlements. At a minimum, this suggests that policy makers should announce in advance that grandfathering will be gradually phased out, as has been the case for instance under the EU-ETS.[39]

3.3 The role of other instruments in the policy mix

43. While price-based instruments form a key building block of any cost-effective mitigation policy framework, they are unlikely to fully exhaust the cheaper abatement opportunities, for at least three reasons that are discussed in this section. First, at the current juncture, it is unclear whether and over what time-frame price-based instruments will achieve global coverage. Second, as discussed below, a number of market imperfections can undermine the responsiveness of individual emitters to price signals. For both motives, there seems to be a case for targeted use of complementary instruments at the domestic level, including command-and-control (CAC) approaches, information instruments and possibly voluntary approaches. By contrast, there seems to be only limited room for subsidies to emission cuts (*e.g.* biofuel subsidies) in a cost-effective policy package. Third, existing policy interventions by many countries in the area of energy and trade offset and/or distort the incentive effects of price-based instruments. Policy reforms in these areas would therefore enhance the cost-effectiveness of mitigation policies. There is also a case for public support to R&D in the broad policy mix, a topic discussed along with other technology-related issues in Section 4.

Standards and information instruments

44. CAC approaches denote regulatory instruments that dictate abatement decisions and fall in two broad categories: *i)* technology standards, which impose on emitters the use of specific abatement technologies; and, *ii)* performance standards, which set specific environmental targets to be met (*e.g.* a certain amount of emissions per unit of output) without mandating particular technologies. Aside from being an option for curbing emissions that would escape price-based instruments,[40] standards can also contribute to address various market imperfections:

- *Imperfect emission monitoring:* when emissions are difficult to observe (*e.g.* fugitive emissions from pipelines, methane from agriculture), technology standards can enhance the cost-effectiveness of mitigation policy. Performance standards are useless in this context since, like price-based instruments, they require adequate emissions monitoring (see *e.g.* Montero, 2005).[41]

- *Enforcement problems:* the lack of institutional – including monitoring – capability may impede the proper functioning of market-based incentives in lower-income countries, while technology standards may be comparatively easier to implement and track (Blackman and Harrington, 2000; Russell and Vaughan, 2003).

- *Asymmetric information problems* have been identified in energy service markets (Sorrell *et al.* 2000, IEA, 2007b). For instance, in the housing market, landlords have better information than

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[39] See Box 6 in Section 6.

[40] For instance, they could be used if some firms, sectors or countries are not covered by an agreement, but, in order to justify their use in this context, standards should target different emission sources from those covered by taxes or permits, and their implicit (shadow) price should not exceed the carbon price.

[41] In such situations, the effectiveness of technology standards can be further enhanced by combining them with market incentives whose effects can be measured, when these are available (see *e.g.* Fullerton and West, 2000).

tenants concerning thermic isolation of buildings but have little incentive to install the most energy-efficient equipment as they do not pay the energy bill. The lack of information about energy-efficiency performance of electrical appliances and light bulbs may also prevent households from optimising energy consumption. Such market failures may be directly addressed through information instruments like public disclosure requirements or eco-labeling. However, when these are costly or insufficient, standards can be justified, and they have been found to yield sizeable welfare gains.[42]

- *Imperfect competition:* Insofar as state enterprises respond little to price signals – due *e.g.* to objectives other than profit-maximisation and soft budget constraints – and cannot be privatised, forcing diffusion of best practices through standards may help raise emissions abatement towards levels that would be undertaken by competitive firms (Sterner, 2003).

45. Nevertheless, standards should be used with parsimony, notably because they may involve three types of risks of policy failure:

- Some of the market failures put forward to justify the use of standards may diminish when carbon is priced. For example, hidden transaction costs and the cost of scrapping existing capital may explain why apparently profitable energy efficiency improvements are in fact not carried out by firms and households, but pricing carbon could provide incentives to meet these costs.[43] As regards information asymmetry for instance, the higher the price of emissions and energy bills, the stronger the incentives for tenants and buyers to find information about the energy efficiency of alternative equipments, and for landlords and sellers to reveal this information.

- In the absence of detailed information about the individual abatement costs implied by the compliance with standards, it is challenging for the regulator to determine the appropriate degree of stringency of the standard, with the risk that they will be either too stringent or too lax. It is also difficult to target standards to meet differences in abatement costs across different categories of firms or consumers (see *e.g.* Bohm and Russell, 1985). This is especially the case with technology standards, which unlike performance standards do not give firms the freedom to choose among alternative abatement options.

- Standards can be subject to “regulatory capture” by lobbies, which gradually undermines economic efficiency, *e.g.* through the establishment of *de facto* entry barriers in regulated industries. Transparent adjustment criteria can help in that regard, such as those embedded for instance in Japan’s “Top Runner” programme, under which today’s most energy-efficient firms serve as a basis for setting tomorrow’s standards (see *e.g.* IEA, 2003).

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42. For instance, Levine *et al.* (1994) and Eto *et al.* (1994) find large net private benefits (without factoring in the environmental gains) from US appliance standards and lighting programmes, respectively.

43. More broadly, economists have often been skeptical with respect to so-called “no regret” policies, *i.e.* profitable abatement opportunities that may remain unseized by rational firms and households in the absence of policy intervention. For instance, Enkvist (2007) argues that a significant amount of GHG emissions abatement at the world level could be undertaken at a net financial benefit. For some theoretical support for the view that regulation can help (non-optimising) firms reap costless pollution abatement opportunities, see Porter and van der Linde (1995). For a skeptical economist view, see Palmer *et al.* (1995).

Voluntary agreements

46. Voluntary agreements (VAs) between governments and one or more private parties have long been used in the environmental policy field in some OECD countries. By contributing to information gathering and diffusion of best practice, they might help address information problems in a way similar to communication instruments. Furthermore, they may pave the way for the adoption of more stringent policies at a later stage, especially if they include measurable emission targets below a well-defined baseline scenario, monitoring and reporting requirements by an independent party, and compliance incentives such as penalties (Hanks, 2002; OECD, 2003). However, the impact of VAs on emissions and their cost-effectiveness are hard to assess, given that more energy-efficient firms have larger incentives to enter into VAs (so-called selection bias) and the difficulty of determining emission trends in the absence of the VA. In this regard, firms may use their informational advantage over policy makers to set emission targets equal to those that would have been achieved anyway, especially if this advantage cannot be reduced significantly through effective verification process. Even when this is not the case, there is no reason to expect any emission cuts to be achieved at least cost, since the targets assigned to different firms are unlikely to reflect divergences in their marginal abatement costs.

Subsidies to emission cuts

47. Subsidies to emission cuts have gained prominence across the OECD in recent years, especially as government support for biofuel production rose drastically. Under unchanged policies, such support could reach about US$25 billion per year on aggregate in the European Union, the United States and Canada over 2013-2017 (OECD, 2008c).[44,45] Available evidence suggests that the implicit costs of ethanol subsidies typically exceed $US300 per ton of CO_2 avoided (Table 3.8), sometimes reaching much higher levels. For example, a recent OECD study estimates that support policies to current – so-called “first-generation” – biofuels in the European Union, the United States and Canada could come at a cost equivalent of about $US960-$US1 700 per ton of CO_2 saved (OECD, 2008d).[46] Biodiesel subsidies are lower, but still far above average estimates of the (marginal) social cost of CO_2 or the CO_2 price levels currently prevailing in the EU-ETS.[47] Furthermore, such estimates do not account for any indirect effects of biofuel subsidies on emissions from land use changes – not least deforestation – that may result from induced pressures on land and food prices, and they ignore the additional social cost from other potential negative environmental externalities.[48] Therefore, there seems to be a strong case for scaling down biofuel subsidies. More broadly, even under low implicit costs, subsidising emission cuts would not be a cost-effective abatement policy, because unlike pricing carbon it needs to be financed through higher taxes. It might sometimes be justified on other grounds, however, as discussed in Section 3.4 below.

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[44] This figure does not take into account mandatory blending requirements. While these boost biofuel consumption, the implicit support they provide to domestic output is not straightforward and depends inter alia on the comparative costs of local biofuels, fossil fuels and imported biofuels – the latter being typically inflated by tariff and non-tariff barriers, see below.

[45] Government support amounting to about $US1 billion also exists in Brazil, but ethanol from sugarcane grown in this country is currently by far the cheapest biofuel produced (OECD Roundtable on Sustainable Development, 2007).

[46] As a matter of comparison, the price of CO_2 in the EU-ETS has been fluctuating between about $US30 and $US45 during the first half of 2008.

[47] For instance, the implicit subsidy from the excise tax exemption for biodiesel in high-tax European countries is equivalent to several thousand euros per car, on the basis of average kilometres driven over a car’s lifetime (Steenblik, 2007).

[48] These include soil acidification, toxicity of agricultural pesticides and biodiversity loss.

[Table 3.8. Subsidies to ethanol and biodiesel per ton of CO_2 equivalent avoided in selected OECD countries, lower-bound estimates, 2006]

International trade policy distortions

48. The cost-effectiveness of climate policy can also be enhanced by reforming a number of policies that either increase GHG emissions or distort the incentives – and, therefore, raise the cost – associated with mitigation instruments. Apart from already-mentioned energy subsidies, tariff and non-tariff barriers to imports of emission-reducing goods and services also unnecessarily hamper the effectiveness of abatement policies. Applied most-favoured nation (MFN) tariffs on bioethanol exceed 20% on an *ad-valorem* basis in many OECD economies, including Australia, the European Union and the United States (Table 3.9).[49] As a result, only about 10% of the world's ethanol consumption is currently met through international trade (Walter *et al.* 2007), even though biofuels produced in tropical regions from sugarcane and palm oil have a considerable comparative advantage over those derived from agricultural crops in temperate zones, owing both to their intensity in cheaper labour and much higher physical yields (Girard and Fallot, 2006). In this context, removing trade barriers and scaling down production subsidies would enable OECD countries to achieve any cut in transport emissions through the use of biofuels at a much lower cost, especially if ambitious medium-term biofuel targets were to be maintained.

[Table 3.9. Applied tariffs on undenatured ethyl alcohol in selected countries, 2007]

49. Existing barriers to imports of energy-efficient electrical appliances (*e.g.* low-energy light-bulbs, refrigerators, air conditioners, clothes washers, water heaters, computer etc.) and renewable-energy products and technologies (*e.g.* solar photovoltaic systems, wind turbines and pump etc.) offer other examples of trade protection hampering the cost-effectiveness of mitigation policy and/or leading to increased emissions. Applied tariffs on such goods are typically low across the OECD but are at or above 15% on an *ad-valorem* basis in many developing countries, with bound tariffs sometimes reaching much higher levels (Steenblik, 2005; Steenblik *et al.* 2006).[50] Overall, there seems to be room both for lower tariffs in many non-OECD countries and for lower non-tariff barriers – at least *via* greater harmonisation of criteria and tests for energy-efficiency requirements – in their OECD counterparts.[51]

3.4 Interactions across policy instruments

50. The wide range of available GHG emissions-reducing policies and possible interactions among them raises the issue of whether and how they can be integrated into a coherent framework. A basic principle is that complementary instruments should always address different market imperfections and/or affect different target groups (Sorrell, 2002; Sorrell and Sijm, 2003; OECD, 2007c). When this principle is not met, policy instruments overlap, leading to higher mitigation costs due to higher administrative costs

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[49] Tariffs on biodiesel are much lower, varying roughly between 0 and 7%, but can be high in developing countries (Steenblik, 2006).

[50] In the case of electrical appliances, standards are also applied in virtually all OECD countries, and increasingly so in non-OECD ones. While these may be partly justified to address market imperfections that limit the penetration of energy-efficient technologies, they can act as non-tariff trade barriers, all the more so as energy-performance metrics and testing criteria vary widely across countries (Steenblik *et al.* 2006). For recent analysis of existing trade barriers in the areas of electricity supply, buildings and industry, see also OECD (2007b).

[51] An opportunity to achieve such an outcome at the multilateral level currently exists in the form of the negotiating mandate given to members of the World Trade Organisation (WTO) in Doha in November, 2001, which explicitly covers "the reduction or, as appropriate, elimination of tariff and non-tariff barriers to environmental goods and services".

and, in many cases, to the loss of least-cost abatement options available to firms. Also, the environmental effectiveness of mitigation policy may be undermined in some cases.[52]

51. One prominent illustration of damaging policy overlap is when price-based instruments are supplemented with other policies to address *only* the climate change externality, *e.g.* transport fuel taxes, energy efficiency standards, or renewable targets for electricity suppliers (for greater details and other examples of policy overlaps, see Duval, 2008, and Sorrell and Sijm, 2003). Under permit-trading, any of these additional policies puts downward pressure on the permit price and thereby encourages higher emissions, ultimately leaving unchanged overall emissions while inducing unnecessary administrative costs and, in some cases, preventing marginal abatement cost equalisation across emitters.[53] Under a carbon tax, overall emissions are reduced, but raising the carbon tax rate would achieve the same result at a lower cost. Therefore, insofar as a credible price is put on carbon, these policies can only be justified by other purposes. For instance, a transport fuel tax should be maintained only insofar as it addresses other externalities (*e.g.* congestion and local pollution), applies to other emission sources, or as a way to raise general tax revenues. Likewise, any renewable or biofuel targets should address well-defined externalities in the areas of innovation and/or energy security, although these seem rather limited in the case of first-generation biofuels.[54] Against this background, in the presence of emission trading schemes, the case for the additional renewable energy targets endorsed by governments in the European Union, Australia or New Zealand remains unclear. The same holds for the energy efficiency and biofuel targets adopted by the European Union in 2007.[55]

4. Lowering the cost of achieving GHG targets through technology policies

4.1. The gains from technological change

52. A cost-effective approach to addressing climate change should not only tend towards marginal abatement cost equalisation across *current* economic activities, but also help shape future economic activities so that marginal abatement costs will be lowered. This can be achieved through efficient R&D, innovation and diffusion of GHG emissions-reducing technologies. Technological progress will be needed both to:

- *Bring down the cost of available or emerging emission-reducing technologies.* In most of the key emitting economic activities, emerging low-carbon technologies are significantly costlier than the

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[52] For instance, when firms are covered by two different permit-trading schemes, there can be a risk of counting the same emissions or the same emission reductions twice, two issues called respectively “double coverage” and “double crediting”. If firms can earn allowances through specific energy-efficiency improvements or renewable energy projects they would have undertaken anyway, there will be double crediting without any compensating double coverage, and the emissions cap will be breached. Another example is when emissions are covered both by an economy-wide tradeable permit system and by an international cap-and-trade scheme at the sectoral level. In such cases, permit fungibility between schemes, along with double crediting of emission reductions for those emitters that are covered twice, is required both to ensure that all emitters face similar emission prices and to preserve environmental integrity.

[53] This holds unless the policy is so stringent that the permit price falls to zero, in which case it is the cap-and-trade scheme that becomes redundant.

[54] Indeed, first-generation biofuels rely on already mature technologies, and are expected to have only minor effects on energy security given their limited potential for replacing traditional petroleum products in the long run (see *e.g.* IEA, 2006b).

[55] These 2020 EU targets include a 20% improvement in energy efficiency, a 20% share of renewable in overall EU energy consumption, and a 10% biofuel component in vehicle fuel. They come on top of a 20% overall emission reduction objective.

fossil-fuel based technologies they could potentially displace, and would remain so in the short term even in the presence of a moderate carbon price (IEA, 2008b). For instance, Anderson (2006) estimates that the average cost of abating emissions through a "representative" portfolio of low-carbon technologies in electricity, industry, transport and buildings exceeded US$80 per ton of CO_2 in 2005, reaching over $US140 in non-electricity sectors.[56]

- *Expand the pool of available technologies and their mitigation potential.* In the current state of knowledge, the scope and scale of low-carbon technologies envisaged for the future might be limited (Anderson, 2006). Most are of a specific rather than general purpose nature, with their potential use being restricted to a narrow range of economic activities (*e.g.* wind, solar and nuclear energy to power generation, hydrogen and bio-fuels to transport etc.). Furthermore, there remain constraints (*e.g.* related to energy storage possibilities) on the extent to which emissions from any industry could be abated through the use of one single mitigating option. For these reasons, a broad portfolio of technological options will probably have to be involved in mitigating climate change (see *e.g.* Pacala and Socolow, 2004).[57]

53. Speeding up the emergence and deployment of low-carbon technologies will ultimately require increases in – and reallocation of – the financial resources channelled into energy-related R&D. Average public energy-related R&D expenditure across the OECD has declined dramatically since its early-1980s peak (Figure 4.1, Panel A), although there is wide variance in levels of spending across countries (Figure 4.1, Panel B). While no comprehensive data exist on private sector energy-related R&D, available evidence suggests that its share in overall private R&D spending is low compared with other sectors and decreasing over the past two decades (OECD Roundtable on Sustainable Development, 2006; IEA, 2008b).[58] Past declines in public and private R&D spending have been partly attributed to the sustained fall in oil prices following the second oil shock, which reduced research incentives and contributed – along with concerns about safety, waste disposal and proliferation – to the gradual scaling down of public nuclear programmes.

[Figure 4.1. Public energy-related R&D expenditures in OECD countries]

54. More broadly, climate change mitigation will involve increased expenditures at all stages of the technology development process, ranging from R&D upstream to demonstration, deployment, and ultimately diffusion downstream. Most importantly, empirical evidence suggests that most emerging low-carbon energy technologies are subject to sizeable "learning effects", *i.e.* their costs fall as experience accumulates through cumulative production (see *e.g.* IEA, 2000; McDonald and Schrattenholzer, 2001;

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[56] Prominent examples of technological advances currently envisaged to reduce the carbon intensity of output in the future include inter alia (see *e.g.* IEA, 2008b): for power generation, wind and solar power, the next generation of nuclear power, or carbon capture and storage (CCS); for transport, advanced biofuels and electric and hydrogen-fuel-cell vehicles; for industry, CCS and a range of industrial energy technologies to improve fuel efficiency and allow fuel substitution away from fossil fuels; for buildings and appliances, a variety of (mostly) incremental improvements in insulation techniques, lighting and cooling systems or the energy efficiency of appliances.

[57] This would reduce not only future abatement costs but also their sensitivity to emission-reduction objectives, thereby providing some hedging against the risk of larger-than-expected need for action against climate change (Stern, 2007, Chapter 16). This is because broadening the portfolio of low-cost options would flatten the slope of the marginal abatement curve, thereby limiting the cost of unexpected shifts in required (optimal) abatement levels due e.g. to unexpected shifts in climate damages.

[58] In power generation, R&D spending as a share of total turnover was about eight times lower than in the manufacturing sector as a whole (OECD Roundtable on Sustainable Development, 2006). This is consistent with disaggregated sectoral analysis for the United States (Alic *et al.* 2003).

Neij *et al.* 2003a, 2003b). For example, learning rates – the percentage reduction in unit investment costs for each doubling of cumulative investment – in the order of 10% to 20% have typically been reported for wind and solar power technologies. In that context, significant technology deployment costs may have to be incurred before low-carbon technologies can become competitive at market prices.[59] However, wide uncertainties remain surrounding the magnitude and even the nature of learning effects, and their policy implications are far from obvious, as discussed below.

4.2. Policy instruments to stimulate R&D and technology deployment

The "dynamic efficiency" of price-based instruments

55. Pricing GHG emissions – including removing implicit emission subsidies such as fossil fuel energy subsidies – increases expected returns from R&D in low-carbon technologies. In the presence of learning effects, it also reduces expected cumulative deployment costs needed for existing climate-friendly technologies to become competitive. The effects of emission pricing on expected returns are likely to be largest for technologies, such as CCS, which would yield no private financial gain otherwise as they affect only the carbon intensity of energy (GHG emissions per unit of energy) but not energy efficiency (number of units of energy per unit of output). More broadly, emission pricing gives emitters a continuing incentive for emissions-reducing R&D and technology deployment, the so-called "dynamic efficiency" of price-based mechanisms.[60] However, as discussed below, the credibility of the price signal also matters since investments in R&D and/or deployment of emerging technologies entail sunk costs. In practice, empirical evidence has found private energy-related R&D and innovation at the firm level to be responsive to past fluctuations in energy prices (Popp, 2002; Johnstone *et al.* 2008), while the fairly strong correlation until recently between fluctuations in oil price and public R&D spending suggests that governments also respond to price incentives.

56. While ambitious technology and performance standards can in principle be set to "force" innovation, available empirical evidence points to ambiguous results (Jaffe *et al.*, 2003). One concern is the difficulty for the regulator to determine the appropriate stance *a priori,* with the risk that innovation incentives will be either too weak or too strong, because CAC instruments do not give persistent abatement incentives (Downing and White, 1986; Jaffe *et al.* 2003; Jung *et al.* 1996; Keohane, 2001; Milliman and Prince, 1989; Zerbe, 1970).[61] Under technology standards, firms have no incentive to develop alternative, potentially more effective technologies than those mandated by regulation. While incentives are stronger under performance standards, they are still limited by the fact that emitters do not gain from reducing

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[59] For example, based on learning rate assumptions across a wide range of technologies and in the absence of any carbon price, IEA (2008b) puts cumulative (undiscounted) deployment costs of low-carbon technologies consistent with a 50% cut in world emissions by 2050 at about $US7 trillion. These costs are computed in the absence of a price on CO_2, and would therefore be smaller in the presence of a world carbon price.

[60] For a comparison of R&D and deployment incentives under taxes and cap-and-trade schemes, see Duval (2008).

[61] For empirical evidence that permit trading yields larger technology adoption incentives than binding performance standards (based on historical experiences in the United States with the phase down in lead in gasoline and the reduction in sulphur dioxide emissions, respectively), see Kerr and Newel (2004) and Keohane (2001). In theory, the greater strength of innovation incentives under market-based instruments may not systematically hold under oligopolistic competition (Montero, 2002).

emissions below compliance levels, although adjusting standards over time partly mitigates such concerns.[62]

Quantifying the effects of carbon pricing on induced technological change and mitigation costs

57. In order to assess the quantitative impact of carbon pricing on R&D and technology deployment, and the extent to which the induced technological change (ITC) may ultimately reduce emission abatement costs, simulations are run here using the World Induced Technological Change Hybrid (WITCH) model, which unlike ENV-Linkages incorporates an endogenous response of technological progress to policy incentives (Bosetti *et al.* 2006, 2007, 2009, Box 3).[63] The simulations confirm the incentive power of carbon pricing. For instance, the model's (inter-temporally optimal) world carbon price path to stabilise long-run CO_2 concentration at 450 ppm and overall GHG concentration at about 550 ppm CO_2eq[64] is estimated to multiply energy R&D expenditures and investments in deployment of renewable power generation by about four in 2050, compared with the baseline scenario (Figure 4.2). These effects grow larger over time and/or as concentration targets become more stringent, reflecting a higher CO_2 price. In fact, because marginal abatement costs rise disproportionately with emission reductions, investment in technology also rises disproportionately with the stringency of the emission reduction objective. A related finding is the need for a strong long-term carbon price signal to foster investment in low-carbon R&D and technology deployment today. Indeed, under similar carbon price levels, R&D investment is found to be noticeably higher under a 550 ppm CO_2eq GHG (450 ppm CO_2 only) concentration objective, reflecting higher expected future increases in carbon prices than under a 650 ppm CO_2eq (550 ppm CO_2 only) scenario (Figure 4.3).

[Figure 4.2. Estimated response of R&D and renewable power generation deployment under alternative world GHG emission price scenarios (650 ppm and 550 ppm GHG concentration stabilisation scenarios)]

[Figure 4.3. World energy R&D investment at given GHG emission prices under 650 ppm and 550 ppm GHG concentration stabilisation scenarios]

Box 3. Key features of the WITCH model

The WITCH model incorporates a detailed representation of the energy sector into an inter-temporal growth model of the economy, thereby allowing technology-related issues to be studied within a general equilibrium framework. Also, following earlier work by Nordhaus and Boyer (2000) and Popp (2004), world countries are grouped in twelve forward-looking regions that interact strategically to determine their optimal R&D and investment strategies in the presence of environmental externalities – expected future climate change damages are explicitly taken into account – and R&D and learning spillovers. The model covers CO_2 emissions but does not incorporate other GHGs.

Four main channels through which ITC may arise are considered in the analysis, namely:

- Higher public R&D increases energy-related knowledge capital and thereby improves energy efficiency,

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[62] Under adjustable standards, R&D may still be discouraged by a perceived risk of "regulatory ratchet", whereby standards would be further tightened a posteriori if a new technology were found (see *e.g.* Hahn and Stavins, 1991).

[63] Technology assumptions have been shown to be critical determinants of differences in the GDP and welfare costs of mitigation across available studies (Barker *et al.* 2002, 2006; Fischer and Morgenstern, 2006). For an overview of recent models featuring ITC, see Edenhofer *et al.* (2006).

[64] This is the optimal world carbon price path under the non-cooperative solution of the model when a 450 ppm long-run CO_2 concentration target is imposed (for details, see Box 3 and Bosetti *et al.*, 2009). Emissions of non-CO_2 gases are not covered by the WITCH model and are therefore excluded from the simulations, However, stabilisation of CO_2 concentration at 450 ppm roughly corresponds to stabilisation of overall GHG concentration at 550 ppm.

with high but diminishing social returns. These returns are entirely appropriated by each region, *i.e.* it is implicitly assumed that intellectual property rights (IPRs) internalise externalities at the regional level. However, energy-related knowledge capital in one region partly spills over to other geographical areas (see below, and Bosetti *et al.* 2008, for details). While – due to data availability constraints – only public R&D is modeled in the current version of WITCH, private R&D would be expected to respond in a qualitatively similar way to the incentives associated with climate change mitigation policies.

- Learning-by-doing (LBD) effects gradually reduce the cost of several low-carbon technologies in the electricity sector, namely wind and solar power. Learning effects apply to *world* cumulative capacity, thereby generating international spillovers.

- The cost of wind and solar technologies, as well as that of coal-based electricity with CCS, are also reduced through public research, albeit again with diminishing returns. There are limitations to the deployment of CCS, however, including the exhaustibility of repository sites and imperfect capture.

- In some of the simulations run specifically for this paper, R&D and LBD effects are also assumed to bring unspecified “backstop” technologies into the electricity and/or non-electricity sectors. This allows for the possibility that investment in R&D may not only improve current technologies but also foster major technological breakthroughs that would add to the portfolio of existing substitutes to high-carbon options. These backstop technologies may best be seen as a combination of new technologies not currently foreseen to penetrate the market, including *e.g.* advanced nuclear technologies in the electricity sector, and electric and hydrogen-fuel-cell vehicles in the non-electricity sector. The calibration of the impacts of R&D and learning-by-doing on the investment cost of these “backstop” technologies relies *inter alia* on past experience with solar, wind and nuclear power, as reflected in the estimates of “two-factor” learning curves in available empirical literature (for details, see Bosetti *et al.*, 2009).

While the calibration of parameters is based on best available empirical evidence, it should be acknowledged that wide uncertainties surround some of these, including the elasticity of R&D to energy prices, social returns to R&D, the creation and diffusion process of new technologies, learning rates or the magnitude of international spillovers. Therefore, while the key policy findings presented below are qualitatively robust to parameter choice, caution should be exerted when interpreting the quantitative results (for further results, including some sensitivity analysis, see Bosetti *et al.*, 2009).

58. However, the analysis suggests that ITC associated with higher investment in R&D and technology deployment may have only modest effects on policy costs, especially under less stringent CO_2 concentration objectives. This can be inferred from the limited increase in the cost estimate of a 550 ppm CO_2eq GHG (450 ppm CO_2 only) concentration scenario when the ITC channel is shut down by forcing R&D to remain at its baseline level and assuming there are no LBD effects (Figure 4.4). Pricing carbon in this model curbs emissions primarily by encouraging the shift towards less carbon-intensive production and consumption patterns, while impacts on ITC are found to be comparatively smaller, for two main reasons:

- In the electricity sector, low-carbon options already exist today, including nuclear energy and, to a lesser extent, CCS. Both are projected to account for an increasing share of the future energy mix under a rising carbon price (Figure 4.5). If, for technological, political or safety reasons the penetration of nuclear energy and CCS were constrained, investments in R&D and renewable power generation would be increased, but at the same time overall mitigation costs would rise, as some relatively cheap abatement opportunities would be lost (Figure 4.6). Thus, exploiting all currently available technological options may be at least as important as fostering new ones through R&D investment in containing the overall costs of addressing climate change.

- Decreasing marginal impacts of R&D on energy efficiency and fading learning effects in renewable energies ultimately limit the gains to be reaped from ITC.

[Figure 4.4. Projected world GDP costs under 550 ppm GHG concentration stabilisation scenarios, with and without induced technological change]

[Figure 4.5. Projected energy technology mix in the electricity sector under baseline, 650 ppm and 550 ppm GHG concentration stabilisation scenarios]

[Figure 4.6. Projected world GDP costs under 550 ppm GHG concentration stabilisation scenarios, with and without constraint on nuclear energy and CCS]

59. The previous analysis does not allow R&D to foster major unforeseeable technological breakthroughs – as represented by unspecified backstop technologies – that could drastically reduce mitigation costs. In order to illustrate the potential implications of this possibility, the following three alternative scenarios are considered under the objective of stabilising long-run GHG concentration at 550 ppm CO_2eq (450 ppm CO_2 only): *i)* two backstop technologies emerge in the electricity and non-electricity sectors, respectively (with penetration of nuclear energy constrained at its current level, as incentives to develop the electricity backstop would be much less relevant otherwise), through R&D and LBD effects similar in magnitude to those typically experienced in the past with wind, solar and nuclear technologies (for details, see Bosetti *et al.*, 2009); *ii)* only the electricity backstop is available; *iii)* only the non-electricity backstop is available, in which case no constraints are put on nuclear energy.

60. These simulations yield four main findings:

- Developing new low-carbon technologies might significantly reduce future mitigation costs and give a greater role to ITC in containing these costs. Mitigation costs in 2050 are halved in the "two backstops" scenario – from about 4% of world GDP in the "no-backstop" scenario to under 2% – and the pay-off from the new technologies becomes increasingly large in the second half of the century (Figure 4.7, Panel A).

- While investing in basic science to develop new technologies might drastically reduce mitigation costs over the long run, a strong price signal still appears to be needed to spur the necessary investments. The optimal carbon price path in the "two backstops" scenario is virtually unchanged from its level in the "no backstop" scenario until 2020, falling significantly below the latter only at a later stage, as the backstop technologies account for a rising share of the energy mix (Figure 4.7, Panel B). Allowing for the fact that in practice future policy may not be fully credible would further reinforce the need for a strong initial price signal.

- Lower long-term mitigation costs come at the price of higher medium-run costs, however (Figure 4.7, Panel A). This reflects the large and sustained increase in R&D investments needed to develop the two backstop technologies, which in the simulations push energy R&D spending above its previous historical peak of the mid-1980s (Figure 4.8). R&D investments of such magnitude entail costs, as they crowd-out other investment opportunities with higher short-run pay-offs.[65]

- The main contribution to reduced long-term mitigation costs might come from the non-electricity sector, as can be inferred here by comparing costs across two scenarios where only the electricity and the non-electricity backstop technologies are available, respectively (Figure 4.9). This is

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[65] While this finding is qualitatively robust, the particular (optimal) increase in R&D spending computed here reflects inter alia the assumed initial cost of the backstop technologies, the effects of R&D and LBD in terms of bringing down these costs, as well as the more general features of the model that drive the optimal path of carbon prices and R&D spending. For details, see Bosetti *et al.* (2009).

because marginal emission abatement costs are typically high in the non-electric sector (*e.g.* in transport) and are expected to rise sharply under stringent emission reduction objectives. By contrast, as already noted, some low-carbon options already exist in the electricity sector. However, the more the penetration nuclear energy and/or the availability of CCS is constrained, the more it would become profitable to search for new power generation technologies.

[Figure 4.7. Projected world GDP costs and GHG emission price levels under 550 ppm GHG concentration stabilisation scenario, with and without backstop technologies]

[Figure 4.8. Projected energy R&D investments under 550 ppm GHG concentration stabilisation scenario, with and without backstop technologies]

[Figure 4.9. Projected world GDP costs under 550 ppm GHG concentration stabilisation scenario, with electricity backstop or non-electricity backstop only]

The case for R&D policies

61. Despite the R&D incentives it generates, putting a price on GHG emissions does not address all the market imperfections undermining R&D and technology deployment. Some of these imperfections are common to all R&D areas, but the following seem to be magnified in climate change mitigation:

- The gap between social and private expected returns from R&D and technology adoption may be widened by the political uncertainty surrounding future climate policy, which in turn fundamentally reflects the lack of credible devices through which current governments can commit future ones. This issue is often less acute in other public policy areas, either because their time scale is shorter or because policies are better established.

- Given the potentially large welfare consequences of any major breakthrough in technological progress - *e.g.* in the area of electricity production - protection of IPRs may not be sufficiently credible to private investors, who may expect governments to deprive them of any major innovation rent *a posteriori.*[66]

- Specific market failures and policy distortions in the electricity sector may explain low levels of R&D compared with other industries. In particular, already installed infrastructure creates network effects that may act as entry barriers to new technologies. For instance, most national grids would not be suited to receive electricity from many small renewable electricity sources, while large scale renewable projects may also encounter problems if located too far from existing grids.[67] Finally, low market competition and distortions such as energy subsidies may also contribute to keep R&D spending low.[68]

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[66] Such concerns have been put forward as an explanation for relatively low private research on vaccines against major worldwide diseases such as malaria, tuberculosis or HIV (Kremer, 2001a, 2001b).

[67] Network effects also exist in road transport, where high penetration of low-carbon technologies (*e.g.* electricity and hydrogen-fuel-cell vehicles, biofuels) would likely require new infrastructure, as current infrastructure (*e.g.* fuel stations) is tailored to fossil fuel technologies.

[68] The cumulative nature of knowledge may also increase uncertainty about returns to R&D. This is because the ultimate penetration of any path-breaking innovation hinges more crucially than in other sectors on a series of additional incremental innovations and learning gains, which are largely unpredictable ex-ante (see *e.g.* Stern, 2007, Chapter 16).

- Adding to these imperfections and distortions, the country and/or sector coverage of price-based instruments is unlikely to be comprehensive at least over the medium run, thereby further raising the gap between social and private returns, and providing a "second-best" case for R&D policies.

62. Therefore, over and above ensuring an appropriate overall innovation framework (for details, see OECD, 2006c, and Jaumotte and Pain, 2005), removing fossil fuel subsidies and increasing competition in energy markets, there is a case for specific policies aimed at boosting climate-friendly R&D.[69] Beyond the use of standard tools such as public R&D, research subsidies or grants,[70] there has been growing interest recently for rewarding innovation through the use of "innovation prizes" (Box 4), as these may address some limitations of other instruments (Newell and Wilson, 2005). One issue in this regard is whether the global public good nature of climate change mitigation, along with the existence of international – as opposed to domestic – R&D spillovers, may justify an international R&D policy. For instance, one option might be to set up a global fund, which might also serve as a vehicle for technology transfers if it not only rewarded innovations but also contributed to deploy them, *e.g.* by buying out the associated patents or through other mechanisms.

Box 4. Fostering R&D and innovation through the use of prizes

The use of "inducement prizes" to reward successful innovation has a long history and has experienced a resurgence in recent years, not least due to highly publicised examples in the space and vaccine industries.[1] One open issue is whether such prizes could also be envisaged in the area of climate change mitigation, *e.g.* through (or as a complement to) the global funds that already exist or are about to be set up to facilitate technology transfers.

Prizes have a number of specificities that make them a potentially useful R&D policy tool. Unlike subsidies and grants, they address governments' lack of information about the likely returns to R&D by shifting the risk of failure to researchers, which may be warranted in the case of applied R&D (see below). Furthermore, they entail low administrative barriers to entry and only limited risks of policy capture by private interests. In theory, prizes could also achieve a given level of R&D spending at a lower cost to the government than subsidies and grants, and would even be temporarily costless as they are only paid in case of success.[2] Compared with patents, prizes are potentially less distortive provided the social value of the invention is not widely uncertain and the distortions associated with prize financing are smaller than the welfare loss from monopoly power under patents (Wright, 1983).

Prizes may have several other attractive features in the specific context of climate change mitigation. Most importantly, they could help alleviate the political uncertainty surrounding future carbon prices and the potential lack of credibility of IPRs, both of which would otherwise adversely affect R&D incentives. In addition, unlike domestic R&D policy instruments, international prizes would pool risks and rewards across countries. Finally, unlike other international instruments (*e.g.* a global R&D fund allocating subsidies across countries), they may avoid political competition for domestic research funding across national governments.

Prizes have a number of limitations, however. In particular, they have a comparative advantage in stimulating applied rather than basic R&D, for at least two reasons (Newell and Wilson, 2005): *i)* the social value of innovation is harder to determine *ex-ante* for major technological breakthroughs than for specific technological outputs, making it more difficult to determine the appropriate size of the prize;[3] *ii)* information asymmetry and the associated risk of misallocation of subsidies and grants can be large for applied R&D, while in basic science the incentives of governments and researchers tend to be better aligned, as the latter have career incentives to advance fundamental research. Also, like patents, prizes entail risks of duplication of research efforts, although these can be mitigated *e.g.* by pre-selecting firms in the context of a multi-stage selection process.

Prize design also greatly matters for R&D incentives. Policymakers can enhance the credibility of their commitment by setting the funds aside, or by purchasing an insurance policy that secures prize payment in case of

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[69] For instance, based on a theoretical model calibrated on US electricity sector data, Fischer and Newell (2007) find that optimal R&D and renewable subsidies could lower by over a third the CO2 emissions price needed to achieve a 5% cut in US electricity sector emissions, and could bring down the overall cost of the policy package to zero, due to the positive spillovers generated by the technology-support policies.

[70] The OECD is also currently undertaking – via its Joint Meeting of Tax and Environment Experts – case studies of the effects of tax policies on environmentally-friendly R&D.

success. Moreover, in order to minimise judicial uncertainty, victory conditions need to be defined precisely – which again may be easier for specific technological outputs (*e.g.* specific achievements in CCS, nuclear fission, renewable power generation or hydrogen vehicles) than for broader advances in science. Also, the size of the prize should depend on whether the purpose of policy makers is only to boost R&D or to foster technology transfers as well. In the latter case, one option might be to buy out *ex-ante* any future patent rights through a higher prize. Along the same lines, while prizes are typically provided in cash, advanced market commitments may be used to facilitate deployment when there is no private market for the invention, as might be the case in some developing countries if these do not put a price on carbon.[4] For instance, developed countries might commit in advance to finance the implementation of prize-winning technologies in developing countries, which would stimulate both R&D and technology transfers.

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1. For an extensive discussion of innovation inducement prizes and concrete policy recommendations to scale them up in the US context, including in the area of climate change mitigation, see National Research Council (2007).
2. In the presence of a "common pool" of knowledge, prizes (or patents) that reward successful researchers with the full social value of innovation would induce excessive research spending, as competitive firms do not internalise the negative impact of their own expenditures on the probability that other firms make a discovery. Therefore, the prize needed to achieve an optimal level of R&D is *less* than the full social value of innovation, and therefore less than the optimal R&D subsidy (see in particular Wright, 1983).
3. From this perspective, patents have an informational advantage, as their market value varies with *ex-post* surprises in returns to research. The determination of the prize amount may be improved by letting contestants propose (and compete on) the size of the prize, in order to reveal their information about research costs and returns (Che and Gale, 2003).
4. For a detailed discussion of advanced market commitments in the case of vaccines, see Kremer (2001a, 2001b).

63. WITCH model simulations suggest tentatively that a global R&D fund to subsidise R&D and/or low-carbon technology deployment could further reduce mitigation costs, if it came on top of pricing carbon (see Bosetti *et al.*, 2009). However, the optimal size of such a fund and its effects are found to be very small, unless R&D investment in new (backstop) technologies is assumed to yield large international spillovers. This partly reflects the assumption in WITCH that social returns are almost entirely appropriated by each region, resulting in rather small international spillovers. Further research about the existence, nature and magnitude of international spillovers might be needed, not least in view of the ongoing debate about how to value some countries' efforts to increase R&D and facilitate technology transfers in the context of a global climate policy agreement. Indeed, from a theoretical perspective, only the returns to public support to R&D and deployment that are not captured by the country itself – *i.e. international* R&D and learning spillovers – should be eligible to be valued in the context of a global agreement.

Is R&D policy alone an option?

64. Another important policy issue is whether, and at what cost, higher R&D expenditures alone might address climate change if no price were put on carbon. WITCH model simulations strongly suggest that world spending on energy-related R&D *alone* would not be able to address climate change, regardless of its magnitude – even if implausibly large, *e.g.* 1 percentage point of world GDP, representing a 30-fold increase with respect to current levels. This reflects the lack of substitution towards less carbon intensive production and consumption patterns during the first decades, along with the lags required for the new technologies to penetrate the market.[71] Figure 4.10 provides one illustration of this finding, assuming a hypothetical global R&D fund is gradually built up over the coming decades to spend ultimately 0.08% of world GDP annually, an amount that would roughly correspond to the early-1980s peak level of public

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[71] Focusing on the electricity sector only, Fischer and Newell (2007) find technology-support policies to be the costliest of all abatement policy options, due to their failure to exploit cheap abatement opportunities that already exist today, and to the time and investments needed for new technologies to become available.

energy R&D spending within the OECD. In order to provide an upper bound to what such spending might achieve, three optimistic assumptions are made: *i)* the fund subsidises R&D investments in the two electricity and non-electricity backstop technologies, which are assumed to be available; *ii)* these subsidies are assumed not to crowd out domestic R&D investments, while in practice countries may be induced to reduce their own R&D spending if major subsidies were received from an international fund and/or provided elsewhere;[72] and *iii)* the fund is financed through a lump sum tax, *i.e.* the potential distortions arising from fund raising are omitted. Even under these favourable conditions, the stylised global R&D policy is found to stabilise world emissions only in the middle of the century, at over twice their current level (Figure 4.10, Panel A).[73] As a result, CO_2 concentration rises continuously, being only roughly 50 ppm below its baseline scenario level at the end of the century (Figure 4.10, Panel B). In fact, no global R&D policy of any size appears to be able on its own to stabilise concentration during this century.

[Figure 4.10. Projected CO_2 emissions and concentration under a global R&D policy only]

Technology deployment policies

65. In the presence of learning spillovers such as learning-by-doing effects, carbon pricing and R&D policies may not be enough to ensure adequate deployment of existing low-carbon technologies (see *e.g.* Jaffe *et al.* 2003, 2005). This may be particularly the case in the electricity sector, where network effects and the cumulative nature of knowledge make it difficult to displace existing technologies. As well, electricity being essentially a homogenous good, market demand for low-carbon energy may remain negligible until it actually becomes competitive, thereby hampering the learning process. This contrasts with a number of other goods (*e.g.* high-technology electronic and computer goods, cars), where "niche markets" exist for new, expensive products (Stern, 2006, Chapter 16). It has also been argued that without policy intervention to speed up the deployment of low-carbon technologies, there might be a risk of locking-in high-carbon energy systems, as major long-term infrastructure investments are expected over the coming years in power generation, transport and buildings, notably in large developing countries (IEA, 2006a, 2007a; OECD, 2008c).

66. At the same time, public support to the deployment of existing technologies raises a number of concerns. Most importantly, with the shape of learning curves being widely uncertain *ex-ante*, promising technologies may prove disappointing *ex-post*. In this context, by trying to exploit learning and/or network effects, policy makers may run the risk of "locking-in" the wrong technologies.[74] At a minimum, a clear exit strategy in the event of technology failures should be announced in advance, as once established swift reversal of public support may face strong opposition. Finally, optimal subsidies have been found to be small under plausible learning rate assumptions (see *e.g.* Fischer and Newell, 2007). Yet most countries already subsidise renewable electricity heavily, with implicit prices per ton of CO_2 abated sometimes exceeding 250 for wind power and 1 000 for photovoltaics (OECD, 2004). Therefore, at a minimum, the case for further national policy action seems rather limited.

67. A wide range of policy tools have been used by OECD countries to support technology deployment, not least in the electricity sector, including fiscal incentives, quota-based schemes or public procurement and infrastructure policies. Perhaps the two most prominent instruments lately have been feed-in tariffs – essentially a fixed price support per unit of electricity produced guaranteed over a given period (*e.g.* Germany, Spain, or Denmark until recently) – and tradable "green" certificates – an overall

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[72] The no-crowding-out assumption is implemented by imposing the constraint that R&D spending in each region remains at least equal to its level in the baseline scenario.

[73] This finding is qualitatively in line with earlier studies (see *e.g.* Buchner and Carraro, 2005).

[74] See the discussion in Jaffe *et al.* (2003).

requirement that a fixed share of electricity be generated from renewable sources, along with allowance for trading among firms (*e.g.* Australia, Italy, United Kingdom). In principle, and in the absence of uncertainty, both instruments could be designed to be equivalent. In practice, insofar as they provide price guarantees over relatively long periods, feed-in tariffs may entail higher inefficiencies, as price support fails to adjust spontaneously to changes in cost conditions (see *e.g.* Sims, 2002). Also, price support has tended to differ across technologies, while tradable certificates have been comparatively more neutral.[75]

5. Dealing effectively with uncertainty

68. A sound climate policy framework needs not only to rely on a cost-effective set of instruments but also to cope effectively with uncertainties surrounding both climate change impacts and abatement costs (Section 2). Policy should be flexible enough to accommodate the changes that will be required by future scientific, economic and technological developments. It should also handle changes in country and/or sector coverage, and ensure long-term commitment in order to boost incentives to invest in clean technology.

5.1. The need for a flexible and predictable framework

69. One major challenge in this regard is to set up a flexible but yet predictable policy framework. Unpredictability would indeed be costly. In most key emitting areas, including electricity and transport, capital goods are long-lived (Table 5.1) and often entail large sunk costs that limit the ability of firms to adjust installed capital to price fluctuations. Firms incorporate such irreversibilities into their investment decisions by delaying investment or requiring an extra return to offset the loss of the (option) value of investing at a later date when new information arrives. The higher the volatility of abatement costs, the higher the expected return required for an investment project to be undertaken, and the more firms are likely to delay and lower their investments in energy-efficient equipment (Dixit and Pindyck, 1994). R&D investments in low-carbon technologies are also affected, as they too entail large sunk costs (IEA, 2007c).

[Table 5.1. Typical service life for selected investments]

70. OECD simulations of a calibrated microeconomic model of firms' investment decisions under price uncertainty and investment irreversibility point to large detrimental effects of energy price volatility on investment (Box 5, and Jamet, 2009). For instance, a degree of carbon price volatility comparable to that observed since the creation of the EU-ETS might reduce firms' energy-efficient investments by as much as a quarter relative to a stable carbon price scenario, *ceteris paribus*.[76, 77] Therefore a key policy

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[75] There is also some evidence that tradable certificates may have stimulated not only technology deployment but also innovation. Based on patent data for a panel of 25 countries over the period 1978-2003, Johnstone *et al.* (2008) find significant effects on patenting from tradable certificates, but not from feed-in tariffs.

[76] While the investment effect of uncertainty is unambiguously negative in the short run, it is less clear-cut in the long-run (for details, see Jamet, 2009). Higher uncertainty induces firms to delay their investments, but it also increases the incentive to invest when conditions are favourable, *i.e.* when energy prices are high. In the presence of large sunk costs and low capital stock depreciation, the capital stock then remains high even if conditions become less favourable. This effect tends to increase the steady-state capital stock, *ceteris paribus*.

[77] The analysis focuses on the impact of carbon price uncertainty coming from exogenous shocks, such as changes in the design of the scheme or the disclosure of new information (e.g. regarding actual emissions, as has happened during the first phase of the EU ETS), but it ignores uncertainty about abatement costs that would come from the emergence of a breakthrough technology and, which would be endogenous to investment decisions. In a stylized model, Zhao (2003) incorporates the latter form of uncertainty and finds that, for some model specifications, firms' investment incentives decrease more under a carbon tax than under a permit trading scheme.

objective should be to minimise uncertainties surrounding carbon abatement costs and, in parallel, to facilitate the development of hedging instruments.

71. Climate policy instruments differ in their ability to cope with uncertainty. An ETS and a carbon tax set either the quantity or the price of emissions, and can be fine-tuned to achieve the other objective over time. By contrast, standards or technology-support policies provide certainty neither about emissions nor about abatement costs. Also, under price based instruments – in particular cap-and-trade schemes - individual emitters' response to unexpected technological change is immediate and decentralised, while under a CAC approach the regulator must re-specify all the standards affecting the many different types of emitters. Technology standards, as well as technology-support policies, may also encourage irreversible investments in specific technologies that could *a posteriori* prove costlier than other options, thereby leading to a "lock-in" effect. At the same time, by forcing firms to invest, well-designed standards may help overcome the lack of long-run predictability of policy, which under price-based instruments would keep investment at sub-optimal levels

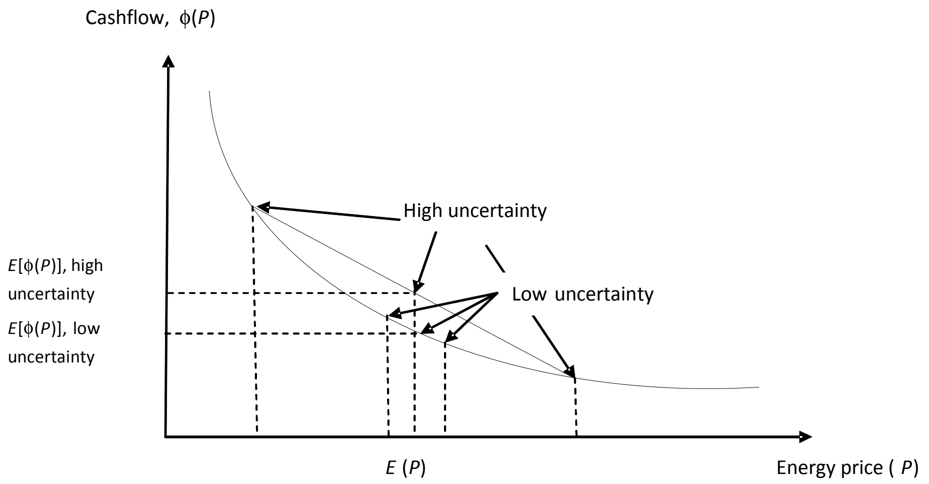
Box 5. The impact of uncertainty on firms' irreversible investments

When investment is reversible, the impact of carbon price uncertainty on firms' decision to invest in emission-reducing equipment is determined by the (convexity of the) relationship between investment cashflows and the carbon price.[1] If – as would be expected in the case of emission-reducing equipment – this cashflow function is convex, the higher the carbon price uncertainty, the higher the expected cashflow and the higher the size of the investment (Figure 1). In practice, however, most investments in clean technologies entail irreversibilities that limit the extent to which firms can adjust their capital stock to fluctuations in carbon and energy prices, and thereby also affect the investment decision.

Here, a stylised, calibrated model is set up to assess the impact of carbon and energy price uncertainty on investment in emission-reducing equipment in the presence of irreversibility. A representative firm is assumed to produce a good with two inputs, capital[2] and fossil fuel energy. While energy purchases entail no sunk costs, *i.e.* they can be resold at no cost, capital is assumed to be irreversible, *i.e.* it becomes specific to the firm once installed and therefore cannot be resold. In this context, the firm can be seen as holding a "real option" that gives it the right to invest in the emission-reducing equipment in order to receive uncertain future cashflows that fluctuate with time, depending *inter alia* on carbon prices. It is then profitable for the firm to exercise this option when the expected return on investment exceeds the sum of its cost *and* the loss of the option to invest later with additional information. Higher carbon price uncertainty increases the value of that option, thereby delaying and reducing the size of the investment, *ceteris paribus* (Dixit and Pindyck, 1994; IEA 2007c[3]).

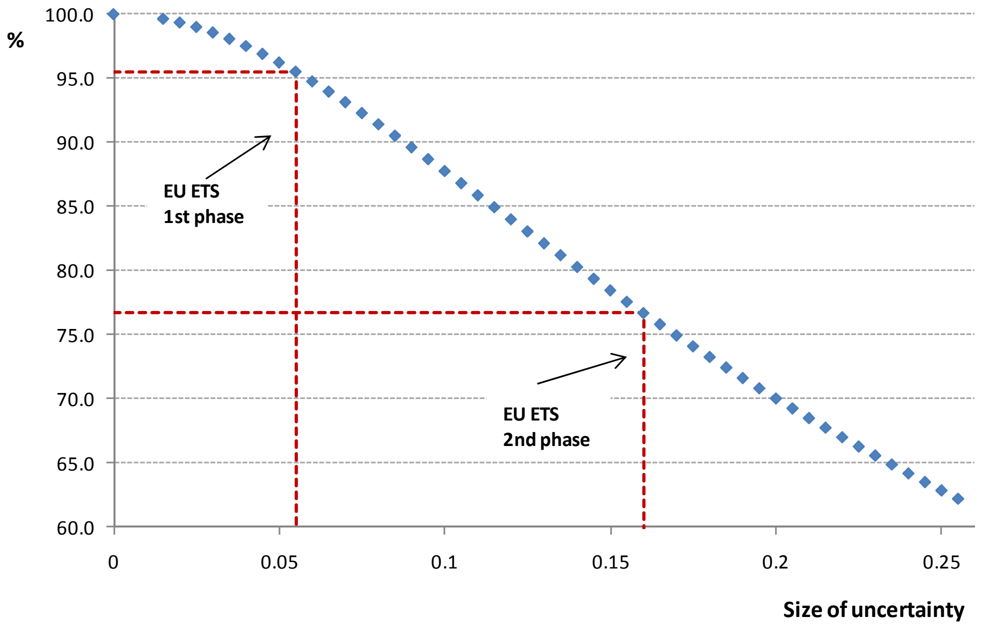
With a convex cashflow function, the "convexity" and "irreversibility" channels through which uncertainty affects the investment decision act in opposite directions, so that the impact of uncertainty on investment is *a priori* ambiguous. However, for reasonable values of the main parameters, it can be shown that the irreversibility effect prevails over the convexity effect (see Jamet, 2009). The higher the uncertainty, the higher the value of the investment option, the more investment is delayed, and the lower the optimal capital stock at the time of investment. For instance, model simulations suggest that a degree of carbon price uncertainty comparable to that observed during the second phase of EU-ETS could lower the capital stock by as much as a 25%, relative to a stable carbon price scenario (Figure 2). The lower carbon price fluctuations that prevailed under the first phase of the scheme would be consistent with a 5% reduction in the capital stock.[4]

Figure 1. The convexity effect of uncertainty



Note: E(.) denotes the expectation operator. Two distributions of the energy price with the same expected price are considered, one with low uncertainty and one with high uncertainty. With a convex cashflow function, the higher the uncertainty, the higher the expected cashflow.

Figure 2. Ratio of the capital stock with and without uncertainty at the time of investment



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1. In other words, the investment decision is determined by the so-called "Jensen's inequality".
2. Capital is a broad aggregate that includes all the technologies that allows producing the good without paying the energy price. It includes for instance renewable energy technologies.
3. Using a similar model for the electricity sector, the IEA finds that extending policy visibility from 5 to 10 years would strongly reduce the delaying impact of uncertainty on investments. The model does not capture the impact of uncertainty on the size of investments.
4. In a global carbon market, carbon price uncertainty would be partly offset by less volatile fossil fuel energy prices, as higher (lower) than expected carbon prices would coincide with lower (higher) than expected world fossil fuel energy prices. However, given the limited coverage of the EU-ETS, this effect is assumed to be small in the analysis undertaken here.

5.2. Coping with short-run uncertainty

72. In the very short run, *i.e.* over a few years horizon, existing theoretical and empirical literature argues more strongly for minimising carbon price fluctuations than changes in the quantity of emissions (Weitzman, 1974; Hoel and Karp, 2001; Newell and Pizer, 2003, Pizer, 2002). A simple quantity instrument would require annual caps to be met regardless of the cost, which may vary substantially from year to year due *e.g.* to growth, energy supply or weather fluctuations. By contrast, a fixed carbon price would allow larger (lower) emission cuts when the cost of doing so is low (high). The gain from such flexibility would come at the cost of increased variability of annual emissions, but this cost would be comparatively smaller since it is *cumulative* past – as opposed to current – emissions that drive future damages from climate change.[78][79]

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[78] This is at least the case in the current situation where GHG concentration levels remain significantly below thresholds that might trigger extreme and irreversible events.

[79] This short-run efficiency gain from fixing the carbon price could be large in practice, under reasonable assumptions about actual marginal damage and cost curves (Hoel and Karp, 2001; Newell and Pizer, 2003, Pizer, 2002). It should be stressed that only shocks to (marginal) abatement costs typically matter in this

73. In the context of cap-and-trade schemes, the above argument points to the need to facilitate the development of financial derivative markets that – insofar as they are adequately regulated – allow emitters to hedge against price volatility. A number of features of permit trading schemes might help in this regard, although recent experience with the EU-ETS suggests such markets are likely to develop in any case, with derivative trades already making up over 95% of trading volume (Box 6). Some of the desirable features, such as the existence of a uniform carbon price and the credibility and predictability of long-term policies are in any case required to minimise the cost of mitigation policies even in the absence of derivatives markets. One way to underpin forward markets and increase investors' confidence in the longevity of the scheme would be to issue a small number of longer-dated permits, all the more so as it would set up a political constituency with a strong interest in enforcing the policy in the future.[80] Furthermore, the larger and more liquid the market, the cheaper it would be to insure against price fluctuations. The issuance of permits with different maturity dates, by providing access to an underlying instrument – *i.e.* the emissions permit – would help enhance market liquidity. Finally, given the potential size of this market – about 6% of world GDP in 2050 under a 550 ppm CO_2eq GHG (450 ppm CO_2 only) concentration target according to ENV-Linkages model simulations,[81] and insofar as the global architecture is initially made up of several segmented regional trading markets, cooperation between countries in setting up a permit market regulator may be helpful. For instance, this entity could define standards for permit design, monitor transactions and set sanctions in the case of non-delivery or non compliance with permit obligations. Nonetheless, lack of cooperation might be partly addressed spontaneously through market mechanisms, with differences in quality across permits issued under different schemes being assessed by rating agencies and resulting in permit price differentials.

74. A number of (possibly complementary) options also exist to further enhance the robustness of permit trading schemes to short-run cost uncertainty (for further details, see Duval, 2008):

- One option is to allow permits to be stored (or "banked") for and/or borrowed from future use in the context of multi-phase programmes. For example, lack of banking provisions seems to have contributed to large fluctuations in the EU-ETS permit price (Box 6). Furthermore, since the emission date of one ton of carbon has little bearing for its ultimate climate impact, banking and/or borrowing provisions make sense from an environmental standpoint – provided the existence and stringency of future climate policy are credible.[82] However, banking and/or borrowing do not provide full certainty about minimum and maximum carbon prices.[83]

- Another option is to set a price floor and/or a price cap (or "safety valve") in order to reduce the risk of large price fluctuations, and thereby to benefit from some of the advantages of a tax. Such

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context. Any shock to (marginal) damages from emissions will typically entail the same welfare loss under a price and a quantity instrument, since such a shock would leave emissions unchanged in both cases.

[80] Longer-dated permits may not necessarily be needed provided banking is allowed and commitment periods are long enough. For instance, as discussed in IEA (2007c), extending the length of commitment period from five to ten years would significantly increase the visibility of the price signal.

[81] By comparison, for instance, the US subprime mortgage market (total outstanding amount of subprime loans) amounted to about 9½% of US GDP, or about 3% of world GDP at current exchange rates, in 2007 (OECD, 2007c).

[82] In particular, in a context where the stringency and even the existence of future climate policy may be uncertain, borrowing provisions may provide excessive incentives for emitters to defer emission reductions to the future.

[83] Indeed, banking (borrowing) can be effective at raising (lowering) permit prices only insofar as individual emitters expect (discounted) future prices to be higher (lower) than the current price.

"hybrid" instruments have been shown to be preferable to standard permit trading, including in the context of climate change (Roberts and Spence, 1976; Pizer, 2002).

- Yet another option would be to set intensity (*e.g.* emissions per unit of output) rather than absolute targets (Marcu and Pizer, 2002; Kolstad, 2006; Gupta *et al.* 2007; Jotzo and Pezzey, 2007). While intensity targets can help reduce carbon price uncertainty by allowing emission objectives to adjust automatically to unexpected economic growth shocks, they do not in general provide as good an insurance device as price caps,[84] may entail higher administration and compliance costs,[85] and could increase the uncertainty surrounding environmental outcomes.

- Finally, linking domestic schemes internationally would be expected to mitigate the impact of shocks and thereby to reduce price volatility, even though shocks could become more frequent as the system is no longer immune to developments in other areas. For instance, the carbon price effect of unexpectedly high short-run economic growth in one country would be lower under linked trading schemes than under a smaller domestic system, all the more so if the country considered is small compared with the overall area covered through linking.

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[84] See Herzog *et al.* (2006), Quirion (2005), Pizer (2005).

[85] See Dudek and Golub (2003) and Müller and Müller-Fürstenberger (2003).

Box 6. Lessons from the European Union Emission Trading Scheme

The EU-ETS was introduced in 2005 as a tool to help EU countries meet their obligations under the Kyoto protocol. After a three-year trial period (Phase I, 2005-2007), a commitment period (Phase II) will run from 2008 until 2012 to coincide with the commitment period of the Kyoto protocol, and is scheduled to continue beyond that horizon. The scheme covers emissions from energy-intensive industrial sectors that represent around half of European emissions.

The “trial” period aimed at developing the infrastructure and at providing a first experience with an international cap-and-trade system covering GHG emissions. It was not intended at reducing GHG emissions, all the more so as it quickly turned out that the amount of emission rights put only limited constraint on overall emissions. The system has successfully led to the emergence of a carbon price and the volume of transactions has steadily increased since 2005. Nonetheless, it has also encountered a number of problems, and from this perspective provides useful lessons for the design of emission trading schemes.

Lack of banking provisions and price volatility

Both spot and future price fluctuations have been very large under the EU-ETS, and the gap between both prices has also been highly volatile (Figure 1). In April 2006, several member states reported 2005 emission below market expectations, causing excess supply in the spot market. Because banking between the trial and the first commitment period was not allowed,[1] the spot price fell close to zero while the future price – which is determined by expectations of future supply and demand for allocations – remained stable. Had banking been allowed, as is the case under Phase II, allowances would have been stored for future use and the spot price collapse would have been avoided.

The impact of price fluctuations on firms’ decisions under Phase I was mitigated by the development of derivative markets. A firm that seeks to purchase rights to cover its emissions or hedge against the risk of unexpected emission changes can either purchase allowances in the spot market or purchase a future contract due in the compliance year, *i.e.* the year when allowances have to be surrendered. Transaction volumes steadily increased on both primary and derivative markets since the inception of the scheme, with transactions in the future market being driven more by financial considerations (hedging and speculation) than by the need for compliance. Although over-the counter trading remains the dominant form of trading, one-third of trades now takes place on exchanges and the main of these, the London Exchange ECX provides a range of derivatives including futures, options and swaps. Evidence suggests there has been no lack of intermediaries to facilitate trading among parties and that the market developed in a fashion similar to other financial and commodity markets (Ellerman and Joskow, 2008; Uhrig-Homburg and Wagner, 2007).

Allocation rules and perverse emission-reduction incentives

The allocation of emission rights to individual emitters, which was left to member countries, raised a number of concerns:

- Not only were permits typically allocated based on recent emissions levels, but individual emitters expected this grandfathering rule to continue to apply in future phases, thereby undermining emission reduction incentives compared with a situation where allowances would have been allocated once and for all (Neuhoff *et al.* 2006).

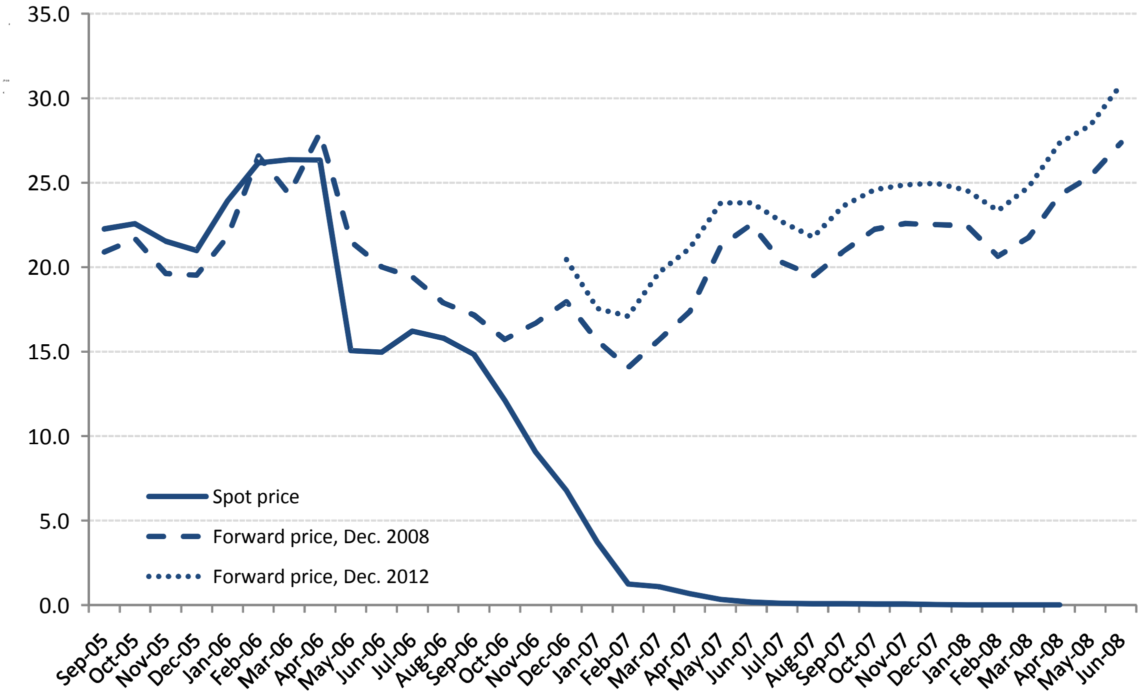
- All member States guaranteed a given volume of free allowances to new entrants, on the basis of their expected emissions.[2] While this provision was intended to boost competition by compensating new entrants for the cost of purchasing allowances, it may also have created incentives to set up fossil fuel power plants and bias technology choices towards more CO_2-intensive options (Buchner *et al.* 2006; Matthes and Ziesing, 2008).

- Virtually all industries received enough allowances to fully cover their emissions, with the exception of the electricity sector. The two main reasons for constraining primarily the electricity sector were its lack of exposure to international competition and the existence of cheap abatement opportunities, typically by switching from coal to natural gas.

Downstream schemes and coverage extension prospects

The EU-ETS is a downstream system (applying at the point of emission) that covers the main energy-intensive sectors. The threshold, in terms of heat input, for inclusion in the ETS is very low, hence a large number of small installations with a low contribution to emissions are included. This generates data collection and monitoring problems, as well as sizeable transaction costs (Buchner *et al.* 2006). In particular, reporting and verification requirements impose costs on small installations that are disproportionate to their emissions. Perhaps more importantly, the downstream nature of the scheme can be an important barrier to any extension of the scheme to other, currently non-covered, emission sources. One answer to these problems might be to move towards an upstream scheme covering refineries, gas terminals, coal mines etc.[3] Such a system would lower transaction costs and expand de facto the coverage of carbon pricing, with small installations facing similar emission abatement incentives than under a downstream scheme provided carbon prices upstream are fully passed onto them.

Figure 1. Carbon price fluctuations in the European Union Emission Trading Scheme



Source: Point Carbon and Caisse des dépôts.

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1. Banking is the possibility to transfer an emission right from one period to another one in the future. The reason for not having allowed banking was to prevent any compliance failure during the trial period to spill over into the second trading period, thereby compromising the chance to meet Kyoto objectives.
2. The amounts of free allowances allocated to new entrants varied from 0.5% in Germany and Poland to 6.5% in the United Kingdom.
3. Imported fossil fuels would also be covered.

5.3. Setting up predictable policy goals and adjustment mechanisms at the international level

75. Over time, permanent – as opposed to temporary – shocks to abatement costs and climate change impacts, reflecting *inter alia* new scientific, economic and technological developments, will call for policy adjustments, be they of taxes, emission caps or hybrid schemes. Permit and hybrid schemes may be most responsive to new information, because any change in the expected path of policy would immediately affect current emission prices,[86] while under a tax prices would remain fixed until a discretionary political

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[86] This holds provided banking is allowed. Otherwise only forward permit prices are affected.

decision is made to reset them. Policy changes will also be required to progressively improve the overall coherence and, hence, cost-effectiveness of the future international climate policy architecture, possibly starting from a situation of heterogeneous commitments and instruments across the main emitting areas. Two features of an international climate policy architecture that would help predictability include:

- *A combination of both long and short commitment periods* (see *e.g.* Buchner, 2007; Philibert *et al.* 2003). A long-term emissions abatement target could be backed up by a series of short-term targets, which could be updated on a regular basis. The former provides the long-run predictability needed for low-carbon investments, while the latter engage current governments and allow more frequent compliance checks, thereby reinforcing the credibility of the framework. In practice, international action against climate change tends to move gradually towards this approach.

- *Built-in adjustment rules.* This is to ensure predictability, alleviate the need for frequent renegotiation, and avoid potential time-inconsistency problems, which may arise insofar as governments may be tempted to ease the policy *a posteriori*, once irreversible investments in R&D and new equipment are made.[87] Such rules would determine in advance how country commitments would be adjusted to reflect new information. They may include "graduation mechanisms" to ensure that developing countries take on more stringent commitments or action as their income levels converge to the higher levels of developed countries, while opportunities for access to international financial and/or technology support then move on to less-developed countries.

76. "Rolling" commitment periods are a way to combine these two features.[88] Under rolling commitments, short-term commitments (*e.g.* over a five-year period), or multi-period commitments (*e.g.* over three five-year periods) would be automatically extended based on built-in adjustment rules, including possibly an "escape clause" to smooth the target under exceptional circumstances. In order to reduce short-run cost uncertainty, emissions may then be allowed to fluctuate from year to year within each commitment period. An extension of this type of commitment is to allow intermediate targets to be reached within a range, or "gateway", instead of fixing them.[89] These gateways would allow greater medium-term flexibility, but they should be consistent with the long term objective. Under both the "rolling commitment" and "gateway" proposals, long- and short-term commitment periods may be renegotiated on a low-frequency basis, in order to reflect fundamental changes in climate damages and/or abatement costs.

6. Building political support for action

6.1. Costs and benefits from mitigation and countries' incentives to participate in a global agreement

77. The costs and benefits from mitigation policies are expected to be unevenly distributed across countries. With a global carbon tax – or equivalently full auctioning of emission permits – and for any given concentration target set in a global emission mitigation agreement, countries that use carbon

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87. Governments might be tempted to reduce energy prices a posteriori in order to meet other policy goals, such as income distribution or international competitiveness objectives (see *e.g.* Helm *et al.* 2004; Helm, 2005; Kennedy and Laplante, 1999). Alternatively, drawing a parallel with the monetary policy literature, the time-inconsistency problem may be addressed by delegating the power to set the price of carbon to an independent climate policy authority, akin to a "conservative" central banker. However, ensuring that such an institution retains full independence may be easier in a national, rather than in an international, context.

88. See in particular the Sao Paulo Proposal (BASIC, 2006), and the UK Climate Change Bill under consideration (http://www.defra.gov.uk/ENVIRONMENT/climatechange/uk/legislation/index.htm).

89. See in particular the Australian Prime Ministerial Task Group on Emissions Trading (2007).

intensively and/or export fossil fuel (see Figure 2.5), such as Russia and the Middle East,[90] would face the largest GDP costs (Figure 6.1).[91] In general, despite their cheaper emission abatement opportunities, non-OECD countries are affected much more than OECD countries because the level and growth of their output is more intensive in fossil fuels. The impacts of climate change – and hence the benefits from mitigation policies – are also expected to vary largely between countries and regions, depending *inter alia* on geography and the profile of economic activity (*e.g.* the share of the agricultural sector activity). Even under moderate temperature increases, developing countries are expected to be more affected than developed countries on average, and to face higher risks of large damages, as reflected by the wider variance across damage estimates (Figure 6.2).[92]

[Figure 6.1. Regional costs from stabilising long-run GHG concentration at 550 ppm]

[Figure 6.2. Regional economic impacts]

78. As a result of this distribution of benefits and costs of mitigation policies, incentives to participate in a global agreement differ across countries. Avoided future climate damages from a uniform world carbon price seem smaller relative to the high costs of action in areas such as Russia and the Middle East. Furthermore, a number of developing countries including China and India would face both costs and benefits from global action above average, but the mismatch between the short-term nature of the costs and the long-run horizon of the benefits could affect their participation incentives in view of their legitimate growth concerns.[93] Finally, all countries – especially small ones – have an incentive to "free-ride" on the mitigation measures taken by others.

Possible strategic response of fossil fuel producers

79. One important, but often ignored issue is the potential strategic response of fossil fuel producers to current and/or expected world mitigation policies. Model-based simulations typically assume constant supply curves for fossil fuels, along which supply would vary as a result of shifts in world demand. In this context, a decline in world demand brought about by mitigation policies is supposed to reduce both the (relative) price and the supply of fossil fuels. However, in order to alleviate the resulting income loss they would incur, producing countries might instead behave strategically. In particular, an international climate policy agreement that implies a rising carbon price path over the future – as would typically be expected to be the case – would lower the expected future world price of fossil fuels relative to their current level, *ceteris paribus*. This might induce fossil fuel producing countries to anticipate some of their projected future output, *i.e.* they might *increase* rather than reduce their current output (Sinn, 2007).[94] *A contrario,*

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[90] This holds at least provided fossil fuel producers do not behave strategically (see below).

[91] Countries with large emissions from deforestation could also face high costs if these emissions were covered by a mitigation policy, but this is not reflected in this simulation.

[92] This variance might be over-estimated, however. This is because the sample of studies from which it is derived includes first-generation estimates that typically did not take into account adaptation and thus might have over-estimated impacts, e.g. in the agricultural sector.

[93] *Ceteris paribus,* above-average expected consumption growth should translate into a higher consumption discount rate, hence lowering the present value of the long-run benefits from action.

[94] In theory, under perfect foresight, in the absence of uncertainty, and assuming fossil fuel reserves are expected to be depleted over a finite horizon, the so-called Hotelling's rule states that fossil fuel producers should adjust their supply until the expected percentage rate of (real) price increase equals the (real) interest rate (abstracting for simplicity from extraction costs). Starting from this equilibrium, any unforeseen event – such as a steeper than expected future carbon price path – that lowers the future expected rate of increase in world fossil fuel prices would make it profitable for producers to sell more

they might coordinate for a preventive supply cut to discourage fossil fuel consuming countries to take action. In principle, a coordinated supply cut could achieve the same reduction in world consumption of fossil fuels as a demand cut, but at a much lower (higher) cost to fossil fuel producers (importers), as they would enjoy an improvement (suffer a deterioration) rather than a deterioration (an improvement) in their terms of trade. This would require a high degree of coordination among oil and coal producers, however.

6.2. Assessing the participation incentives associated with co-benefits from mitigation policies

80. There is a potentially large and diverse range of co-effects from climate change mitigation policies, which lower the net costs of emission reductions and thereby may strengthen the incentives to participate in a global agreement. Two important co-effects discussed below are the reduction in local air pollution (LAP), which has effects on human health and crop yield,[95] and the implications for energy security. There are other co-benefits of GHG mitigation policy, however, for instance on ecosystems and biodiversity.

Local air pollution co-benefits of mitigation policies

81. There are local air pollution (LAP) benefits from pursuing GHG mitigation policies, and the participation incentives they provide depend positively on: *i)* on the size of these co-benefits; and *ii)* the cost of achieving the same level of reduction in LAP through direct policies.[96][97] The majority of past studies have focused on local air pollution (LAP) control co-benefits that stem from GHG mitigation policies. The main conclusion is that GHG mitigation could yield large near-term co-benefits in terms of reduced human health risks, which might cover a significant part of GHG mitigation costs (Figure 6.3; OECD *et al.* 2000; OECD, 2001). However, little is currently known about the incentive power of these co-benefits. Here, analysis is undertaken based on an extension of the Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE) that includes, however, only outdoor LAP and its health impacts (Bollen *et al.* 2008, 2009). The analysis covers the main pollutants having impacts on health,[98] with the important exception of tropospheric ozone.[99] The model is used to simulate the costs and benefits of GHG and LAP policies in a general equilibrium, dynamic, multi-regional and multi-sectoral framework.

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today and invest the revenues at the prevailing interest rate. World output would then rise until current fossil fuel prices fall – and their expected rate of increase rises – sufficiently to restore Hotelling's rule.

[95] There are also effects of LAP on visibility, water supply and water quality that have been seldom quantified.

[96] Indeed, the net return from investing in mitigation policy should be computed as the benefit – in terms of avoided global climate change and local air pollution – of the policy minus the cost of mitigation policy, to which the opportunity gain of not having to achieve the same level of LAP reduction through direct policies should then be added.

[97] Ideally, given that there are also co-benefits from pursuing LAP control on GHG emissions, policies to control GHG and LAP would be jointly pursued and optimised (see Bollen *et al.,* 2008, 2009).

[98] The model includes "fine" particulate matter (PM2.5) from the combustion of solid or liquid fuels in both rural and urban areas – which account for a large amount of the health damages of outdoor LAP – as well as secondary aerosols (SO_2, NOx) from the combustion of oil and coal and NH3 from agriculture.

[99] The impact of ozone on health is not treated as a co-benefit but is included in the damages from climate change. The impacts of climate change are represented in a stylised way through region-specific market and non-market damages functions. Non-market damages depend on the average global temperature level and include the damages from exposure to high ozone concentrations.

[Figure 6.3. Review of existing regional estimates of the co-benefits in 2010 at different GHG emission prices]

82. Somewhat surprisingly, under a global carbon price scenario and for modest world emission cuts (*e.g.* 25%) and/or over relatively short horizons (*e.g.* 2020), the percentage of decline in premature deaths relative to baseline induced by GHG mitigation policies is estimated to be smaller in China and India than in OECD countries (Figure 6.4, Panel A). This is partly because LAP in the OECD is mainly driven by the demand for transport services, whereas outside the OECD a major driving force is coal burning by households.[100] Moreover, compared with OECD countries, cheap GHG abatement opportunities in developing countries over the next twenty years are more in the electricity sector than in transport, and emission reduction technologies have less impact on LAP in the former than in the latter. Also, population exposure to LAP is usually larger when pollution results from small point sources in transport and homes than from large-scale point sources such as power plants. However, for more stringent emissions cuts or over longer horizons, co-benefits ultimately become higher in many non-OECD countries than in their OECD counterparts, as cheaper CO_2 abatement opportunities in the electricity sector in non-OECD countries get exhausted and OECD countries run out of options to reduce LAP through GHG mitigation policies, not least in the transport sector (Figure 6.4, Panel B).

[Figure 6.4. Avoided premature deaths from reduced local air pollution through GHG mitigation policies]

83. To compare the co-benefits to the cost of mitigation policies, the number of avoided premature deaths needs to be converted into a monetary equivalent, based on an explicit assumption about the value of statistical life (VSL). Here, the premature death from long-term exposure to air pollution is valued at 1 million US$ in Europe in 2000, corresponding to the median value across a range of available studies (Holland *et al.* 2005).[101] For other regions and years, this value is adjusted proportionally with the GDP per capita gap relative to Europe in 2000 (for details and sensitivity analysis, see Bollen *et al.*, 2009). As a result, the co-benefits of mitigation policies per ton of carbon in monetary units are lower in non-OECD countries than in their OECD counterparts, although they are projected to increase somewhat over time with income growth and urbanisation (Figure 6.5).While the average co-benefit per ton of carbon cannot be directly compared to the carbon price, which is the marginal cost of abatement and as such exceeds the average cost, the analysis suggests that co-benefits could cover a sizeable part of mitigation costs. Finally, under a uniform carbon price scenario, emissions reductions would be larger in non-OECD countries, and as a result co-benefits would also be larger when expressed in percentage points of GDP (Figure 6.6).

[Figure 6.5. Co-benefits per ton of CO_2 equivalent and GHG emission prices]

[Figure 6.6. Co-benefits of reducing GHG emissions by 50% in 2050]

84. Although – in line with previous literature – LAP co-benefits are found to be large and to offset a sizeable share of GHG mitigation costs, they alone are unlikely to provide sufficient incentives for wide participation into a global GHG mitigation agreement (Figure 6.7).[102] This is because the cost of achieving

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[100] The model includes the impact of emissions from households' energy consumption on outdoor pollution but not on indoor pollution.

[101] This median value is computed across a range of estimates that specifically value mortality from air pollution (Holland *et al.* 2005). It is lower than existing estimates for other risks, such as occupational hazard. Sensitivity analysis around this parameter is provided in Bollen *et al.* (2009).

[102] Over a longer horizon (*e.g.* 2100), the gains from GHG mitigation are expected to be large and to outpace mitigation costs. Given the valuation assumptions and the fact that GDP per capita is projected to remain higher in China than in India, co-benefits are found to be higher in China than in India at the 2050 horizon.

the same level of LAP reduction through direct policies is estimated to be low, thereby reducing the incentive to reduce LAP indirectly *via* GHG mitigation (see Bollen *et al.*, 2009).[103] This finding should be interpreted with care, however, given the various uncertainties surrounding for instance the baseline projection for local pollutant emissions or the link between average pollutant concentration and the number of deaths.[104] Furthermore, as in the rest of the literature, the above estimates omit the possible co-effects of GHG mitigation on indoor air pollution (cooking smoke) from biomass and coal, which could be significant but of uncertain sign.[105]

[Figure 6.7. GDP impact of participating in a global climate change agreement to reduce GHG emissions by 50% in 2050: with and without co-benefits from local air pollution control]

The energy security implications of mitigation policies

85. By reducing the reliance of economic activity on fossil fuels, mitigation action may also provide co-benefits in terms of improved energy security. Energy security may be broadly defined as a low risk of disruption to energy supply, both in terms of physical availability and price stability (see *e.g.* Bohi and Toman, 1996). Given that oil and coal markets have been liberalised in OECD and many non-member countries, any physical shortage is likely to be short lived, as prices ultimately adjust. Furthermore, in fairly integrated world oil and coal markets, all countries essentially face similar import prices, regardless of the geographical structure of their imports. In the case of natural gas, longer-lasting physical shortages may still occur where national prices are regulated or pegged to the price of oil under long-term contracts, as in a number of European countries. Furthermore, the geographical source of the disruption can matter because gas-pipeline infrastructure is inflexible, so that any supply loss cannot always readily be offset by an increase in supply from other sources. Insofar as gas markets will increasingly function like oil and coal markets over the horizon considered – as they are further liberalised and liquefied natural gas gains prominence-, energy insecurity would depend primarily on the overall energy intensity of the economy, as well as on overall import dependence and the fuel mix, with some fossil fuels being more prone to price volatility than others. Governments have used a variety of tools – *e.g.* coordinated use of emergency oil stocks –to address short-run energy security risks. However, these do little to tackle longer-term energy security concerns, stemming in particular from inelastic supplies and high concentration of world fossil fuels output into the hands of a small number of producers, which carry a risk of large unexpected price shifts, *e.g.* as a result of political events. This is primarily an issue for oil – as the share of OPEC in world output is projected to rise significantly over the next three decades in the absence of any further policy action – and gas (IEA, 2007d).[106]

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[103] However, for stringent levels of LAP, structural adjustments would be needed that would incidentally lead to GHG emissions reductions. More broadly, there are synergies and higher returns to control both GHG and LAP and to maximise benefits across these areas (see Bollen *et al.*, 2008, 2009).

[104] The parameter linking average pollutant concentration to the number of deaths is calibrated to relatively low concentration levels of PM2.5 in the United States (see Pope *et al.* 2002). Insofar as it turns out to be smaller (higher) for higher concentration levels, the size of the co-benefits estimated here would be biased upwards (downwards). Also, the baseline projection for LAP assumes that regulations remain in place and are implemented, leading to fairly benign trends in PM. With higher local pollutant emissions in the baseline, the co-benefits of GHG policies would be larger. However, the current baseline appears to be consistent with the recent dynamics of LAP substances in China (MNP, 2008).

[105] These co-effects might be negative. Indeed, since a carbon price would not be imposed on (carbon neutral) biomass fuels, it could provide (perverse) incentives to use or maintain biomass fuels for cooking, thereby increasing LAP and the local health damages from GHG mitigation policy.

[106] However, no cartel structure currently exists in world gas markets, and concentration is projected to decline from already lower levels than in the oil market – at least when OPEC is considered as one single oil

86. Climate change mitigation action would be expected to improve long-term energy security on three main grounds: *i)* by slowing the pace of depletion of oil reserves in non-OPEC regions, it would curb the projected rise in the OPEC market share and thereby reduce the potential for large unforeseen shifts in world oil prices;[107] *ii)* by reducing the energy and fossil fuel intensity of economies, it would soften the macroeconomic impact of any future price shocks; *iii)* by fostering greater use of renewable and nuclear energy, and the development of alternative energy sources more broadly, mitigation policy may also lead to greater energy risk diversification. Such energy security gains are likely to vary across countries, depending *inter alia* on their overall fossil fuel intensity, the diversity of their energy mix – in particular their reliance on more volatile oil, the extent to which local production provides a hedge against consumption exposure – with terms of trade gains then partly offsetting any macroeconomic cost from price spikes, or their degree of resilience to macroeconomic shocks. Given that pricing carbon induces firms to shift away from more carbon-intensive coal towards less carbon-intensive oil and gas, gains in the energy security of large coal producers and consumers (*e.g.* Australia, United States, China, India, Indonesia, or South Africa) might be lower, *ceteris paribus*.[108]

87. OECD ENV-Linkages simulations provide some preliminary, incomplete illustration of the energy security benefits of world emission cuts. While the gains from reduced concentration of world fossil fuels output and greater diversification of the energy mix cannot yet be explored with the current version of the model,[109] a world carbon price scenario consistent with a 550 ppm CO_2eq GHG (450 ppm CO_2 only) concentration stabilisation target would significantly reduce fossil fuel intensity (Figure 6.8). However, this decline would be comparatively smaller than that already projected in the baseline scenario, which reflects future expected improvements in energy efficiency. It would also be somewhat smaller for oil and gas than for coal, reflecting both greater incentives to shift away from coal and more limited substitution options for oil and/or gas in the non-electricity sector. Yet, the risk of oil price shocks is expected to be the most significant source of energy insecurity over the coming decades.

[Figure 6.8. Projected fossil fuel intensities in world regions under baseline and 550 ppm GHG concentration stabilisation scenarios]

88. In assessing individual country mitigation incentives, it is important to account for the free riding incentives associated with the world public good nature of energy security. Indeed, international action by a sufficiently large group of countries to curb their demand for fossil fuels would lower future world prices and market concentration, thereby benefiting non-participants. On the other hand, preliminary evidence suggests that free riding does little to reduce macroeconomic exposure to fossil fuel price shocks. For instance, a 50% cut in Annex I country emissions by 2050 would only marginally affect fossil fuel intensity in China and India, as the impact from reduced world prices would be offset by a rise in demand (Figure 6.9). Comparatively, a 50% cut in world emissions involving action by China and India – here through a world carbon price – would have a much greater impact on the fossil fuel intensity of these two countries, and therefore on their vulnerability to oil price shocks, *ceteris paribus*.

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producer. In the case of coal, the marginal cost of production rises only slowly with global output, due to ample world reserves. The resulting high world supply elasticity is expected to limit the risk of long-lasting price shocks (IEA, 2007a).

[107] This holds only insofar as expectations of future carbon price increases do not induce OPEC producers to raise output – and thereby deplete their reserves – more than assumed over the coming decades (see above).

[108] Wide expansion of CCS would induce a major change in that regard, as it would make it possible for countries to cut their emissions while continuing to rely heavily on coal.

[109] This is due to lack of explicit stock-flow modelling of fossil fuels reserves and insufficient disaggregation of the electricity sector in the model.

[Figure 6.9 Projected fossil fuel intensities in world regions under different mitigation policy coverages]

6.3. *Distributing the costs of mitigation policies across countries*

89. Insofar as the benefits of mitigation policies are not large enough to induce all main emitters to join an international agreement, at least in the near term, redistributing the costs of action in a way that boosts participation incentives might be considered. Possible burden-sharing devices include *inter alia* permit allocation rules in the context of a global permit trading architecture, the Clean Development Mechanism (CDM), technology transfers and setting up funds or market-based incentives to curb deforestation. Depending on their design, they may vary with regard to their ability to shift costs, cost effectiveness and environmental integrity.

Redistributing costs within a global permit trading architecture

90. Emission allowance allocation rules would have large effects on the distribution of overall mitigation costs across countries, and could be designed to shift at least some of the burden away from developing countries, compared with a global auctioning or world carbon tax scenario. In a hypothetical benchmark scenario where a world carbon market is implemented, one possible allocation rule would be to distribute allowances on a per-capita basis, *i.e.* to grant the same amount of emission allowances to every human being. Another possibility would be an ability-to-pay rule based on income per capita, as was apparently an implicit outcome of negotiations on the Kyoto Protocol (OECD, 1999). By contrast, a *grandfathering* rule that allocates future emission rights based on current or past emissions would primarily benefit developed countries, especially those that emit most on a per-capita basis. Whatever the allocation rule, overall mitigation costs at the world level would be little affected provided the allowances were tradable at the world level, as the geographical structure of emission reductions would then be roughly unchanged across scenarios, and be driven by marginal abatement cost differences.[110] In other words, allowance allocation rules essentially create a disconnection between who takes action – ensuring mitigation action takes place wherever it is least cost – and who pays for that action.

91. Under a global permit trading architecture, the impact of any rule on the cross-country distribution of costs would ultimately depend on whether countries become permit exporters or importers once permits are allocated. Permit exports are equivalent to a net financial inflow, and as such they boost national income and the real exchange rate. Looking at the 2050 horizon, ENV-Linkages simulations show that under a *per capita* rule, poorer countries – such as India and the "Rest of the World" region of the model – would be permit exporters, while all other areas would import permits (Figure 6.10, Panel A), with these flows growing with the carbon price (Figure 6.10, Panel B). Russia, and to a lesser extent China, would be penalised by their demographic decline and carbon intensity. Results would be roughly comparable under the illustrated ability-to-pay rule simulated here.[111] By contrast, under a *grandfathering* rule,[112] Russia and China, but also carbon-intensive developed economies, such as the United States and

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[110] In practice, permit allocation rules have second-order effects on aggregate mitigation costs in the ENV-Linkages model, due to the impact of the income transfers on capital accumulation in the different regions of the model. For instance, compared with a grandfathering rule, a per capita rule is found to be less costly, as it redistributes world income towards regions where the marginal product of capital is higher.

[111] Under this rule, permits are assumed to be allocated every year to each individual worldwide in inverse proportion to the gap between this individual's GDP per capita and average world GDP per capita (in PPP terms).

[112] Under the grandfathering rule considered here, permits are assumed to be allocated based on each region's share of world emissions in 2012.

the "Australia-New Zealand" region, would be permit exporters, while India and the "Rest of the World" would import permits.

[Figure 6.10. International permit trade flows under alternative permit allocation rules]

92. Reflecting these large international financial transfers, allocation rules affect the distribution of income more than the distribution of GDP across countries (Figure 6.11). This is because the large financial flows associated with permit trading would induce significant changes in the terms of trade, over and above the GDP effects of mitigation action.[113]

[Figure 6.11. The impact of permit allocation rules on the distribution of mitigation costs across countries, 2050]

93. None of the simple illustrative rules examined here would alone address all key distributional issues. Regardless of the allocation rule, world mitigation efforts would impose large income losses – reflecting declines in both terms of trade and GDP – on Russia and OPEC countries, at least if these do not engage in strategic behaviour. With the exception of China, developing countries would lose more from grandfathering than from world permit auctioning or a world carbon tax.[114] The reverse would hold for most OECD countries – albeit marginally for the European Union – and Russia.[115] Unlike grandfathering, a per capita allocation rule would reduce the cost and even provide a gain for less developed countries, but it would impose very large income losses on Russia and other CIS countries and, to a lesser extent, China, Canada and Australia-New Zealand. An ability to pay rule would not fundamentally reduce the costs for middle-income economies that use carbon intensively and/or export fossil fuels, although it has the advantage of taking explicitly into account cross-country differences in income per capita levels. Finally, it should also be borne in mind that no simple allocation rule would specifically address the "free-rider" problem, *i.e.* even those countries that gain from a particular rule may still not have an incentive to participate in an agreement if the gain from opting out is even larger.

94. Permit allocation rules may also need to be designed in a way that avoids creating market power in world permit markets. Under sovereign permit trading, insofar as permits can be stored for future use (*e.g.* in the context of multiphase programmes) a monopolistic permit seller would drive a wedge between the permit price and its own marginal abatement cost, thereby preventing marginal abatement cost equalisation across all emitters, with the consequence that permit buyers would be forced to abate more at a higher cost.[116] As a result, the overall cost-effectiveness of mitigation policies would be reduced. The market power issue arose in the context of the Kyoto Protocol, with studies showing that a cartel formed by transition countries – including, in particular, Russia and Ukraine – could lower the gains from the international trade mechanism (Maeda, 2003; OECD, 1999). The most straightforward way to alleviate this

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[113] Financial transfers could range from 0.8% of world GDP under a grandfathering rule to 1.5% of GDP under a per capita rule.

[114] As in the rest of this paper, the world carbon tax scenario assumes there is no redistribution of the tax revenues across countries.

[115] In some cases, this is despite a "Dutch disease" effect through which the real exchange rate appreciation induced by permit exports would have detrimental effects on output.

[116] Even in the case where permits cannot be stored, a monopolistic permit seller might still find it profitable not to use or sell some of its permits.

concern would be to avoid international permit trading among sovereign states, *e.g.* by agreeing that governments allocate their allowances to their (typically smaller) domestic firms.[117]

The transfer of funds through CDM and other cooperation devices

95. Transfers of private funds from developed to developing countries are already underway as part of the CDM, one of the flexibility mechanisms of the Kyoto Protocol, under which industrialised countries with a GHG emissions constraint ("Annex I "countries) are allowed to meet their commitments by financing (typically cheaper) emission-reducing projects in developing countries. The number of CDM projects and the associated amount of emission credits has risen rapidly since 2005, especially as European firms covered by the EU-ETS used it increasingly to meet their emission commitments (Figure 6.12). However, emissions cuts through CDM remain a very small share of total emissions. Over half of the expected credits from the CDM come from projects implemented in China, and about a quarter in India and Brazil. More broadly, recipient countries have not been the poorest economies, but rather emerging countries with relatively advanced infrastructure and large emissions reduction potential. So far, the bulk of emissions credits have come from non-CO2 gas reductions and renewable projects and, to a lesser extent, from energy efficiency improvements and fuel switching projects.

[Figure 6.12. CDM development, host countries and allocation across sectors]

96. The cornerstone of the CDM is the so-called additionality criterion, under which only emission reductions that would not have taken place without the additional incentive provided by the CDM should give rise to emission reduction credits. The certification process, which requires supervisory authorities in the host country and, most importantly, the CDM Executive Board (EB) to validate and verify projects by companies, have faced increasing problems as the CDM gained prominence in recent years:

- Validation on a project-by-project basis is a lengthy process, with risks of delays at many stages of the project cycle. It takes on average ten months for a project to be submitted to the EB as a result of bottlenecks in the auditing process, and the time needed for the EB to reach a final decision has been increasing over time, reflecting the difficulty of checking the additionality (Figure 6.13). With a major scaling up in the global carbon market, pressures on the system would intensify further, creating a *de facto* supply constraint that could raise carbon price levels and volatility in cap-and-trade systems.

- Transaction costs can be large, including consulting and registration fees at each stage of the project cycle, reaching up to $US200 000 for a large project (Ellis and Kamel, 2007).

97. Furthermore, certified emission credits may not always correspond to actual emission cuts, in which case they amount to a mere income transfer to recipient countries and generate carbon leakage. This reflects fundamental problems associated with checking the "additionality" criterion, due to both the inherent difficulty of establishing a counterfactual and the information asymmetry between investors and the regulator (the EB). Moreover, integrity problems may have emerged since part of the evaluation is done within the host country by staff paid by the project developer (Wara and Viktor, 2008). The mere existence of the CDM might also slow down the pace of energy efficiency gains in developing countries, as firms have an incentive to wait for the corresponding projects to be financed through the CDM. Finally, even when projects generate actual emissions reductions relative to baseline, the financial transfer still generates some leakage. This is because emissions remain set by the cap(s) in developed countries, while

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[117] Another argument for avoiding sovereign permit trading is that states are likely to have insufficient information about the marginal abatement costs of their domestic firms to define their own aggregate marginal abatement costs (see *e.g.* Aldy and Stavins, 2008).

they rise in developing countries as a result of increased income and aggregate spending (Bollen *et al.* 2005).

[Figure 6.13. Bottlenecks associated with checking the "additionality" criterion]

98. Despite these drawbacks, scaling up the CDM may be warranted in the absence of a global permit trading architecture involving all main emitters. It would be a first step towards putting a price on carbon in developing countries, while allowing developed countries to meet their commitments at a lower cost. To this end, ways will have to be found to reduce bottlenecks and transaction costs drastically without undermining the environmental integrity of the mechanism. One option would be to move away from a project-by-project approach towards "policy" or "sectoral" CDMs, where emissions would have to be cut relative to a baseline policy scenario (including *e.g.* energy subsidies) or relative to baseline emissions of a particular sector (*e.g.* energy intensive industries), respectively (see *e.g.* Bosi and Ellis, 2005; Baron and Ellis, 2006; Aldy and Stavins, 2008).[118] This could raise dramatically the supply of credits and reduce transaction costs. Nonetheless, it would not address the "additionality" problem, it would not fully contain leakage more broadly (Baron *et al.* 2007), and it would not deal with the potentially perverse incentives to slow the pace of energy efficiency gains. From this (environmental) perspective, a binding international sector-wide agreement featuring sectoral emission caps and permit trading could be more effective. Another option would be to remove the links between the CDM and the world carbon market, *e.g.* by replacing the CDM by a world fund that would finance emission reductions in developing countries through reverse auctioning. While this would not address the "additionality" problem *per se*, it would at least preserve the environmental integrity of emission trading schemes.

99. Scaling up the CDM may also facilitate technology transfers to developing countries, but formal technology transfers could also be fostered – thereby providing incentives for developing countries to participate in an agreement – through global funds to finance mitigation or adaptation projects.[119,120] Nonetheless, as noted in Section 4, transferring specific technologies may run a number of risks.[121] Therefore, the impact of technology transfers should be closely monitored. Patent buy-outs offer another, fairly neutral way to ease technology diffusion, as they would leave firms in developing countries free to choose their technology mix.

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[118] Another, complementary option to mitigate the "additionality" problem would be to introduce competition between the various proposals to reduce emissions in a particular area or sector in order to help reveal the baseline emissions path.

[119] Various funds for technology transfers already exist, including the "Global Environment Facility" by the UNDP, UNEP and World Bank. The United States, the United Kingdom and Japan have recently announced the launch of a "Clean Technology Fund" to help developing countries finance advanced technologies to cut greenhouse gas emissions and other pollutants, and Mexico as proposed a "World Climate Change Fund" that would act as a complement to the Kyoto protocol by gathering and extending existing funds.

[120] Formal cooperation to share technologies might have played a role in phasing out ozone-depleting substances, in the context of the Montreal Protocol (de Coninck *et al.* 2007). As part of the Montreal protocol, industrialised countries provided funding to help developing countries take measures and implement technologies to phase out ozone-depleting substances. While the experience was successful, it is unclear whether success came from cost sharing or strictly from technology transfers.

[121] These include locking-in technologies that may not be fully adapted to each country's characteristics – due *e.g.* due to lack of human capital – and "crowding out" other investments. See also Philibert (2004).

Finding an appropriate way to integrate actions to reduce deforestation into an agreement

100. As noted previously (Section 3), a cost-effective post-2012 climate policy framework would likely have to include specific mechanisms to reduce emissions from deforestation and forest degradation in developing countries – and to enhance forest carbon sinks more broadly. Reducing deforestation specifically for its global climate benefits would however also deprive developing countries in Central and South America, Africa and South East-Asia of significant sources of income. In contrast, many developed countries enjoyed these economic gains from deforestation in the past, and policy options to address deforestation may have to deal with this asymmetry. An international financing mechanism could provide incentives to curb either deforestation relative to a baseline scenario, or the rate of utilisation of each country's overall *potential* capacity to grow forest (*i.e.* including potential reforestation).[122] This option raises several technical and methodological issues associated with: *i)* measuring and monitoring emissions from deforestation; *ii)* projecting future emissions from deforestation in a baseline scenario, or estimating overall potential forest capacity; *iii)* estimating the opportunity cost of avoided deforestation; *iv)* avoiding leakages, if some countries are not covered by the agreement; and, *v)* addressing the so-called "permanence" problem, *i.e.* the risk that some of the carbon emissions avoided through the financial mechanism may be merely postponed until later in the future (Karousakis and Corfee-Morlot, 2007).

101. Major improvements in the monitoring and reporting of emissions from deforestation and forest degradation are urgently needed in order to develop consistent and comparable national emission inventories across countries. Insofar as these technical issues can be addressed, deforestation and forest degradation could be incorporated into a global permit trading architecture. This would address leakage concerns insofar as a sufficiently large share of world forestry is covered. In the absence of an international carbon price covering emissions from forestry, two types of financial incentive mechanisms may be considered and are currently under discussion.[123] Countries that reduce emissions from deforestation relative to a baseline could either receive a direct financial transfer (*e.g.* through a fund mechanism) or could benefit from emission reduction credits that could then be sold in carbon markets, including as part of the CDM. Should the direct transfer option prevail, it would be important for cost-effectiveness to link the amount of transfers to international carbon prices, at least insofar as available funding for such transfers is unconstrained.[124] Nonetheless, both options should best be viewed as transitory, as none of them would fully address the permanence problem or the risk of leakage, unlike a permanent economy-wide emissions cap.[125]

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[122] Reducing emissions from deforestation and forest degradation would also provide co-benefits to countries with forests, such as the conservation of biodiversity and the protection of watersheds.

[123] Reducing emissions from deforestation in developing countries (REDD) is currently discussed under the UNFCC. Recent proposals to integrate avoided deforestation in an international climate policy architecture are presented in Santilli *et al.* (2005) and Schlamadinger *et al.* (2005), and reviewed in Karousakis and Corfee-Morlot (2007).

[124] Cost-effectiveness requires that the marginal (opportunity) cost of carbon emissions from deforestation (and forest degradation) abated through the direct financial transfer be equal to the marginal abatement cost in other areas and countries, which in turn is equal to the international carbon price. In case funding available for such income transfers is constrained, their cost-effectiveness could be maximised through reverse auctioning.

[125] In the presence of a permanent economy-wide cap and under adequate monitoring, forest owners would not have incentives to merely postpone deforestation, as future deforestation would entail an opportunity cost – the cost of buying permits or the opportunity cost of not selling them. Without a permanent economy-wide cap, the risk of non-permanence could still be mitigated by holding forest owners fully liable for their carbon stocks, even in future commitment periods.

6.4. National income distribution effects and policy answers

102. Obstacles to mitigation action may arise from lack of consensus not only at the international but also at the domestic level. One reason is that energy-intensive industries exposed to international competition might oppose the adoption of cost-effective policies. Section 3 has argued that stringent sector-wide agreements in energy-intensive industries can help address such competitiveness-driven concerns. Grandfathering emission permits is another option, but it comes at a cost to society and therefore needs to be at most partial and to be phased out quickly.

103. Another source of opposition to mitigation policies could be the possible impact on employment and income distribution across households. Employment effects are likely to be very limited and transitory, especially if the price of carbon increases only gradually. Regarding income distribution, the limited available evidence suggests that in developed countries, poorer households are more likely to be affected by policies that raise energy prices, as they spend a somewhat larger proportion of their income on energy-related products (OECD, 2006, Hasset *et al.* 2008).[126][127] On the other hand, the benefits of policies in terms of health outcomes may disproportionately accrue to lower-income households. Existing social transfer schemes would mitigate any income distribution effects of carbon pricing. More fundamentally, mitigation policies are just one among many influences – such as technological change – on income distribution. In any event, targeted exemptions to carbon pricing should be avoided, as they distort incentives to reduce fossil fuel consumption and thereby entail costs for the economy and/or the environment. In developing countries, the impact of higher energy prices on income distribution may be less of a concern, since expenditure patterns suggest that richer households may be more affected than poorer ones.[128] The challenge there is rather to gradually replace existing fuel and other subsidies to GHG-emitting activities by more advanced and less costly social policy tools.

7. Agenda for future work

104. A number of the main issues future international climate policies will have to address have merely been touched upon in this paper, but many of these warrant further analysis as part of the planned follow up to this project. Reflecting the discussions at the last OECD Ministerial Council Meeting in June 2008, as well as those of Environment Ministers when they met in April 2008, issues to be explored in greater depth in a second phase of joint work between the Economic Policy Committee's Working Party No.1 (WP1) and the Environment Policy Committee's Working Party on Global and Structural Policies (WPGSP) might include:

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[126] The impact of carbon pricing is found to be regressive in countries such as Australia, Sweden, the United Kingdom or the United States, and neutral or progressive in Italy and Spain (OECD, 2006b). Furthermore, partly because poorer households have lower saving rates, carbon pricing appears to be less regressive when measured in terms of consumption – which would be expected to capture lifetime expected income – than in terms of current income (Poterba, 1991 and Hasset et al. 2008). Also, the direct impact of carbon pricing on the consumption of fossil fuels is found to be more regressive than its indirect effect via the rise in the price of other goods (Hasset *et al.* 2008).

[127] The regressivity of carbon pricing might be larger under grandfathering insofar as the rents associated with grandfathered permits would ultimately accrue to shareholders and stock ownership is skewed towards the better-off (Parry, 2003).

[128] Carbon taxation has been found to be progressive in China, India, Mexico and some African countries (on India, see Datta, 2008; on China, see Boyce et al. 2005). This reflects the concentration of car ownership in the hands of high-income households, and the fact that poorer households use less fuel for home heating and more biofuel for cooking. Therefore, while a tax on kerosene only would be regressive, a broader tax on fossil fuels would not.

- Further work on leakage and competitiveness issues. Further simulations would be undertaken to explore the effects of a broad range of possible international climate policy arrangements, including various combinations of economy-wide and sector-wide mitigation actions. Also, more work is needed to assess fossil fuel supply elasticities, as well as their influence on the leakage rate and competitiveness effects of mitigation policies. Sensitivity analysis relating to other parameters, not least international trade elasticities, would also be carried out.

- Analysis of concrete arrangements to increase incentives for immediate action by all major emitters. In particular, building on the country-specific estimates of the benefits, co-benefits and costs of climate change mitigation presented in this paper, the potential for (rule-based or *ad hoc*) international financial arrangements to trigger wide and stable country participation and their macroeconomic consequences would be explored.[129] A related issue to be explored is the dynamic features of a post-2012 international agreement, in particular how an international framework could be set up that accommodates new information and enables additional countries to assume obligations without a need for full renegotiation.

- Discussion of how to build up a global carbon market *gradually* by linking heterogenous domestic policy schemes, as would be required to reduce overall abatement costs in case burden sharing arrangements do not succeed in fostering immediate participation by all major emitters to a binding international agreement. Linking can be achieved either directly – in which case some of the design features of domestic schemes, *e.g.* carbon price caps, may spread across countries – or indirectly through flexibility mechanisms such as the CDM. The policy implications of alternative paths towards integrated carbon markets could be explored *inter alia* through OECD model simulations. The pre-conditions for and consequences of the development of deep financial markets that allow emitters to hedge against carbon price volatility may also be analysed.

- Analysis of the potential contribution of the forest sector, and land-use more broadly, to low-cost mitigation action and how they might be incorporated into a post-2012 international agreement. On the analytical side, this would imply introducing land-use changes in the OECD model to study the potential contribution to world emission-reduction costs of incorporating the forest sector into a post-2012 agreement. At this time, such a full general equilibrium assessment of the mitigation potential and costs of the forestry option – including impacts on land and food prices – is still missing from the literature. On the policy side, further thinking is needed on how to proceed in practice, given the many specificities of this sector, including measurement, enforcement and monitoring problems.

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[129] See *e.g.* the game-theoretical analysis provided by Brechet *et al.* (2007).

BIBLIOGRAPHY

Aldy, E. and R. Stavins (2008), “Economic Incentives in a New Climate Agreement”, *Issue Paper,* The Harvard Project on International Climate Agreements.

Alic, J., D. Mowery and E. Rubin (2006), “US Technology and Innovation Policies: Lessons for Climate Change”, *Report for the Pew Center on Global Climate Change*, Arlington, VA.

Anderson, D. (2006), “Costs and Finance of Abating Carbon Emissions in the Energy Sector”, *Background Report for the Stern Review*, Imperial College London.

Arrow, K.J., and A.C. Fisher (1974), “Environmental Preservation, Uncertainty, and Irreversibility”, *Quarterly Journal of Economics* 88: 312–19.

Australian Prime Ministerial Task Group on Emissions Trading (2007), *Report of the Task Group on Emissions Trading*, The Department of the Prime Minister and Cabinet, Commonwealth of Australia.

Barker, T., J. Köhler, and M. Villena (2002), “The Costs of Greenhouse Gas Abatement: A Meta-Analysis of Post-SRES Mitigation Scenarios”, *Environmental Economics and Policy Studies*, Vol. 5, No. 2.

Barker, T., M. Qureshi, and J. Köhler (2006), “The Costs of Greenhouse Gas Mitigation with Induced Technological Change: A Meta-Analysis of Estimates in the Literature, *Tyndall Centre for Climate Change Research Working Paper* No. 89.

Baron, R. and J. Ellis (2006), “Sectoral Crediting Mechanisms for Greenhouse Gas Mitigation: Institutional and Operational Issues”, OECD, COM/ENV/EPOC/IEA/SLT(2006)4.

Baron, R., J. Reinaud, M. Genasci, C. Philibert (2007), "*Sectoral Approaches to Greenhouse Gas Mitigation – Exploring Issues for Heavy Industry"*, IEA Information Paper.

BASIC (2006), The Sao Paulo Proposal for an Agreement on Future Climate Policy, Discussion Paper for COP12 and COP/MOP2, http://www.basic-project.net/data/SP_prop_rev_nairobi.pdf.

Bassanini, A. and R. Duval (2006), “Reassessing the Role of Policies and Institutions for Labour Market Performance: A Consolidated Analysis”, *OECD Economics Department Working Paper* No. 486.

Blackman, A. and W. Harrington (2000), “The Use of Economic Incentives in Developing Countries: Lessons from International Experience with Industrial Air Pollution”, *Journal of Environment and Development,* Vol. 9, No. 1.

Bohi, D. and M. Toman (1996), *The Economics of Energy Security*, Kluwer Academic Publishers, Massachussets.

Bohm, P. and C. Russell (1985), “Comparative Analysis of Alternative Policy Instruments”, in A. Kneese and J. Sweeney (eds.), *Handbook of Natural Resource and Energy Economics*, Vol. 1, North Holland, Amsterdam.

Bollen, J., C. Brink, H. Eerens and T. Manders (2008), “Co-benefits of Climate Policy”, PBL Report No. 500116005, PBL, Bilthoven, the Netherlands.

Bollen, J., B. Guay, S. Jamet and J. Corfee-Morlot (2009), “Co-benefits of Climate change Mitigation Policies: Literature Review and New Results”, *OECD Economics Department Working Paper*, forthcoming, Paris.

Bollen, J., A.J.G. Manders, P.J.J. Veenendaal (2005) “Caps and Fences in Climate Change Policies”**,** Report 500035003/2005, Netherlands Environmental Assessment Agency.

Bosetti, V., C. Carraro, M. Galeotti and E. Massetti (2006), “A World Induced Technical Change Hybrid Model”, *The Energy Journal*, Hybrid Modeling of Energy Environment Policies: Reconciling Bottom-up and Top-down, Special Issue.

Bosetti, V., C. Carraro, R. Duval, A. Sgobbi and M. Tavoni (2009), “The Role of R&D and Technology Diffusion in Climate Change Mitigation: New Perspectives Using the WITCH Model”, *OECD Economics Department Working Paper*, forthcoming, Paris.

Bosetti, V., C. Carraro, E. Massetti and M. Tavoni (2008), “International Energy R&D Spillovers and the Economics of Greenhouse Gas Stabilisation”, *Energy Economics*, forthcoming.

Bosetti, V., E. Massetti and M. Tavoni (2007), “The WITCH Model. Structure, Baseline, Solutions”, *FEEM Working Paper,* 10-2007.

Bosi, M and J. Ellis (2005) *Exploring Options for “Sectoral Crediting Mechanisms”*, OECD/IEA Information Paper, http://www.oecd.org/dataoecd/55/61/34902644.pdf.

Boyce, J., M. Riddle and M.D Brenner (2005), "A Chinese Sky Trust? Distributional Impacts of Carbon Charges and Revenue Recycling in China", Working Papers, Political Economy Research Institute, University of Massachusetts at Amherst.

Brechet, T., F. Gerard and H. Tulkens (2007), “Climate Coalitions: A Theoretical and Computational Appraisal”, *CORE Discussion Paper,* 2007/3, Université Catholique de Louvain.

Buchner, B. (2007), “Policy Uncertainty, Investment and Commitment Period”, International Energy Agency, Paris.

Buchner, B. and C. Carraro (2005), “Economic and Environmental Effectiveness of a Technology-based Climate Protocol”, *Climate Policy,* Vol. 4, No. 3.

Buchner, B., C. Carraro and D. Ellerman (2006), “The Allocation of European Union Allowances. Lessons, Unifying Themes and General Principles", MIT Global Change Forum, Report No. 140.

Burniaux, J-M. and J. Chateau (2008), “An Overview of the OECD ENV-Linkages Model”, *OECD Economics Department Working Paper* No. 653, Paris.

Burniaux, J-M. and J. Oliveira Martins (2000), “Carbon Emission Leakages: a General Equilibrium View”, *OECD Economics Department Working Paper* No. 242, Paris.

Burtraw, D., D. Kahn and K. Palmer (2006), “Dynamic Adjustment to Incentive Based Policy to Improve Efficiency and Performance”, *mimeo*, Resources for the Future, Washington D.C.

Byatt, I., I. Castles, I. Goklany, D. Henderson, N. Lawson, R. McKitrick, J. Morris, A. Peacock, C. Robinson and R. Skidelski (2006), “The Stern Review: A Dual Critique, Part II: The Economic Aspects”, *World Economics*, Vol. 7, No. 4.

Che, Y-K. and I. Gale (2003), “Optimal Design of Research Contests”, *American Economic Review*, Vol. 93, No. 3.

Congressional Budget Office (2008), “Options for Offsetting the Economic Impact on Low- and Moderate-Income Households of a Cap-and-Trade Program for Carbon Dioxide Emissions”, Letter to the Honorable Jeff Bingaman, US Congress, Washington D.C.Dasgupta, P. (2007), “Commentary: The Stern Review’s Economics of Climate Change”, *National Institute Economic Review*, Vol. 199, No. 1.

Datta, A. (2008), “The Incidence of Fuel Taxation in India”, Indian Statistical Institute, Discussion Paper No 08-05.

De Coninck, H., C. Fischer, R. Newell and T. Ueno, “International Technology-Oriented Agreements to Address Climate Change”, Discussion Paper 06-50, Resources for the Future.

De la Chesnaye, F. and J. Weyant (eds) (2006), “Multi-Greenhouse Gas Mitigation and Climate Policy”, *The Energy Journal*, Special Issue.

De Mooij, R. (1999), “The Double Dividend of Environmental Tax Reform”, in J.C. van der Bergh (ed.), *Handbook of Environmental and Resource Economics*, Cheltenham, Edward Elgar, UK.

Dixit, A and R. Pindyck (1994), “Investment under Uncertainty”, Princeton University Press, Princeton NJ.

Downing, P. and L. White (1986), “Innovation in Pollution Control”, *Journal of Environmental Economics and Management*, Vol. 13, No. 1.

Duval, R. (2008), “A Taxonomy of Instruments to Reduce Greenhouse Gas Emissions and Their Interactions”, *OECD Economics Department Working Papers*, No. 636.

Duval, R. and C. de la Maisonneuve (2009), “Long-run GDP Growth Scenarios for the World Economy”, *OECD Economics Department Working Paper*, forthcoming, Paris.

Edenhofer, O., K. Lessmann, C. Kemfert, M. Grubb and J. Köhler (2006), “Induced Technological Change: Exploring its Implications for the Economics of Atmospheric Stabilisation”, *The Energy Journal*, Endogenous Technological Change and the Economics of Atmospheric Stabilisation, Vol. 27, Special Issue.

Ellerman, D. and P.L. Joskow (2008), “The European Union’s Emissions Trading System in Perspective”, *Document prepared for the Pew Center on Global Climate Change*.

Ellis, J. and S. Kamel (2007): "Overcoming Barriers to Clean Development Mechanism Projects, COM/ENV/EPOC/IEA/SLT(2007)3, Paris: OECD/IEA.

Ellis, J. and R. Baron (2005), “Sectoral Crediting Mechanisms: An Initial Assessment of Electricity and Aluminium”, OECD, COM/ENV/EPOC/IEA/SLT(2005)8.

Enqvist, P-A. (2007), “A Cost Curve for Greenhouse Gas Reduction”, *McKinsey Quarterly*, No. 1.

Eto, J., E. Vine, L. Shown, R. Sonnenblick and C. Payne (1994), *The Cost and Performance of Utility Commercial Lighting Programmes,* Lawrence Berkeley Laboratories, Berkeley, CA.

Fischer, C. and R. Newell (2007), “Environmental and Technology Policies for Climate Mitigation”, *Journal of Environmental Economics and Management*, Vol. 55, No. 2.

Fischer, C. and R. Morgenstern (2006), “Carbon Abatement Costs: Why the Wide Range of Estimates?”, *The Energy Journal*, Vol. 27, No. 2.

Fisher, B., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-Ch. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. van Vuuren, R. Warren (2007), “Issues Related to Mitigation in the Long Term Context” in Climate Change 2007: Mitigation, *Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change (IPCC),* B. Metz., O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fullerton, D. and S. West (2000), “Tax and Subsidy Combinations for the Control of Car Pollution”, *NBER Working Paper* No. 7774.

Girard, P. and A. Fallot (2006), “Review of Existing and Emerging Technologies for the Production of Biofuels in Developing Countries”, *Energy for Sustainable Development*, Vol. 10, No. 2.

Global Subsidies Initiative (2008), “Getting to the Bottom of the Well: A Proposal to Reveal the Scale, Pattern and Impacts of Subsidies to Fossil Fuels”, *mimeo*.

Goulder, L. and S. Schneider (1999), “Induced Technological Change and the Attractiveness of CO2 Abatement Policies”, *Resource and Energy Economics*, Vol. 21, Nos. 3-4.

Goulder, L., I. Parry, R. Williams and D. Burtraw (1999), “The Cost-effectiveness of Alternative Instruments for Environmental Effectiveness in a Second-Best Setting”, *Journal of Public Economics,* Vol. 72, No. 3.

Goulder, L. (1995), “Environmental Taxation and the Double Dividend: A Reader’s Guide”, *International Tax and Public Finance*, Vol. 2, No. 2.

Hahn, R. and R. Stavins (1991), “Incentive-Based Environmental Regulation: A New Era from an Old Idea?”, *Ecology Law Quarterly,* Vol. 18, No. 1.

Hanks, J. (2002), “Voluntary Agreements, Climate Change and Industrial Energy Efficiency”, *Journal of Cleaner Production,* Vol. 10, No. 2.

Hassett, K., A. Mathur, and G. Metcalf (2008), “The Incidence of a U.S. Carbon Tax: A Lifetime and Regional Analysis”, *NBEResearch Working Paper* No. 13554, Cambridge, MA.

Helm, D. (2005), *Climate Change Policy,* Oxford University Press, Oxford.

Helm, D., C. Hepburn and R. Mash (2004), “Time-inconsistent Environmental Policy and Optimal Delegation”, *Oxford University Department of Economics Discussion Paper* No. 175.

Henry, C. (1974), “Investment Decisions Under Uncertainty: the Irreversibility Effect”, A*merican Economic Review* 64: 1006–12.

Herve, K., I. Koske, N. Pain and F. Sedillot (2007), “Globalisation and the Macroeconomic Policy Environment”, *OECD Economics Department Working Papers* No. 552.

Herzog, T., J. Pershing and K. Baumert (2006), "*Target: Intensity. An Analysis of Greenhouse Gas Intensity Targets",* World Resources Institute (WRI), Washington D.C.

Hoogwijk, M., D. van Vuuren, S. Boeters, K. Blok, E. Blomen, T. Barker, J. Chateau, T. Masui, G.J. Nabuurs, A. Novikova, D. Urge-Vorsatz, K. Riahi, S. de la Rue du Can, J. Sathaye and S. Scriecu (2008), *“Sectoral Mitigation potentials : Bottom Up and Top Down Comparison Project”*, Netherlands Environmental Assessment Agency (available at www.mnp.nl).

IEA (2008a), *World Energy Outlook*, Paris, *forthcoming*.

IEA (2008b), *Energy Technology Perspectives,* Paris.

IEA (2007a), *World Energy Outlook*, Paris.

IEA (2007b), *Mind the Gap,* Paris.

IEA (2007c), *Climate Policy Uncertainty and Investment Risk,* Paris.IEA (2007d), *Energy Security and Climate Policy: Assessing Interactions,* Paris.

IEA (2006a), *World Energy Outlook,* Paris.

IEA (2006b), *Energy Technology Perspectives,* Paris.

IEA (2003), *Cool Appliances: Policy Strategies for Energy-Efficient Homes,* Paris.

IEA (2000), *Experience Curves for Energy Technology Policy*, Paris.

Jaffe, A., R. Newell and R. Stavins (1999), “Energy-Efficient Technologies and Climate Change Policies: Issues and Evidence”, *Resources for the Future Climate Issue Brief No. 19*, Resources for the Future, Washington, DC.

Jaffe, A., R. Newell and R. Stavins (2003), “Technological Change and the Environment”, in K-G. Mäler and J. Vincent (eds.), *Handbook of Environmental Economics*, Vol. 1, North Holland, Amsterdam.

Jaffe, A., R. Newell and R. Stavins (2005), “A Tale of Two Market Failures: Technology and Environmental Policy”, *Ecological Economics*, Vol. 54, Nos. 2-3.

Jamet, S. (2009), “Carbon Price Uncertainty and Firms’ Investment Decisions: A Theoretical Analysis”, *OECD Economics Department Working Paper,* forthcoming, Paris.

Jamet S. and J. Corfee-Morlot (2009), “Assessing the Impacts of Climate Change: A Literature Review”, *OECD Economics Department Working Paper,* forthcoming, Paris.

Jaumotte, F. and N. Pain (2005), “Innovation Policies and Innovation in the Business Sector”, *OECD Economics Department Working Paper* No. 459.

Johansson, A, C. Heady, J. Arnold, B. Brys and L. Vartia (2008), "Taxation and Economic Growth", *OECD Economics Department Working Paper* No. 620.

Johnstone, N., I. Hascic and D. Popp (2008), "Renewable Energy Policy and Technological Innovation: Evidence Based on Patent Counts", *NBER Working Paper* No. 13760.

Jung, C., K. Krutilla and R. Boyd (1996), "Incentives for Advanced Pollution Abatement Technology at the Industry Level: An Evaluation of Policy Alternatives", *Journal of Environmental Economics and Management,* Vol. 30, No. 1.

Karousakis, K. and J. Corfee-Morlot (2007), "Financing Mechanisms to Reduce Emissions From Deforestation: Issues in Design and Implementation", *OECD Working Paper,* Paris.

Kennedy, P. and B. Laplante (1999), "Environmental Policy and Time Inconsistency: Emissions Taxes and Emissions Trading", in E. Petrakis, E. Sarzetakis and A. Xepapadeas (eds.), *Environmental Regulation and Market Power: Competition, Time Inconsistency and International Trade,* Northampton, Edward Elgar, UK.

Keohane, N. (2001), *Essays in the Economics of Environmental Policy,* Ph.D. Dissertation, Harvard University.

Kerr, S. and R. Newell (2004), *"Policy-Induced Technology Adoption: Evidence from the U.S. Lead Phasedown", Journal of Industrial Economics,* Vol. 51 No. 3.

Kremer, M. (2001a), "Creating Markets for New Vaccines: Part I: Rationale", in B. Jaffe, J. Lerner and S. Stern (eds.), *Innovation Policy and the Economy,* Vol. 1, MIT Press, Cambridge, Massachussets.

Kremer, M. (2001b), "Creating Markets for New Vaccines: Part II: Design Issues", in B. Jaffe, J. Lerner and S. Stern (eds.), *Innovation Policy and the Economy,* Vol. 1, MIT Press, Cambridge, Massachussets.

Levine, M., D. Hirst, E. Koomey, J. McMahon and A. Sanstad (1994), *Energy Efficiency, Market Failures and Government Policy,* Lawrence Berkeley Laboratory and Oak Ridge Laboratory, Berkeley, CA.

Maeda, A. (2003), "The Emergence of Market Power in the Emission Rights Markets: The Role of Initial Permit Distribution", *Journal of Regulatory Economics,* Vol. 24, No. 3.

Matthes, F.C. and H.-J. Ziesing (2008), "Die Entwicklung des deutschen Kraftwerksparks und die aktuelle Debatte um die künftige Strombedarfsdeckung", Öko-Institut Discussion Paper 2008, available at: http://www.oeko.de/oekodoc/722/2008-196-de.pdf?PHPSESSID=u3nhgdkbn8h6kt4783js54pd62

McDonald, A. and L. Schrattenholzer (2001), "Learning Rates for Energy Technologies", *Energy Policy,* Vol. 29, No. 4.

McKibbin, W. and P. Wilcoxen (1998), "The Theoretical and Empirical Structure of the G-Cubed Model", *Economic Modelling,* Vol. 16, No. 1.

McKibbin, W. and P. Wilcoxen (2006), "A credible Foundation for Long Term International Cooperation on Climate Change", *Brookings Discussion Papers in International Economics,* No. 171.Meinshausen, M. (2006), "What Does a 2°C Target Mean for Greenhouse Gas Concentrations? A Brief Analysis Based on Multi-Gas Emission Pathways and Several Climate

Sensitivity Uncertainty Estimates", in J.S. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe (eds.), *Avoiding Dangerous Climate Change,* Cambridge University Press, Cambridge.

Mendelsohn, R.O., W.N. Morrison, M.E. Schlesinger and N.G. Andronova (1998), "Country-specific Market Impacts of Climate Change", *Climatic Change* 45 (3-4), 553–569.

Milliman, S. and R. Prince (1989), "Firm Incentives to Promote Technological Change in Pollution Control", *Journal of Environmental Economics and Management,* Vol. 17, No. 3.

MNP (2008), Environmental Compendium, Bilthoven, the Netherlands.

Montero, J-P. (2005), "Pollution Markets with Imperfectly Observed Emissions", *RAND Journal of Economics,* Vol. 36, No. 3.

Nabuurs, G.J, O. Masera, K. Andrasko, P. Penitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainen, O. Krankina, W.A. Kurz., M. Matsumoto, W. Oyhantcabal, N.Ravindranath, M.J. Sanz Sanchez, X. Zhang (2007), "Forestry" in Climate Change 2007: Mitigation, *Contribution of Working Group II to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change (IPCC),* B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenham, S. Gaffin, K. Gregory, A. Grübler, T-Y. Jung, T. Kram, E. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Reohrl, H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. Van Rooijen, N. Victor and Z. Dadi (2000), *Special Report on Emission Scenarios. Working Group III, Inter-governemental Panel on Climate Change (IPCC)*, Cambridge University Press, Cambridge.

Neij, L., P. Andersen and M. Durstewitz (2003a), "The Use of Experience Curves for Assessing Energy Policy Programmes", in IEA (eds), *Experience Curves: Tool for Energy Policy Analysis and Design,* Proceedings of joint EU/IEA Workshop, Paris.

Neij, L., P. Andersen, M. Durstewitz, P. Helby, M. Hoppe-Kilpper and P. Morthorst (2003b), "Experience Curves: A Tool for Energy Policy Assessment", *Environmental and Energy Systems Studies*, Lund University, Sweden.

National Research Council (2007), *Innovation inducement prizes at the National Science Foundation*, National Academies Press, Washington D.C.

Neuhoff, K., K.K. Martinez and M. Sato (2006), "Allocation, Incentives and Distortions: the Impact of EU ETS Emissions Allowance Allocations to the Electricity Sector", *Climate Policy* No.°6.

Newell, R. and N. Wilson (2005), "Technology Prizes for Climate change Mitigation", *Resources for the Future Discussion Paper* No. 05-33.

Nordhaus, W. (2002), "Modeling Induced Innovation in Climate change Policy", in A. Grubler, N. Nakicenovic and W. Nordhaus (eds), *Technological Change and the Environment,* Resources for the Future Press, Washington D.C.

Nordhaus, W. (2007), "A Review of the Stern Review on the Economics of Climate Change", *Journal of Economic Literature*, Vol. 45, No. 3.

Nordhaus, W. and J. Boyer (2000), *Warming the World*, Cambridge, MIT Press.

Nordhaus, W.D. and J. Boyer (2000), **“**Warming the World: Economic Models of Global Warming", The MIT Press.

OECD (2008a), *Costs of Inaction on Key Environmental Challenges*, OECD, Paris.

OECD (2008b), *OECD Environmental Outlook to 2030*, OECD, Paris.

OECD (2008c), “Infrastructure Investment: Links to Growth and the Role of Public Policies”, *ECO/CPE/WP1(2008)17*.

OECD (2008d), *Biofuel Support Policies: An Economic Assessment*, OECD, Paris.

OECD (2007a), “Environmentally Related Taxes and Tradable Permits in Practice”, *COM/ENV/EPOC/CTPA/CFA(2007)31*.

OECD (2007b), “Instrument Mixes for Environmental Policy”, *ENV/EPOC/WPNEP(2006)9/REV2*, Paris.

OECD (2007c), *Financial Market Trends*, No. 94, Paris.

OECD Roundtable on Sustainable Development (2007), “Biofuels: Is the Cure Worse than the Disease?”, *Round Table on Sustainable Development, SG/SD/RT(2007)3*, Paris.

OECD (2006a), “Sensitivity analysis in ENV-Linkages”, *ENV/EPOC/GSP(2006)6*, Paris

OECD (2006b), *The Political Economy of Environmentally Related Taxes*, Paris.

OECD (2006c), *Economic Policy Reforms: Going for Growth,* Paris.

OECD Roundtable on Sustainable Development (2006), “Do We Have the Right R&D Priorities and Programmes to Support the Energy Technologies of the Future?”, *Round Table on Sustainable Development, SG/SD/RT(2006)1,* Paris.

OECD (2004), *Sustainable Development in OECD Countries*, Paris.

OECD (2003), *Voluntary Approaches for Environmental Policy: Effectiveness, Efficiency and Usage in Policy Mixes*, Paris.

OECD (1999), *Action Against climate Change,* Paris.

Pacala, S. and R. Socolow (2004), “Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies”, *Science*, Vol. 305, No. 5686.

Palmer, K., W. Oates and P. Portney (1995), “Tightening Environmental Standards: The Benefit-Cost or the No-Cost Paradigm?” *Journal of Economic Perspectives*, Vol. 9, No. 4.

Parry, I. (2003), "Fiscal Interactions and the Case for Carbon Taxes over Grandfathered Carbon Permits,"Discussion Papers dp-03-46, Resources For the Future.Perez, R. (2007), “Towards a Generalized System of Environmental Tariffs?”, *mimeo*, United Nations.

Pezzy, J. and A. Park (1998), “Reflections on the Double Dividend Debate: The Importance of Interest Groups and Information Costs”, *Environmental and Resource Economics,* Vol. 11, Nos. 3-4.

Philibert, C. (2004), “International Energy Technology Collaboration and Climate Change Mitigation”M, COM/ENV/EPOC/IEA/SLT(2004)1,OECD/IEA, Paris.

Philibert, C., J. Pershing, J. Corfee-Morlot and S. Willems (2003), “Evolution of Mitigation Commitments: Some Key Issues”, *OECD/IEA Information Paper, Annex I Expert Group on the UNFCCC,*COM/ENV/EPOC/IEA/SLT(2003)3.

Pindyck, R. (2007), “Uncertainty in Environmental Economics”, *Review of Environmental Economics and Policy,* Vol. 1, Issue 1, Winter 2007, pp. 45–65.

Pizer, W. and D. Popp (2007), “Endogenizing Technological Change”, *Resources for the Future Discussion Paper* No. 07-11.

Pizer, W. (2002), “Combining Combining Price and Quantity Controls to Mitigate Global Climate Change”, *Journal of Public Economics,* Vol. 85, No. 3.

Pope, C.A. (III), R. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, and G.D. Thurston (2002), "Lung Cancer, Cardiopulmonary Mortality and Long-Term Exposure to Fine Particulate Air Pollution", *Journal of the American Medical Association*, Vol. 287, No. 9.

Popp, D. (2002), “Induced Innovation and Energy Prices”, *American Economic Review,* Vol. 92, No. 1.

Popp, D. (2004), “ENTICE: Endogenous Technological Change in the DICE Model of Global Warming”, *Journal of Environmental Economics and Management,* Vol. 48, No. 1.

Popp, D. (2006), “Innovation in Climate Policy Models: Implementing Lessons from the Economics of R&D”, *Energy Economics,* Vol. 28, Nos. 5-6.

Porter, M. and C. van der Linde (1995), “Toward a New Conception of the Environment-competitiveness Relationship”, *Journal of Economic Perspectives,* Vol. 9, No. 4.

Poterba, J.M. (1991) “Tax Policy to Combat Global warming: On Designing a Carbon Tax” in R. Dornbush and J.M. Poterba (eds.) *Global Warming: Economic Policy Responses to Global Warming*, pp. 71-98, Cambridge Mass.: The MIT Press.

Riahi, K., K. Grübler, A. and N. Nakicenovic (2006) "Scenarios of Long-Term Socio-Economic and Environmental Development under Climate Stabilization", Technological Forecasting & Social Change 74 (2007) 887–935

Roberts, M. and M. Spence (1976), “Effluent Charges and Licenses Under Uncertainty”, *Journal of Public Economics,* Vol. 5, No. 3-4.

Russell, C. and W. Vaughan (2003), “The Choice of Pollution Control Policy Instruments in Developing Countries: Arguments, Evidence and Suggestions”, in H. Folmer and T. Tietenberg (eds.), *The International Yearbook of Environmental and Resource Economics*, 2003/2004, Cheltenham, Edward Elgar, UK.

Santilli, M.P., P. Moutinho, S. Schwartzman, D. Nepstad, L. Curran, and C. Nobre (2005) “2005: Tropical Deforestation and the Kyoto Protocol: an Editorial Essay.” *Climatic Change,* Vol. 71.

Schlamadinger, B., L. Ciccarese, M. Dutschke, P.M. Fearnside, S. Brown, and D. Murdiyarso (2005), "Should We Include Avoidance of Deforestation in the International Response to Climate Change?", in D. Murdiyarso and H. Herawati (eds), *Carbon Frestry:Who Will Benefit?,* Proceedings of Workshop on Carbon Sequestration and Sustainable Livelihoods, held in Bogor on 16-17 February, 2005. Bogor, Indonesia, CIFOR.

Sijm, J. (2002), "The Performance of Feed-in Tariffs to Promote Renewable Electricity in European Countries", The Energy Centre of the Netherlands, ECN-C-02-083.

Sinn, H-W. (2007), "Public Policies Against Global Warming", *NBER Working Paper* No. 13454.

Sorrell, S. (2002), *The Climate Confusion: Implications of the EU Emissions Trading Scheme for the UK Climate Change Levy and Climate Change Agreements,* Science and Technology Policy Research (SPRU), University of Sussex, Brighton, UK.

Sorrell, S., J. Schleich, S. Scott, E O'Malley, F. Trace, U. Boede, K. Ostertage and P. Radgen (2000), *Barriers to Energy Efficiency in Public and Private Organisations, Science and Technology Policy Research*, University of Sussex, Brighton, UK.

Sorrell, S. and J. Sijm (2003), "Carbon Trading in the Policy Mix", *Oxford Review of Economic Policy,* Vol. 19, No. 3.

Steenblik, R. (2005), "Liberalisation of Trade in Renewable-Energy Products and Associated Goods: Charcoal, Solar Photovoltaic Systems, and Wind Pumps and Turbines", *OECD Trade and Environment Working Paper* No. 2005-07.

Steenblik, R. (2006), "Liberalisation of Trade in Renewable Energy and Associated Technologies: Biodiesel, Solar Thermal and Geothermal Energy", *OECD Trade and Environment Working Paper* No. 2006-01.

Steenblik, R. (2007), "Subsidies: The Distorted Economics of Biofuels", in OECD/ITF Roundtable, *Biofuels: linking support to performance*, Paris.

Steenblik, R., S. Vaughan and P. Waide (2006), "Can Energy-Efficient Electrical Appliances be Considered "Environmental Goods"?", *OECD Trade and Environment Working Paper* No. 2006-04.

Stern, N. (2007), *The Economics of Climate Change: The Stern Review*, CUP, Cambridge.

Stern, N. (2008), "The Economics of Climate Change", *American Economic Review*, Vol. 98, No. 2.

Sterner, T. (2003), *Policy Instruments for Environmental and Natural Resource Management,* Resources for the Future Press, Washington D.C.

Stiglitz, J. (2006), "A New Agenda for Global Warming", *The Economists' Voice,* Vol. 3, No. 7.

Tol, R. (2005), "The Marginal Damage Costs of Carbon Dioxide Emissions: an Assessment of the Uncertainties", *Energy Policy*, Vol. 33, pp. 2064-2084.

Tol, R. (2002), "New Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates", *Environmental and Resource Economics,* 21 (2), 135-160.

Wagner, M. and M. Uhrig-Homburg (2007), “Instruments in the EU Emissions Trading Scheme - An Early Market Perspective”, *Energy and Environment*, 2008, Available at SSRN: http://ssrn.com/abstract=882792

Walter, A., F. Rosillo-Calle, P. Dolzan, E. Piacente and K. Borges da Cunha (2007), “Market Evaluation: Fuel Ethanol”, *Task 40 Sustainable Bio-energy Trade: Securing Supply and Demand (Deliverable 8),* State University of Campinas (Unicamp), Campinas, Brazil.

Wara, W. and D. Victor, “A Realistic Policy on International Carbon Offsets”, Working Paper no.°74, Stanford University.

Watkiss, P. and T. Downing (2008), “The Social Cost of Carbon: Valuation Estimates and their Use in IK Policy”, *The Integrated Assessment Journal*, Vol. 8, No 1.

Weitzman, M. (2007a), “A Review of the Stern Review on the Economics of Climate Change”, *Journal of Economic Literature*, Vol. 45, No. 3.

Weitzman, M. (2007b), “Structural Uncertainty and the Value of Statistical Life in the Economics of Catastrophic Climate Change”, *NBER Working Paper* No. 13490.

Weitzman, M. (2001), “Gamma Discounting”, *American Economic Review*, Vol. 91, No. 1.

Weitzman, M. (1974), “Prices vs. Quantities”, *Review of Economic Studies*, Vol. 41, No. 4.

Wigley, T.M.L. (2008), “*MAGICC/SCENGEN 5.3: User Manual*”, Boulder, Colorado, National Center for Atmospheric Research (available on http://www.cgd.ucar.edu/cas/wigley/magicc/index.html Wright, B. (1983), “The Economics of Invention Incentives: Patents, Prizes and Research Contracts”, *American Economic Review*, Vol. 73, No. 4.

Yohe, G. (2006), “Some Thoughts on the Damage Estimates Presented in the Stern Review — An Editorial”, *Integrated Assessment Journal* Vol. 6, No. 3.

Zerbe, R. (1970), “Theoretical efficiency in Pollution Control”, *Western Economic Journal*, Vol. 8, No. 4.

Zhao, J. (2003), "Irreversible Abatement Investment under Cost Uncertainties: Tradable Emission Permits and Emissions Charges," *Journal of Public Economics*, Vol. 87, No. 12.

TABLES AND FIGURES

Tables

Figures

Table 2.1 Baseline economic scenario: main features

(Average annual growth rates)

Panel A. In PPPs US$

	GDP per worker			**GDP per capita**			**GDP**		
	2000-2006	2006-2025	2025-2050	2000-2006	2006-2025	2025-2050	2000-2006	2006-2025	2025-2050
United States	1.7	1.7	1.6	1.6	1.6	1.6	2.6	2.4	2.2
Canada	0.7	2.0	1.7	1.6	1.9	1.6	2.6	2.7	2.1
Japan	1.7	1.9	1.9	1.5	1.7	1.5	1.6	1.5	0.8
China	8.6	6.4	3.7	9.0	6.1	3.3	9.7	6.6	3.2
India	5.0	5.2	4.6	5.6	6.3	5.1	7.3	7.6	5.6
Brazil	0.0	2.5	3.3	1.5	3.0	3.5	2.9	4.0	3.9
Russian Federation	5.4	3.8	2.5	6.7	4.0	2.5	6.2	3.4	1.8
Australia-New Zealand	0.9	2.0	1.7	1.9	2.0	1.6	3.1	2.9	2.1
EU27 + EFTA	1.1	2.1	1.8	1.7	2.3	1.8	2.1	2.4	1.7
OPEC + Other oil producers	1.9	2.3	3.7	2.9	3.0	4.2	4.8	4.4	5.0
Rest of the World	2.1	3.1	3.5	2.8	3.3	3.7	4.5	4.9	4.7
Total World	2.0	2.5	2.8	2.5	2.8	2.9	3.7	3.8	3.4

Panel B. In MERs US$

	GDP per worker		**GDP per capita**		**GDP**	
	2006-2025	2025-2050	2006-2025	2025-2050	2006-2025	2025-2050
United States	1.7	1.6	1.6	1.6	2.4	2.2
Canada	2.0	1.7	1.9	1.6	2.7	2.1
Japan	1.9	1.9	1.7	1.5	1.5	0.8
China	6.4	3.7	6.1	3.3	6.6	3.2
India	5.2	4.6	6.3	5.1	7.6	5.6
Brazil	2.5	3.3	3.0	3.5	4.0	3.9
Russian Federation	3.8	2.5	4.0	2.5	3.4	1.8
Australia-New Zealand	2.0	1.7	2.0	1.6	2.9	2.1
EU27 + EFTA	2.1	1.8	2.3	1.8	2.4	1.7
OPEC + Other oil producers	2.3	3.7	3.0	4.2	4.4	5.0
Rest of the World	3.1	3.5	3.3	3.7	4.9	4.7
Total World	1.9	2.3	2.2	2.4	3.2	3.0

Source: OECD, ENV-Linkages model.

Table 2.2. Projected emission growth rates by country/region[1]

(2005-2050)

Region	All greenhouse gases			CO_2 only			Non-CO_2		
	2005-2030	2030-2050	2005-2050	2005-2030	2030-2050	2005-2050	2005-2030	2030-2050	2005-2050
Australia and New Zealand	0.8	0.3	0.6	0.8	-0.1	0.4	0.7	0.9	0.8
Brazil	1.6	0.8	1.2	2.1	0.7	1.5	1.3	0.9	1.1
Canada	1.2	0.2	0.8	1.2	-0.2	0.6	1.4	1.5	1.4
China	3.2	1.0	2.2	3.6	1.0	2.4	1.4	1.3	1.4
EU27 plus EFTA	0.1	0.0	0.1	0.1	-0.1	0.0	0.4	0.2	0.3
India	3.4	1.9	2.7	4.5	2.0	3.4	1.5	1.5	1.5
Japan	-0.2	-0.2	-0.2	-0.3	-0.5	-0.4	1.0	1.6	1.3
Middle East [2]	2.6	0.9	1.8	2.7	0.8	1.9	2.3	1.0	1.7
Rest of Annex I	1.3	0.3	0.9	1.2	0.2	0.7	1.6	0.7	1.2
Rest of the World	2.0	0.8	1.5	2.3	0.6	1.5	1.6	1.0	1.3
Russia	0.8	0.6	0.7	0.8	0.4	0.6	0.8	0.9	0.9
United States	0.8	0.4	0.6	0.7	0.3	0.5	0.9	1.1	1.0
BRICs	2.8	1.2	2.1	3.3	1.1	2.3	1.4	1.2	1.3
OECD [3]	0.5	0.2	0.4	0.4	0.1	0.3	0.7	0.9	0.8
Non-OECD	2.5	1.0	1.8	2.9	1.0	2.0	1.6	1.1	1.4
World	**1.8**	**0.8**	**1.4**	**2.0**	**0.7**	**1.4**	**1.4**	**1.0**	**1.2**

1. Emissions from Land Use, Land-Use Change and Forestry are not included.
2. The region includes Middle East oil-producing as well as Algeria,Lybia,Egypt, Indonesia, and Venezuela.
3. OECD includes some non-OECD countries that are part of EU27 plus EFTA. Korea, Mexico and Turkey are not included in OECD numbers but are aggregated in ROW.

Source: OECD, ENV-Linkages model.

Table 2.3. The influence of the social discount rate on the estimated impacts of climate change

Pure Rate of Time Preference	**Discount Rate (%)**	**Discounted impacts**[1] (per cent loss in permanent consumption due to climate change)
0.1	1.3	10.9
0.5	1.8	8.1
1.0	2.3	5.2
1.5	2.8	3.3

1. Baseline climate scenario includes market and non-market impacts as well as risks of catastrophe.
Source: Stern (2007b).

Table 3.1. Economic costs and environmental impacts of alternative cost-effective policy scenarios

Scenario	Peaking year	Change in total emissions in 2050 relative to 2005 [1]		Economic costs				Maximum CO_2 concentration over 2012-2150	
	year	All greenhouse gases	CO_2	Marginal abatement cost in 2050 (2005 $US per ton of CO_2)	GDP loss in 2050 (%)	Average GDP loss 2012-2050 (%)	Average annual GDP growth rate loss 2012-2050 (percentage points)	Year	Level (ppm)
A) 550ppm-base: Stabilisation of CO_2 concentration at 450ppm, and of overall GHG concentration at about 550ppm CO_2 eq, with modest overshooting	2020	-34%	-36%	396	-4.8	-2.2	-0.13	2065	461
B) 550ppm-high: Stabilisation of CO_2 concentration at 450ppm, and of overall GHG concentration at about 550ppm CO_2 eq, with high overshooting	2030	-9%	-6%	213	-2.3	-0.6	-0.06	2060	495
C) 50 rel. to 2005: Less 50% in 2050 relative to 2005	2020	-50%	-52%	894	-9.2	-4.3	-0.26	2050	447
D) 650ppm: Stabilisation of CO_2 concentration at 550ppm, and of overall GHG concentration at about 650ppm CO_2 eq, without overshooting	2030	17%	22%	48	-0.7	-0.3	-0.02	2130	548

1. Including emissions from Land Use, Land-Use Change and Forestry. These are exogenous and similar across all policy scenarios, as they are not yet incorporated in the OECD ENV-Linkages model.

Source: OECD, ENV-Linkages model.

Table 3.2. Decomposition of world GHG emission trends under alternative scenarios [1]

Index 2005=100

	2025			2050		
	Baseline	650ppm (Scenario D) [4]	550ppm-base (Scenario A) [5]	Baseline	650ppm (Scenario D) [4]	550ppm-base (Scenario A) [5]
GHG emissions	145.6	135.4	117.8	183.1	124.7	68.6
Population	122.8	122.8	122.8	140.7	140.7	140.7
GDP/Population	154.2	154.1	153.6	278.4	276.5	265.1
Energy [3] /GDP	67.1	66.6	63.4	34.3	29.8	18.1
GHG/Energy [3]	114.6	107.4	98.5	136.3	107.6	101.5

1. The amount of GHG emissions at any point in time can be decomposed as the product of population, GDP per capita, energy intensity and the GHG intensity of energy. This is commonly known as the so-called "Kaya identity".

2. Primary energy demand.
3. Stabilisation of CO_2 concentration at 550ppm, and of overall GHG concentration at about 650ppm CO_2 eq, without overshooting.
4. Stabilisation of CO_2 concentration at 450ppm, and of overall GHG concentration at about 550ppm CO_2 eq, with modest overshooting.

Source: OECD, ENV-Linkages model.

Table 3.3. Economic costs from stabilising overall GHG concentration below 550 ppm with incomplete coverage of industries or GHGs

Scenario	**Marginal abatement cost in 2050 (2005 $US per t CO_2 eq)**	**Average cost 2012-2050 (% of real GDP)**	**Cost in 2050 (% of real GDP)**
550ppm-base (Scenario A) [1]	396	-2.2	-4.8
550ppm-base with CO_2 only	621	-4.0	-9.3
550ppm-base without energy intensive industries	685	-3.3	-7.5

1. Stabilisation of CO_2 concentration at 450ppm, and of overall GHG concentration at about 550ppm CO_2 eq, with modest overshooting.

Source: OECD, ENV-Linkages model.

Table 3.4. Impact of country and GHGs coverage on carbon leakage rates

Leakage rates implied by an emission reduction of 2.7 Gt in 2050 with respect to 2005 levels [1]

Leakage rates (%)	**2020**	**2050**
EU acting alone:		
CO_2 only	30.2%	28.7%
All GHG	12.6%	19.9%
Region acting (across all GHGs) :		
EU	12.6%	19.9%
Annex I	-0.1%	1.4%
Annex I and Brazil, India and China	-0.7%	-0.3%

1. The size of this emission cut is equivalent to a 50% cut in EU emissions in 2050 relative to 2005 levels.

Source: OECD, ENV-Linkages model.

Table 3.5. Impact of alternative policy scenarios on the output of energy-intensive industries[1] in 2050

Scenario	Region	Production
		% deviation in reference to baseline
Panel A. Sectoral output effects		
Scenario -50% rel. to 2005 (Global action)	World	-14
	Western Europe	-7
	Rest of the world	-16
Scenario "leakages" (EU action only)	World	-0.5
	Western Europe	-6
	Rest of the world	0.4
Panel B. Sectoral output effects of different policy responses to leakage		
Scenario "countervailing tariff" (EU action only)	World	-1
	Western Europe	-7
	Rest of the world	0.2
Scenario "sectoral cap" (EU action only with permit fungibility)	World	-4
	Western Europe	-5
	Rest of the world	-4

1. Energy-intensive industries include chemicals, metallurgic, other metal, iron and steel industry, paper, and mining products.

Source: OECD, ENV-Linkages model.

Table 3.6 Effects of countervailing import tariffs on carbon leakage and mitigation costs

	Reduction of 50% in EU countries in 2050		Reduction of 50% in Annex I countries in 2050	
	without a countervailing tariff	with a countervailing tariff	without a countervailing tariff	with a countervailing tariff
Leakage rates in 2050	19.9%	6.5%	9.1%	5.2%
Average GDP effect 2012-2050				
In participating countries	-2.0%	-2.2%	-1.7%	-1.8%
In non-participating countries	0.0%	-0.1%	-0.1%	-0.4%
World	-0.4%	-0.5%	-1.0%	-1.2%
GDP effect in 2050				
In participating countries	-3.0%	-3.4%	-2.7%	-2.9%
In non-participating countries	0.0%	-0.2%	-0.1%	-0.5%
World	-0.5%	-0.7%	-0.8%	-1.7%

Source: OECD, ENV-Linkages model.

Table 3.7. Effects of international sector-wide agreements on emissions and mitigation costs

	Reduction of 50% in EU countries in 2050	**Reduction of 50% in EU countries + reduction of 50% in energy-intensive industries worldwide**	
	EU countries only [A]	Without permit fungibility [1] [B]	With permit fungibility [2] [C]
GHG emission reductions in 2050			
In EU countries	-51%	-54%	-58%
In non-EU countries	1%	-11%	-10%
World	-3%	-15%	-14%
Marginal abatement cost (2005USD per tCO_2 eq)			
In EU countries	293	328	454
In energy-intensive industries	0	682	454
GDP loss in 2050			
In participating countries [3]	-3.0%	-3.5%	-3.9%
In non-participating countries	0.0%	-1.8%	-1.4%
World	-0.5%	-2.1%	-1.8%
Average GDP loss 2012-2050			
In participating countries [3]	-2.0%	-2.2%	-2.5%
In non-participating countries	0.0%	-1.2%	-1.0%
World	-0.4%	-1.4%	-1.3%

1. Same as [A] but considering world sectoral agreements for energy intensive industries, without permit fungibility.
2. Same as [B] but with permit fungibility.
3. Participating countries do not include those countries covered only by international sector wide agreements.

Source: OECD, ENV-Linkages model.

Table 3.8. Subsidies to ethanol and biodiesel per ton of CO_2 equivalent avoided in selected OECD countries, lower bound estimates, 2006

($US per ton of CO_2 eq)

	Ethanol	Biodiesel
United States	300	250
European Union	700	250
Australia	400	150
Canada	250	250
Switzerland	300	250

Source: Steenblik (2007).

Table 3.9. Applied tariffs on undenatured ethyl alcohol in selected countries, 2007

	Applied MFN tariff (local currency or ad valorem rate)	Ad valorem equivalent pre-tariff unit value of 0.50/litre	Exceptions (in addition to other WTO member economies with which country has a free-trade agreement) or notes
Australia	5% + Australian $ 38.143/litre	52%	USA, New Zealand
Brazil	0%	0%	Lowered from 20% in March 2006
Canada	Canadian $ 0.0492/litre		Free Trade Agreement partners
European Union	19.2/hectolitre	38%	European Free Trade Association countries, developing countries in General System of Preferences
Switzerland	CHF 35 per 100kg	34%	EU, developing countries in General System of Preferences
United States	2.5% + $0.51/gallon	22%	Free Trade Agreement partners, Caribbean Basin Initiative partners

Source: OECD International Transport Forum, *Biofuels: Linking support to performance* .

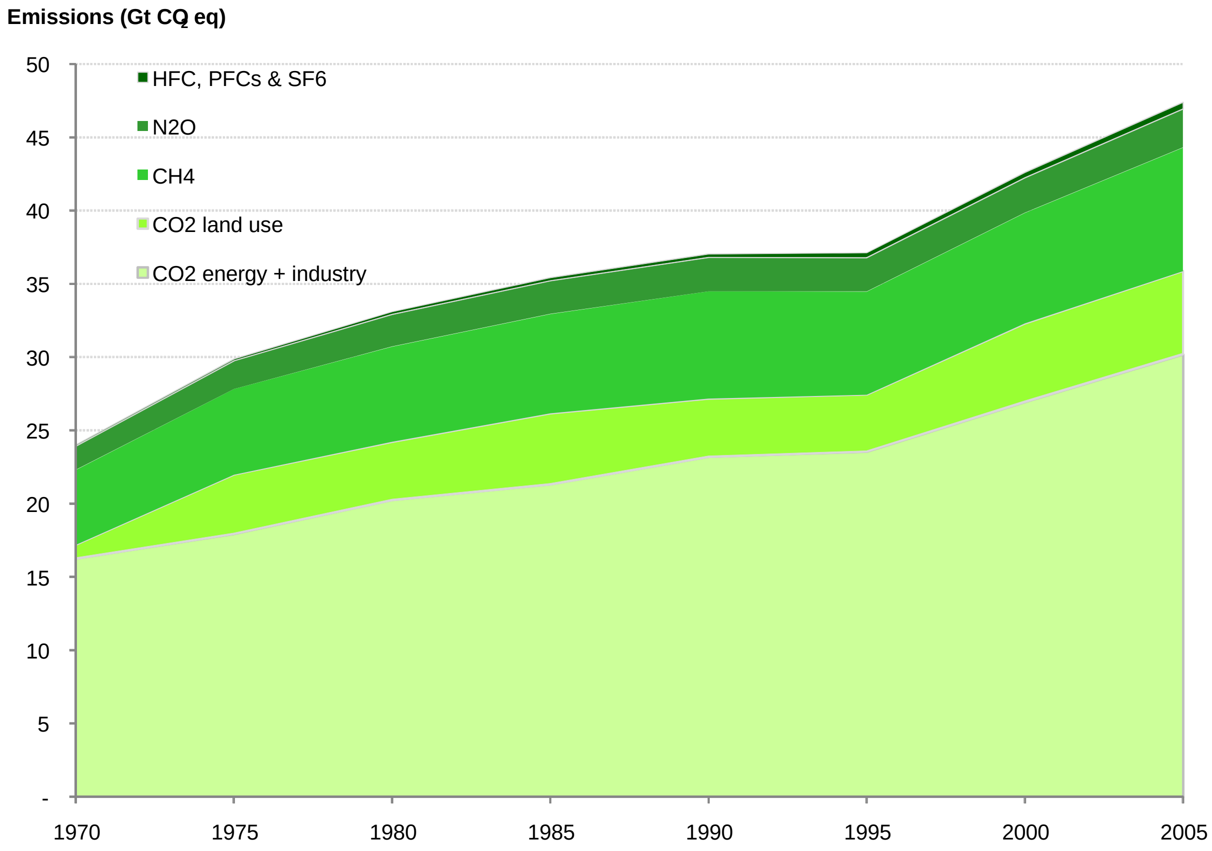
Table 5.1. Typical service life for selected investments

Type of asset	Typical service life (years)
Household appliances	8-12
Automobiles	10-20
Industrial equipment/machinery	10-70
Aircraft	30-40
Electricity generators	50-70
Commercial/industrial buildings	40-80
Residential buildings	60-100

Source: Jaffe(1999).

Figure 2.1. World emission trends by gas

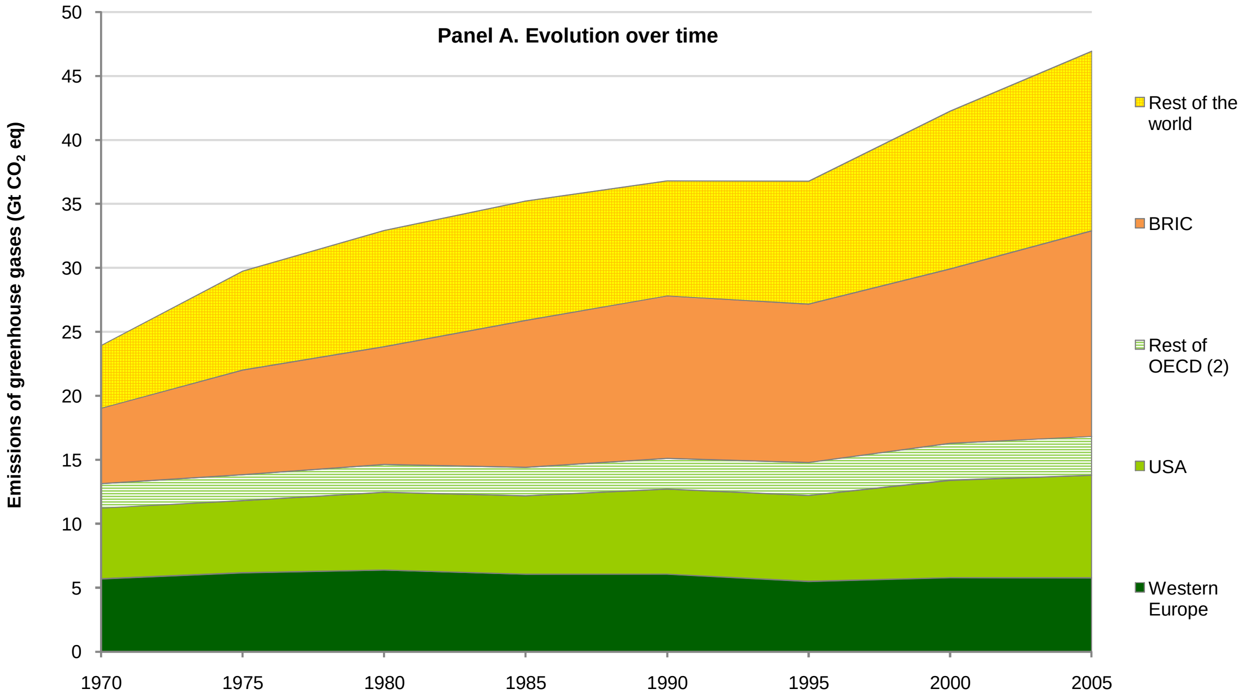
(1970-2005)



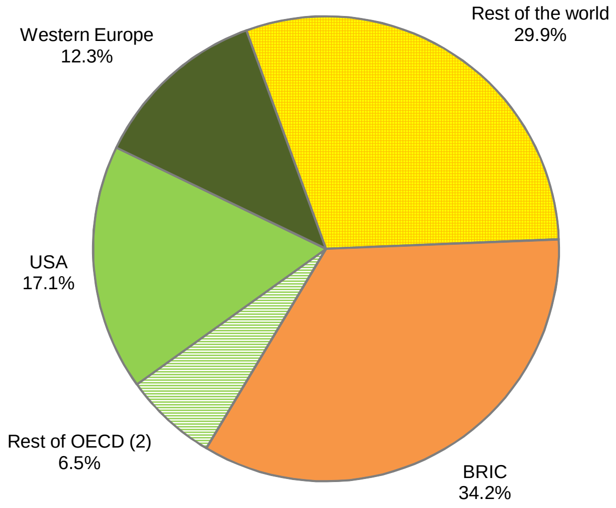
Source: OECD Environmental Outlook to 2030 (2008).

Figure 2.2. World emission trends by country/region[1]

(1970-2005)



Panel B. Breakdown in 2005



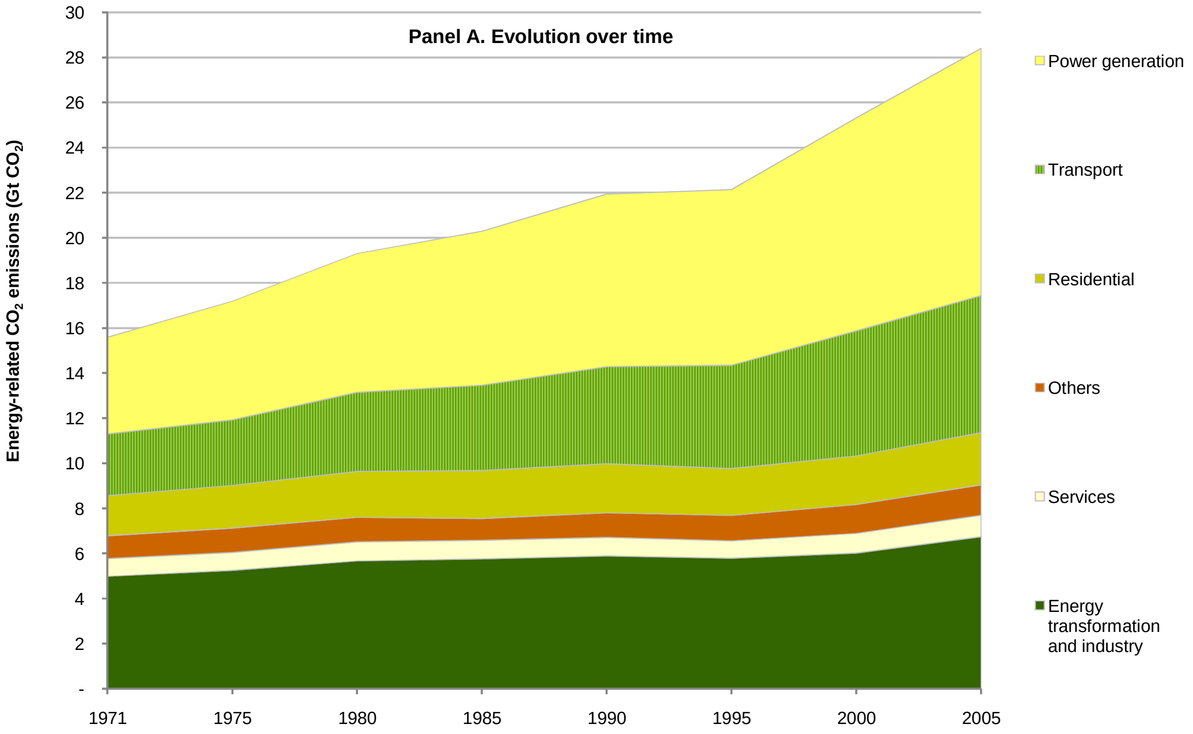
1. Including emissions from Land Use, Land-Use Change and Forestry.

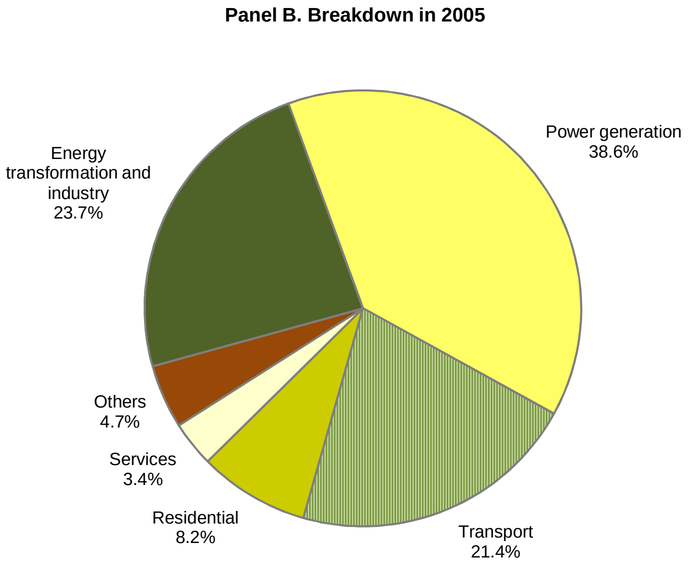
2. Rest of OECD does not include Korea, Mexico and Turkey, which are aggregated in Rest of the World (ROW).

Source: *OECD Environmental Outlook to 2030 (2008).*

Figure 2.3. World energy-related CO_2 emission trends by sector

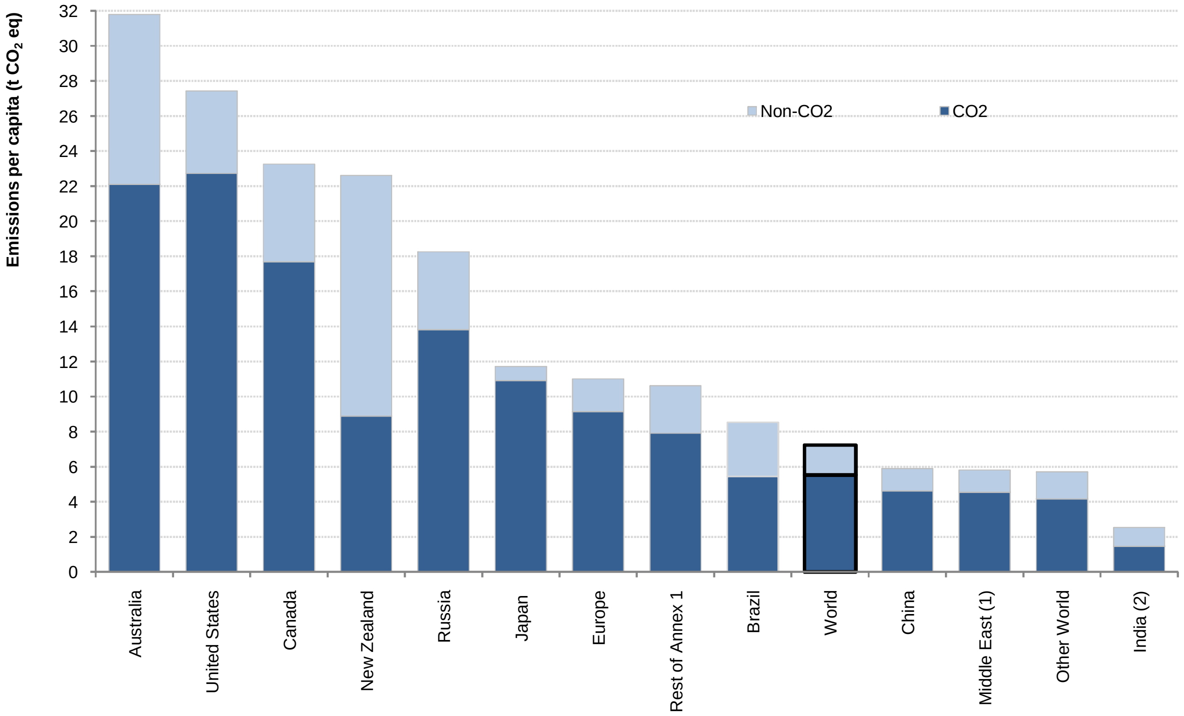
(1970-2005)





Source: OECD Environmental Outlook to 2030 (2008).

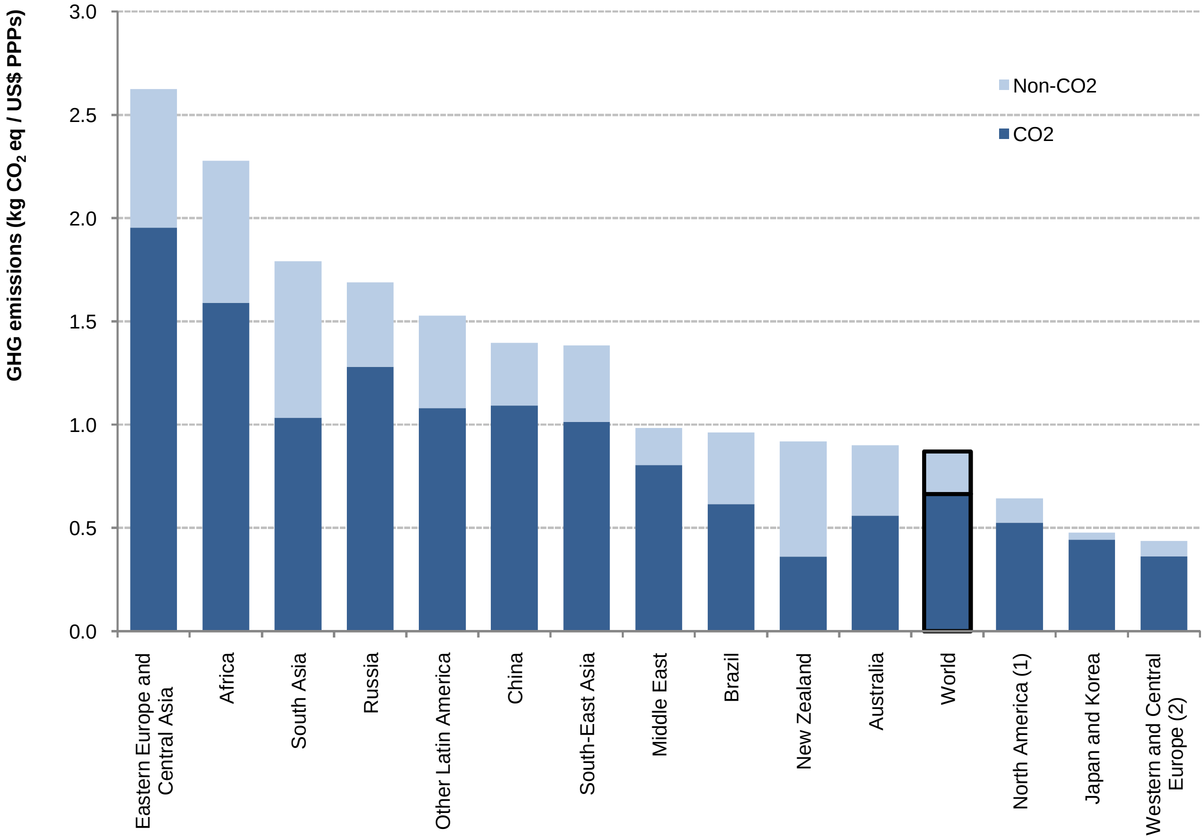
Figure 2.4. GHG emissions per capita, by country/region, 2005



1. Includes also Indonesia and North Africa.
2. Includes also other South Asian countries.
Source: *OECD Environmental Outlook to 2030 (2008).*

Figure 2.5. GHG emissions per unit of GDP, by region, 2005

(kg CO_2eq / US$2005)



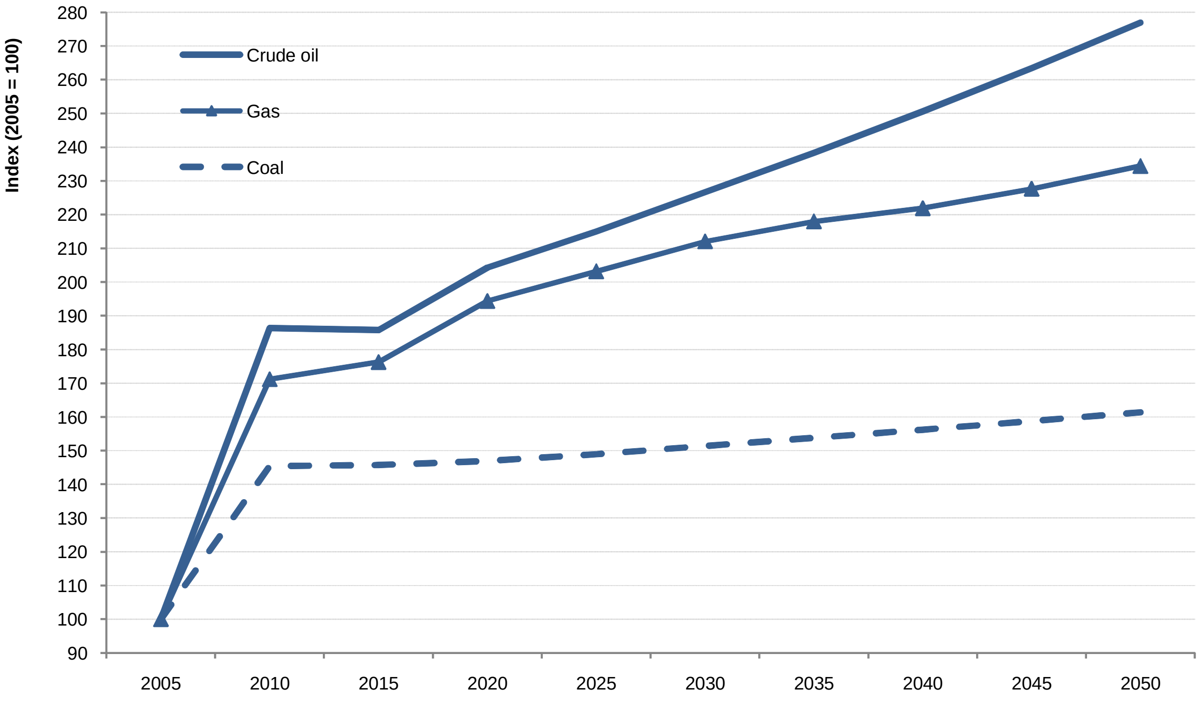
1. Including Mexico.

2. Including Turkey.

Source: OECD Environmental Outlook to 2030 (2008).

Figure 2.6. International fossil fuel price trends in the baseline scenario

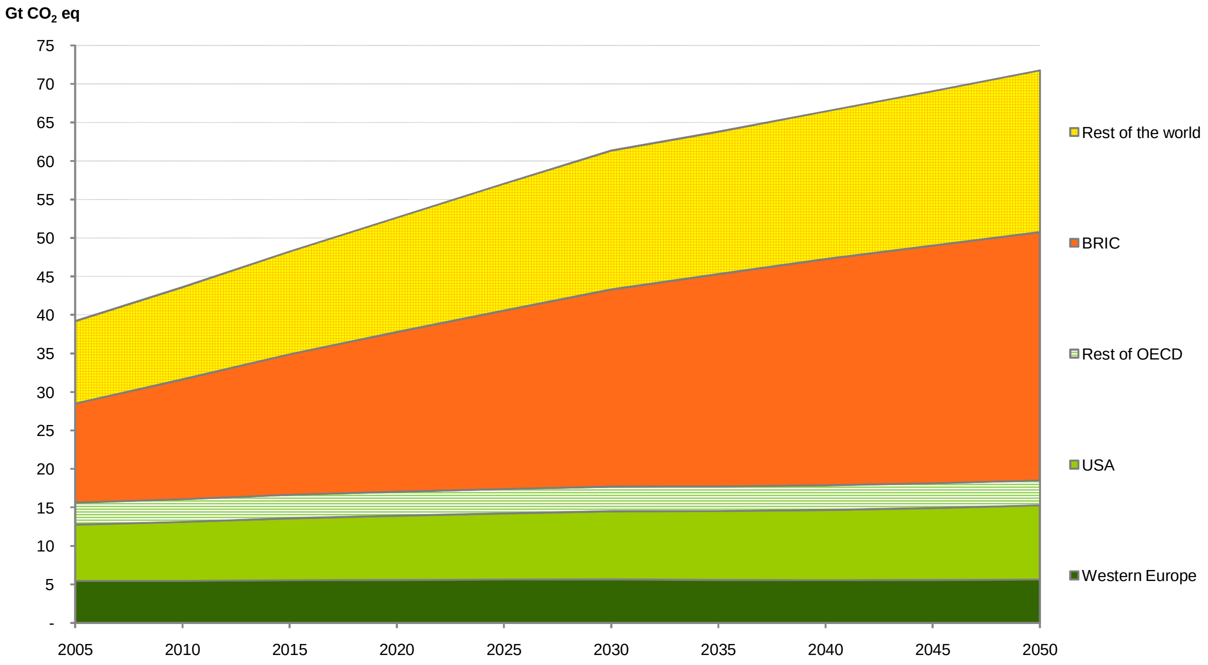
(Index 2005= 100)



Source: ENV-Linkages model

Figure 2.7. Projected GHG emissions[1] by country/region

(2005-2050, Gt CO_2 eq)



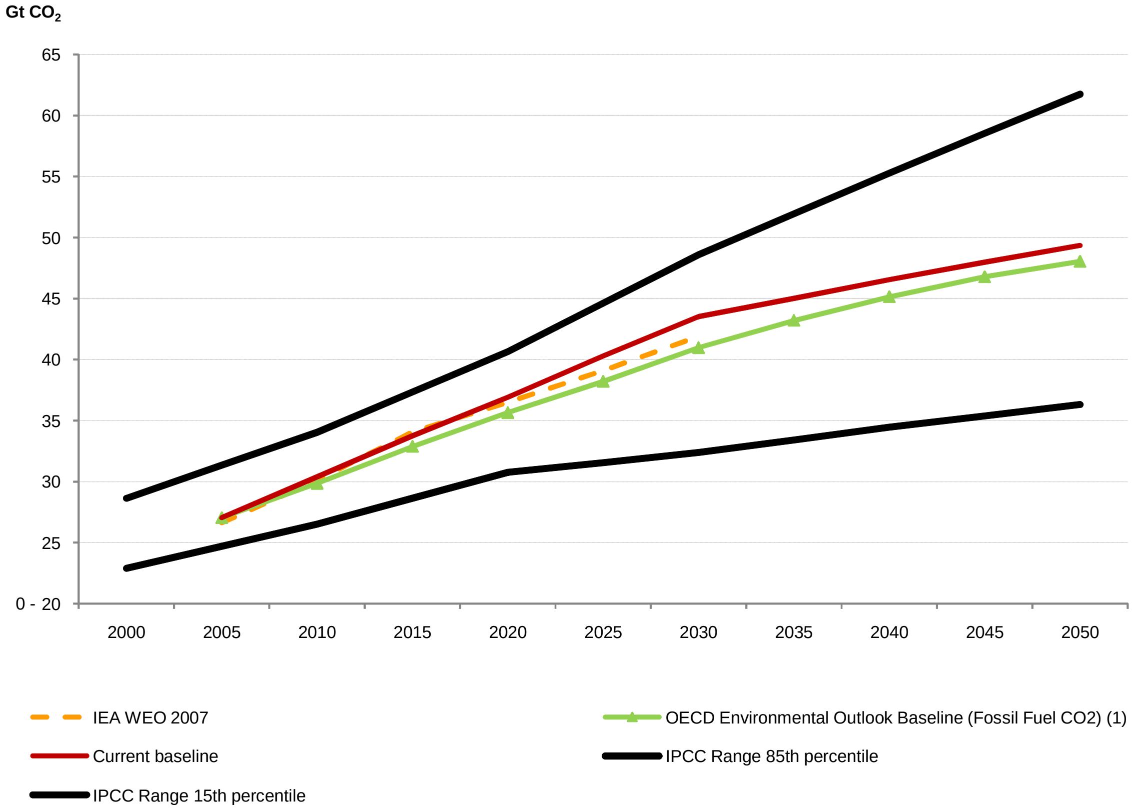
1. Excluding emissions from Land Use, Land-Use Change and Forestry.

Note: Countries/regions in this figure are based on the 12-regions aggregation of the ENV-Linkages model. Korea, Mexico and Turkey are included in the Rest of the World (ROW).

Source: OECD*, ENV-Linkages model.*

Figure 2.8. Comparison of the baseline projection of CO_2 emissions with other studies

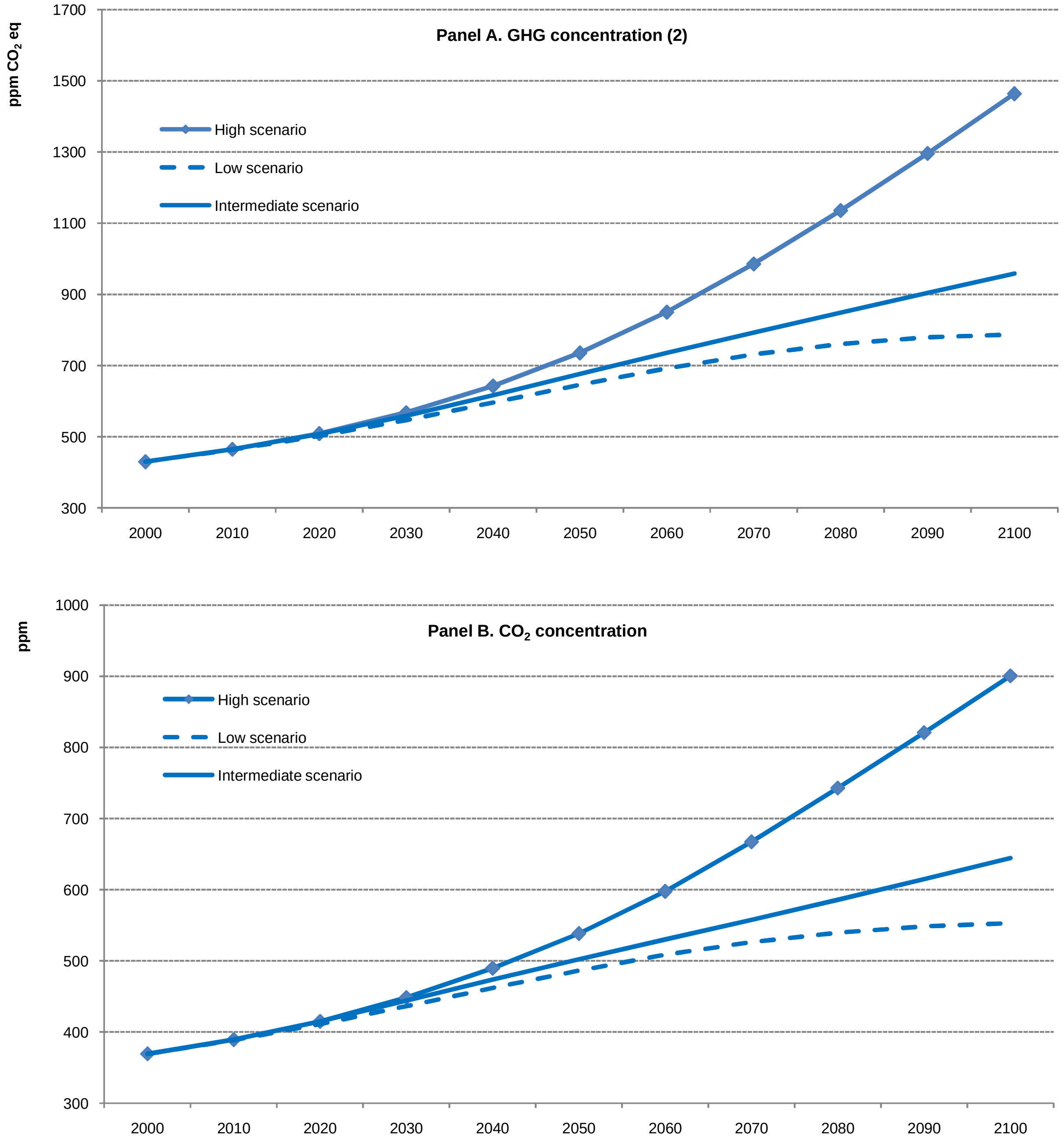
(2000-2050)



1. For comparative purposes, the OECD Environmental outlook baseline projection is calibrated to the 2005 (base year) data of the baseline projection used in the paper.

Source: IEA World Energy Outlook (2007); OECD Environmental Outlook to 2030 (2008); OECD, ENV-Linkages model and IPCC (2007), AR4.

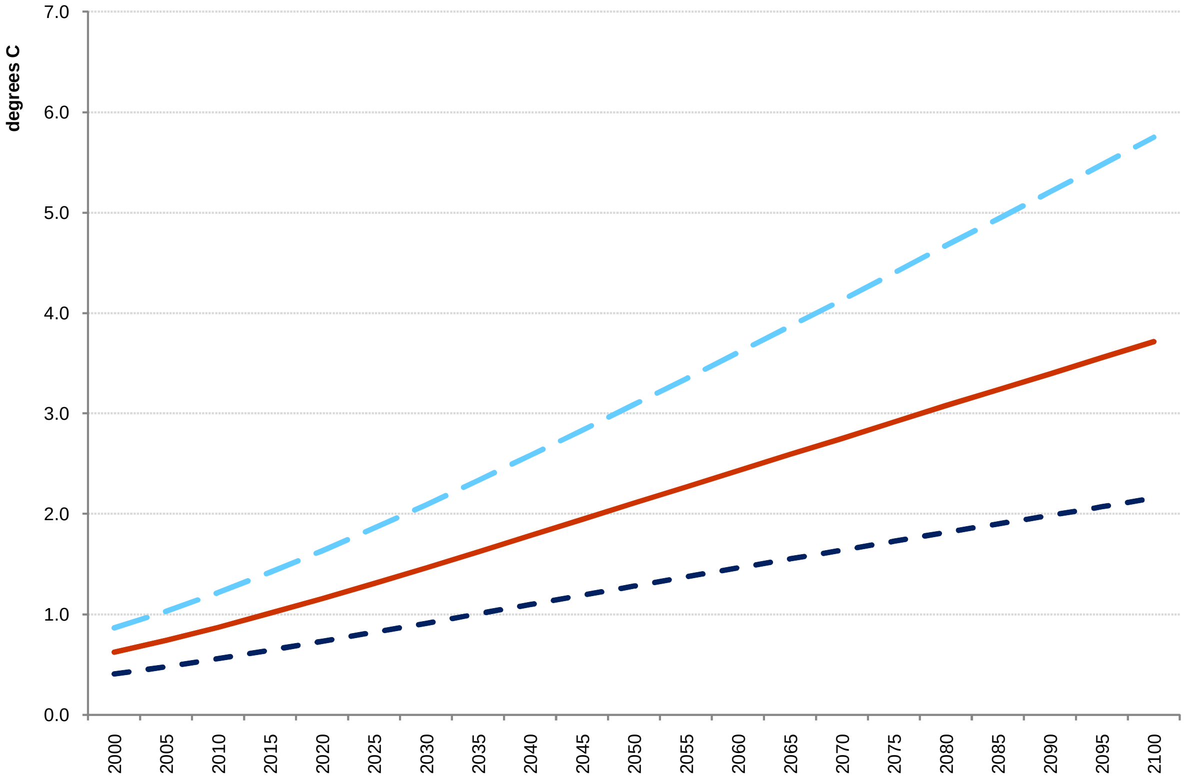
Figure 2.9. Projected trends in GHG concentration across a range of previous studies[1]



1. The three baseline scenarios have been constructed to be representative of the various existing scenarios discussed at the Intergovernmental Panel on Climate Change (IPCC) and the Energy Modeling Forum (EMF) (Riahi *et al*., 2006). They do not include any explicit climate policies beyond those already in place.
2. GHG concentration in CO_2eq, covering six types of GHGs, namely Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6).

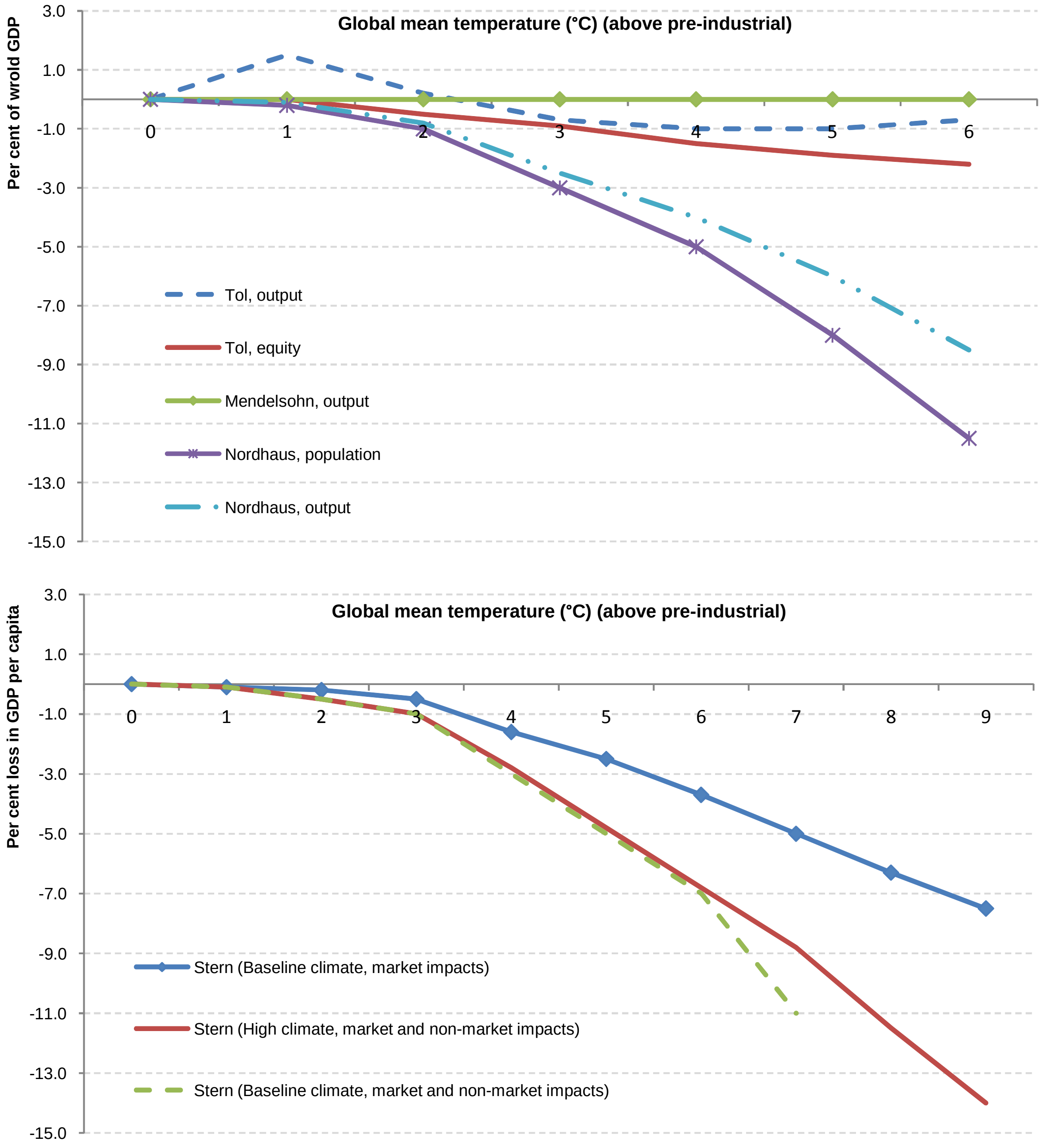
Source: IIASA GGI Scenario Database (Version 1.0.9).

Figure 2.10. Projected temperature increase in the baseline scenario (relative to pre-industrial levels)



Note: lower and upper bounds corresponding to lower and upper values of the climate sensitivity parameter.
Sources: Magicc 5.3 and OECD ENV-Linkages model.

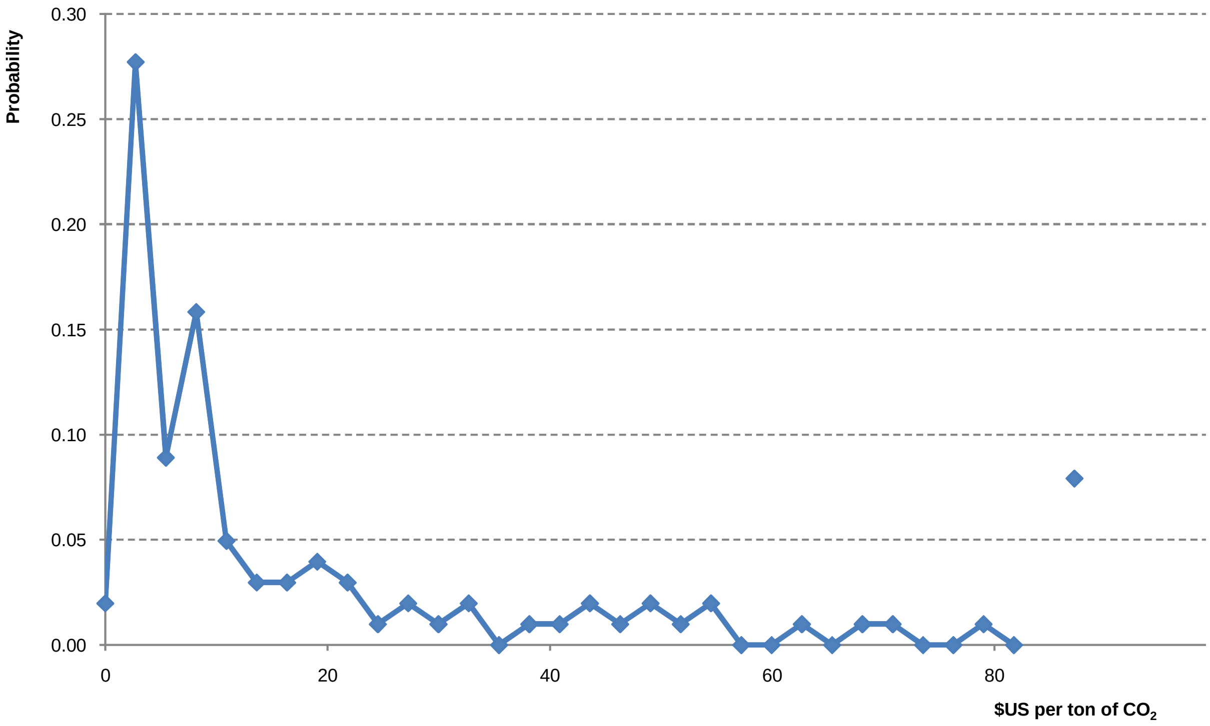
Figure 2.11. Global impacts of climate change from various studies[1]



1. Estimates represent the annual GDP impact (relative to a no-climate-change scenario) of a given increase in temperature, as observed at the time when this increase in temperature is reached. They come from studies by Tol (2002), Mendelsohn (1998), Nordhaus and Boyer (2000) and Stern (2007). There are several ways to aggregate impacts across regions. In “Tol, output”, impacts across regions are simply added while in “Tol, equity”, they are weighted by regional per capita income. In “Nordhaus output”, impacts are weighted by GDP while in “Nordhaus equity”, they are weighted by population. Weighting by population or GDP per capita attributes more weight to impacts in developing countries, which are expected to be higher than in developed countries, hence increasing the estimate of global impacts. Finally, “Stern (High climate, market and non-market impacts)” includes, in addition to market and non-market impacts that are covered in the “baseline climate” scenario, the impacts of catastrophic events. “High climate” scenarios explore the impact of large increases in temperatures on GDP.

Source: IPCC (2007) and Stern (2007)

Figure 2.12. Distribution of the social cost of carbon across a range of existing studies[1]

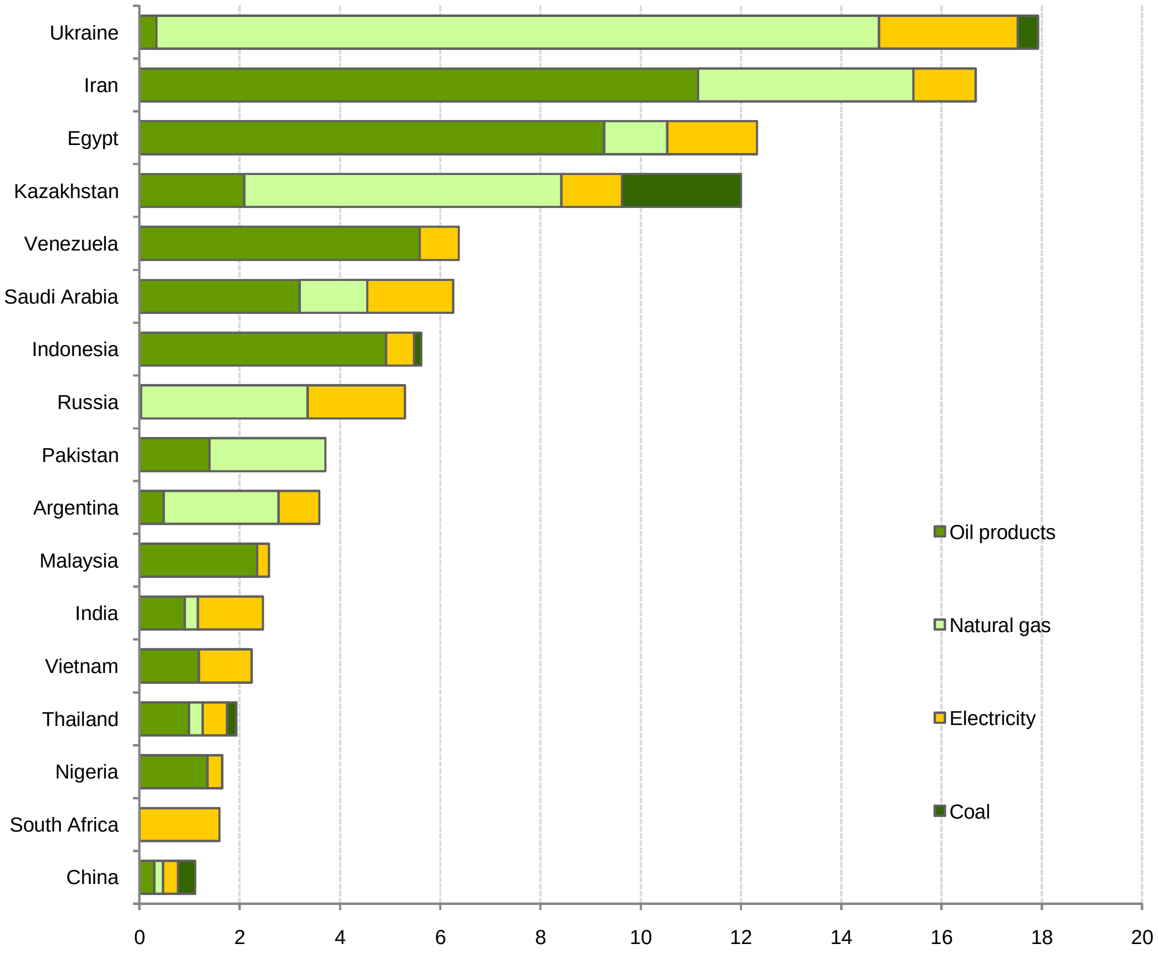


1. The social cost of carbon is the net present value (over the simulation horizon) of the climate change impact of one additional ton of CO_2 emitted in the atmosphere today. The observation on the right hand side of the figure is the cumulative probability of Social Cost of Carbon in excess of 85$/t$CO_2$.

Source : Tol (2004).

Figure 3.1. Energy subsidies[1] in selected developing and middle-income countries, 2005[2]

(Per cent of GDP)



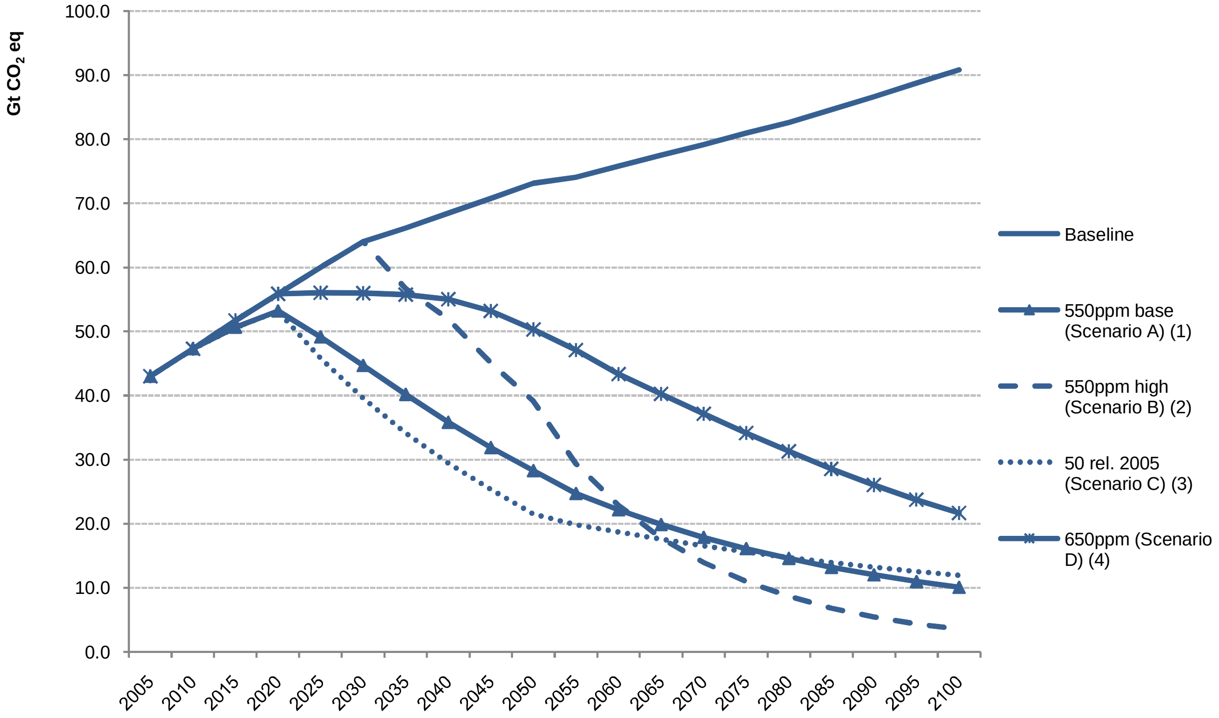
1. Such subsidies can take the form of direct financial interventions by government, such as grants, tax rebates or deductions and soft loans, and indirect interventions, such as price ceilings and free provision of energy infrastructure and services.

2. Energy commodity prices have increased dramatically since 2005. To the extent that local price levels have not been adjusted accordingly, the data shown in this graph are likely to understate the current magnitude of subsidies in a number of areas.

Source: IEA (2006).

Figure 3.2. GHG emissions in alternative cost-effective policy scenarios

(2005-2100)

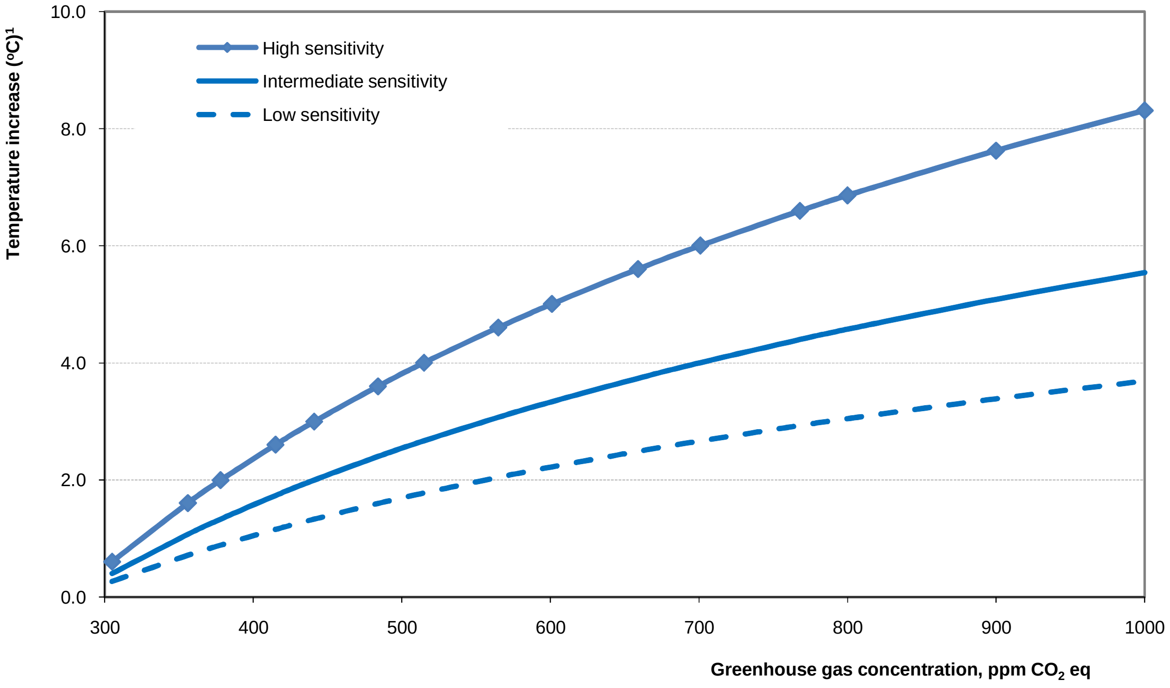


1. Stabilisation of CO_2 concentration at 450ppm, and of overall GHG concentration at about 550ppm CO_2 eq, with modest overshooting.
2. Stabilisation of CO_2 concentration at 450ppm, and of overall GHG concentration at about 550ppm CO_2 eq, with high overshooting.
3. 50% GHG emission cut in 2050 with respect to 2005 levels.
4. Stabilisation of CO_2 concentration at 550ppm, and of overall GHG concentration at about 650ppm CO_2 eq, without overshooting.

Source: OECD, ENV-Linkages model.

Figure 3.3. Link between long-run GHG concentration and global temperature

Increases in temperature with concentration for the "likely" range of climate sensitivity values

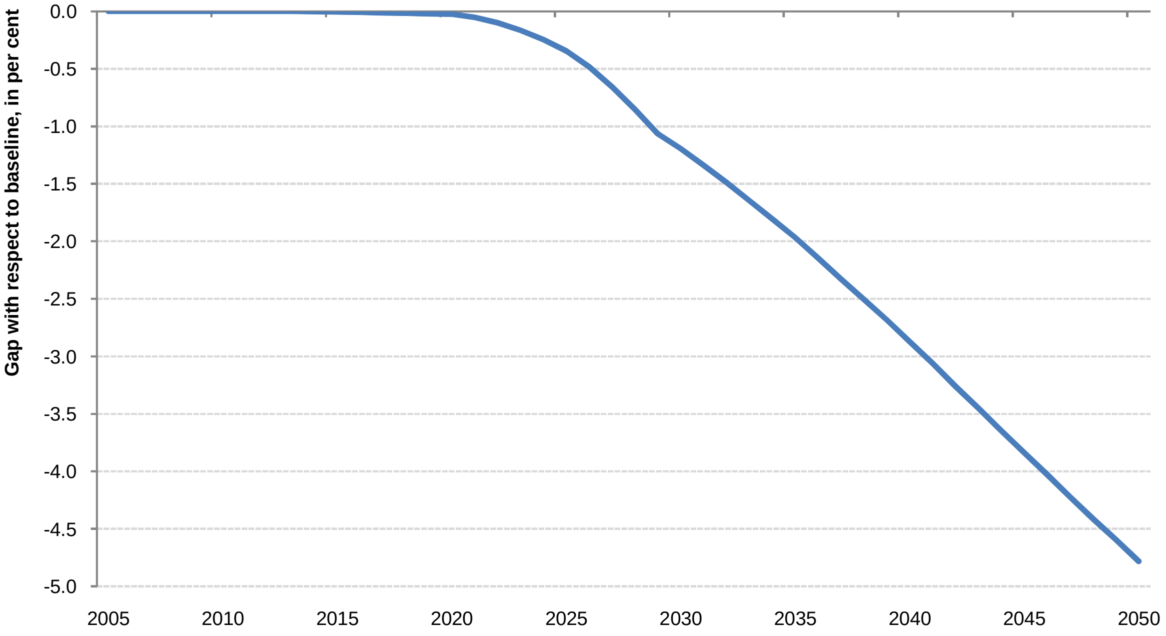


Note: The climate sensitivity parameter measures the impact on temperature of a doubling of concentration (see section 2.4) and determines the link between long-run GHG concentration and global temperature at the steady state. Because of the inertia of the system, steady-state temperatures may be reached several decades after concentration stabilisation. This parameter equals 4.5 in the "high sensitivity" scenario, 3 in the "intermediate sensitivity" scenario, and 2 in the "low sensitivity" scenario.

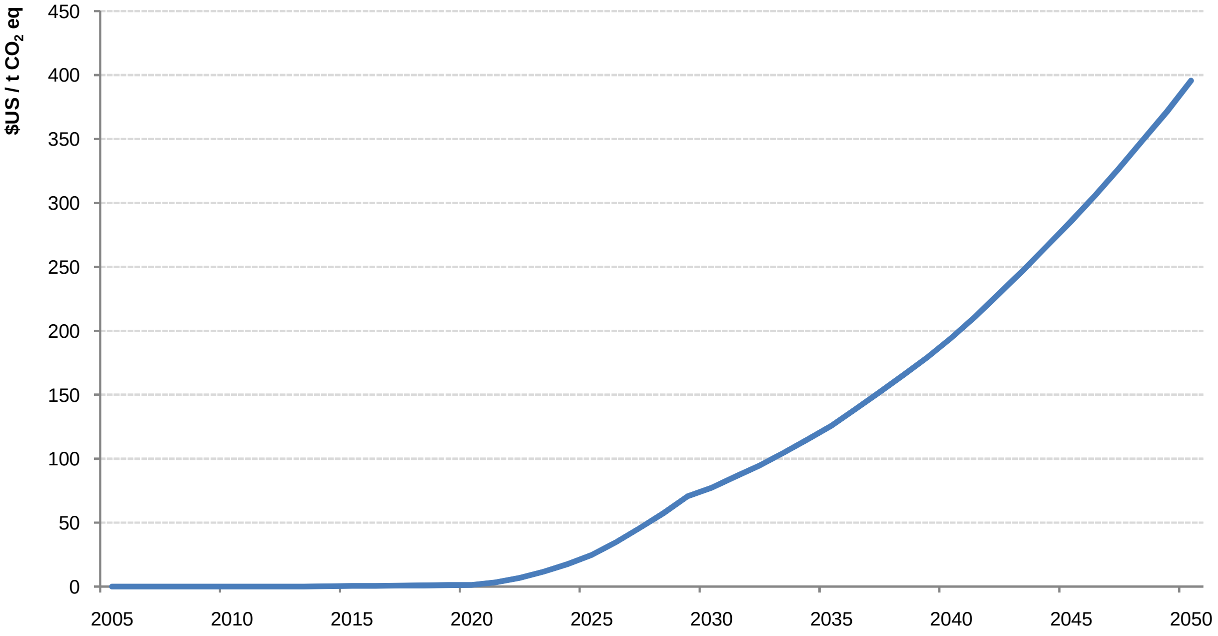
Source : IPCC (2007), AR4.

Figure 3.4 Time profile of economic costs and GHG emissions price under the "550ppm-base" GHG concentration scenario (Scenario A)

Panel A. GDP loss



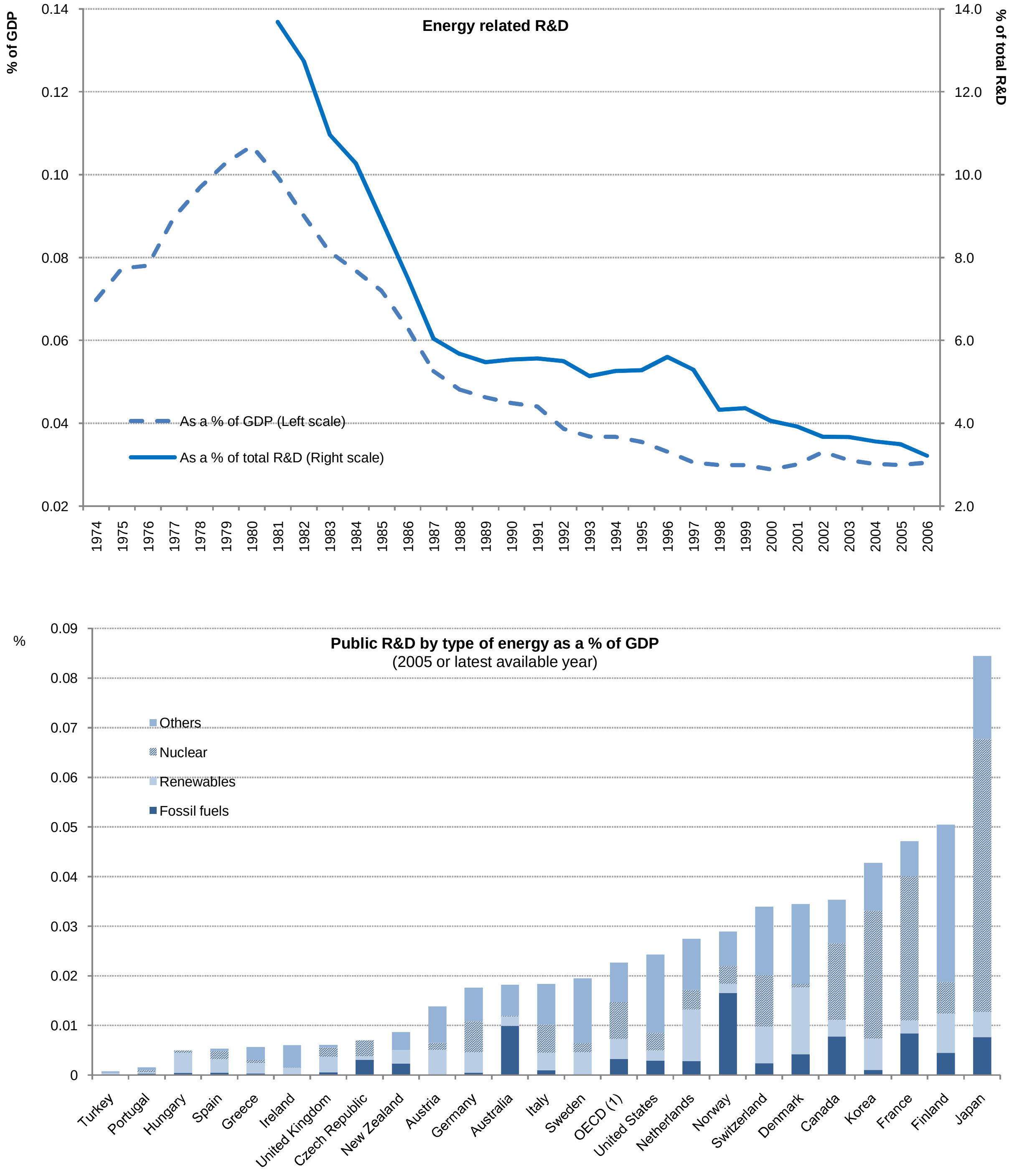
Panel B. GHG emissions price



Source: OECD, ENV-Linkages model.

Figure 4.1. Public energy related R&D expenditures in OECD countries

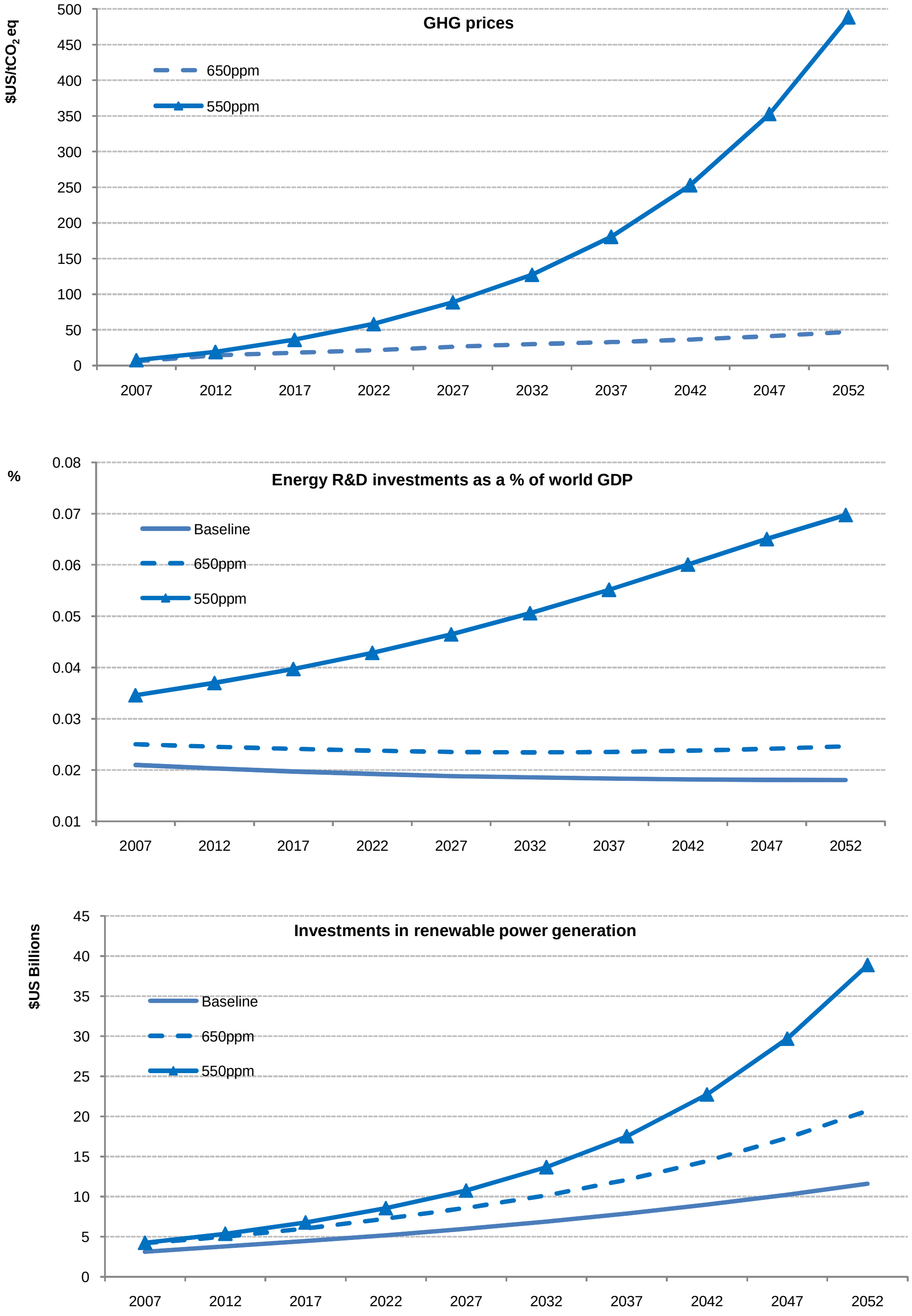
(Per cent of GDP)



1. Unweighted average of OECD countries less non-IEA member countries (Iceland, Mexico, Poland and Slovak Republic). Due to lack of data, Belgium and Luxembourg are also excluded.

Source: IEA database.

Figure 4.2. Estimated response of R&D and renewable power generation deployment under alternative world GHG emission price scenarios (650ppm and 550ppm GHG concentration stabilisation scenarios) [1]

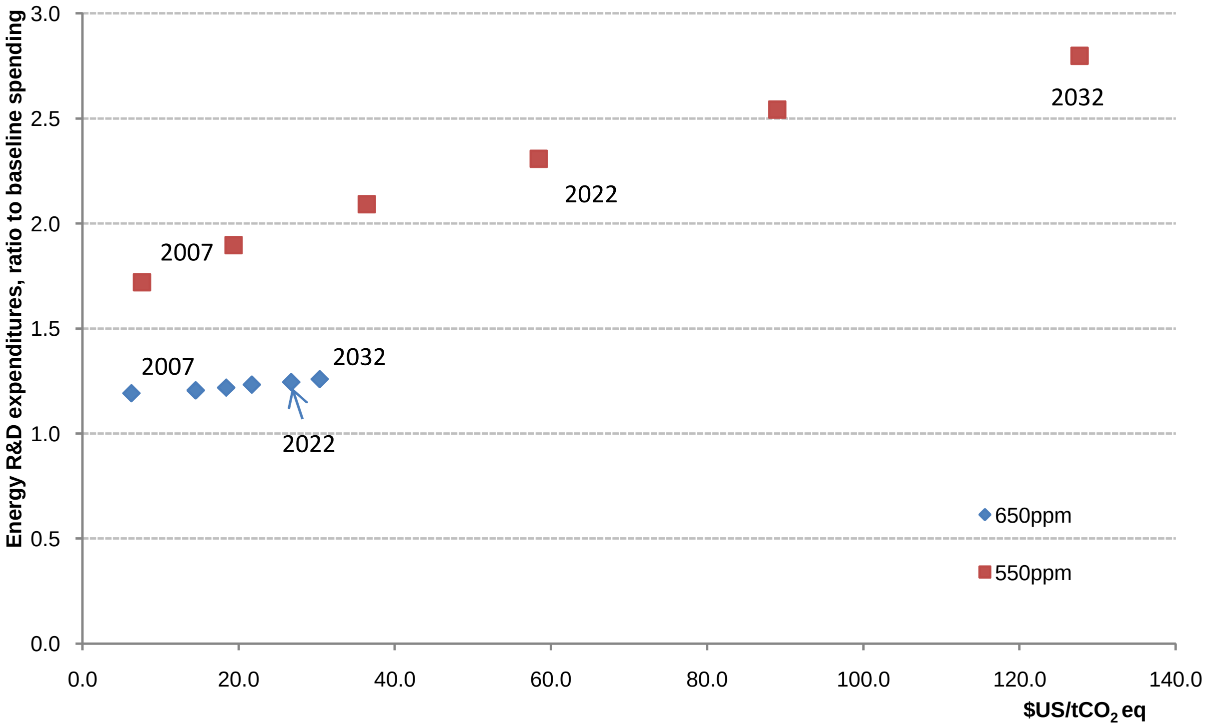


[1] Emissions of non-CO_2 gases are not covered by the model used in this analysis and are therefore excluded from these simulations. The 550ppm greenhouse gas concentration stabilisation scenario run here is in fact a 450 ppm CO_2 only scenario and greenhouse gas prices are CO_2 prices. Stabilisation of CO_2 concentration at 450ppm corresponds to stabilisation of overall greenhouse gas concentration at about 550ppm.

Source: WITCH model simulations.

Figure 4.3. World energy R&D investment at given GHG emission prices under 650ppm and 550ppm GHG concentration stabilisation scenarios [1]

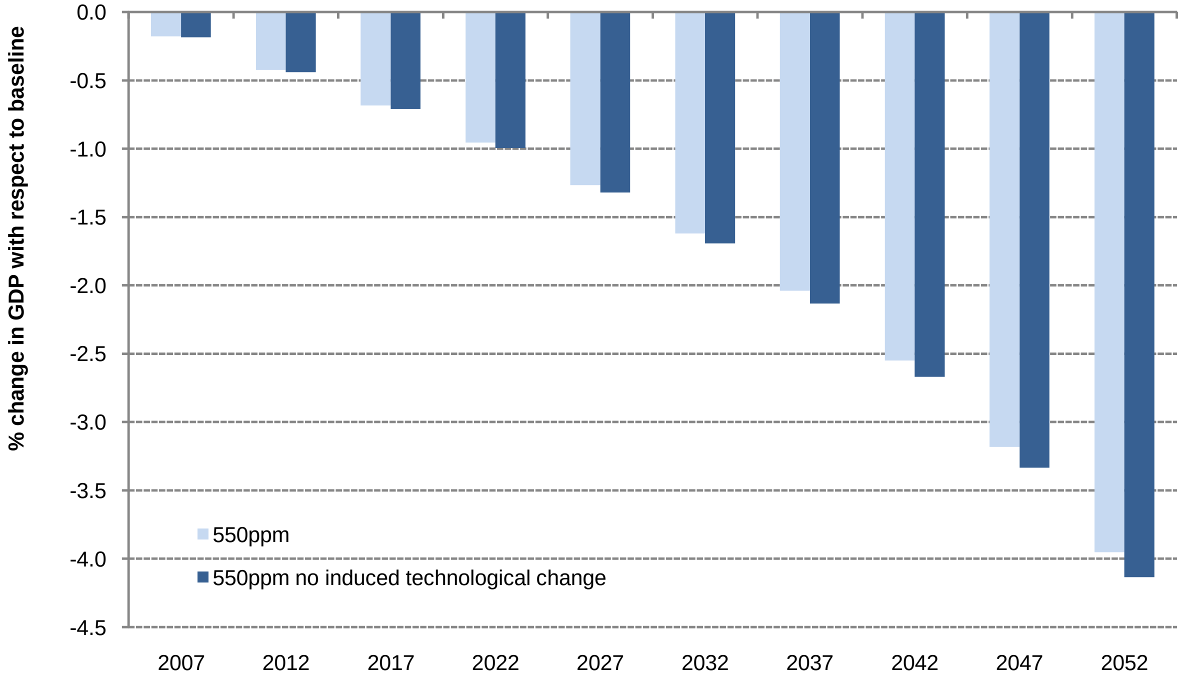
2007-2032



1. Emissions of non-CO_2 gases are not covered by the model used in this analysis and are therefore excluded from these simulations. The 550ppm greenhouse gas concentration stabilisation scenario run here is in fact a 450 ppm CO_2 only scenario and greenhouse gas prices are CO_2 prices. Stabilisation of CO_2 concentration at 450ppm corresponds to stabilisation of overall greenhouse gas concentration at about 550ppm.

Source: WITCH model simulations.

Figure 4.4. Projected world GDP costs under 550ppm GHG concentration stabilisation scenarios, with and without induced technological change [1]



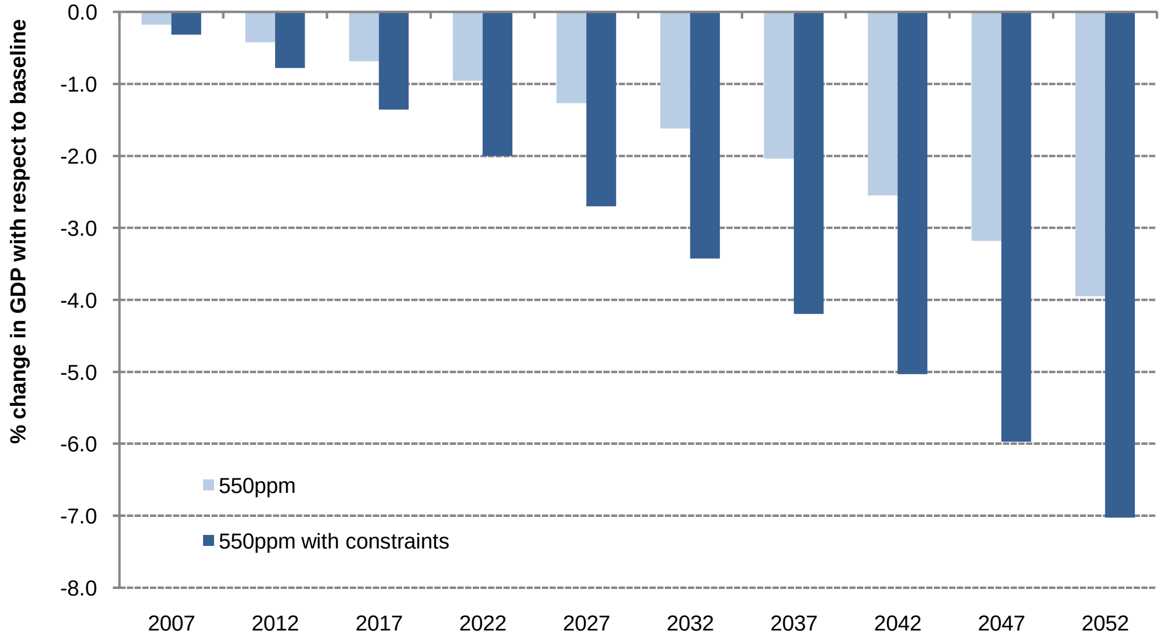
1. Emissions of non-CO_2 gases are not covered by the model used in this analysis and are therefore excluded from these simulations. The 550ppm greenhouse gas concentration stabilisation scenario run here is in fact a 450 ppm CO_2 only scenario and greenhouse gas prices are CO_2 prices. Stabilisation of CO_2 concentration at 450ppm corresponds to stabilisation of overall greenhouse gas concentration at about 550ppm.

Source: WITCH model simulations.

Figure 4.5. Projected energy technology mix in the electricity sector under baseline, 650ppm and 550ppm GHG concentration stabilisation scenarios [1]

1. Emissions of non-CO_2 gases are not covered by the model used in this analysis and are therefore excluded from these simulations. The 550ppm greenhouse gas concentration stabilisation scenario run here is in fact a 450 ppm CO_2 only scenario and greenhouse gas prices are CO_2 prices. Stabilisation of CO_2 concentration at 450ppm corresponds to stabilisation of overall greenhouse gas concentration at about 550ppm.
Source: WITCH model simulations.

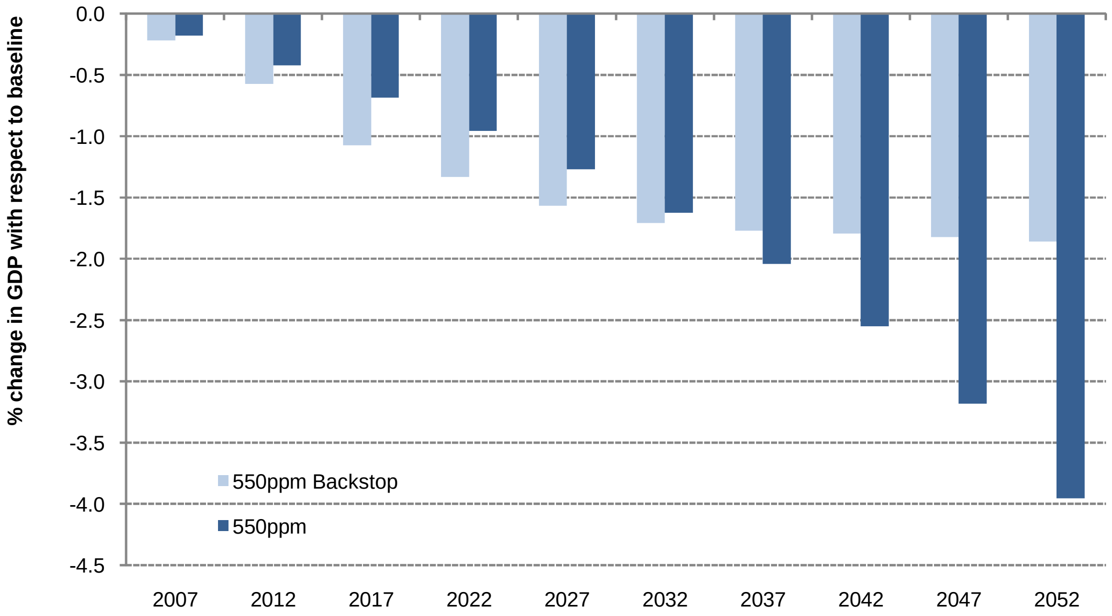
Figure 4.6. Projected world GDP costs under 550ppm GHG concentration stabilisation scenarios, with and without constraint on nuclear energy and CCS [1]

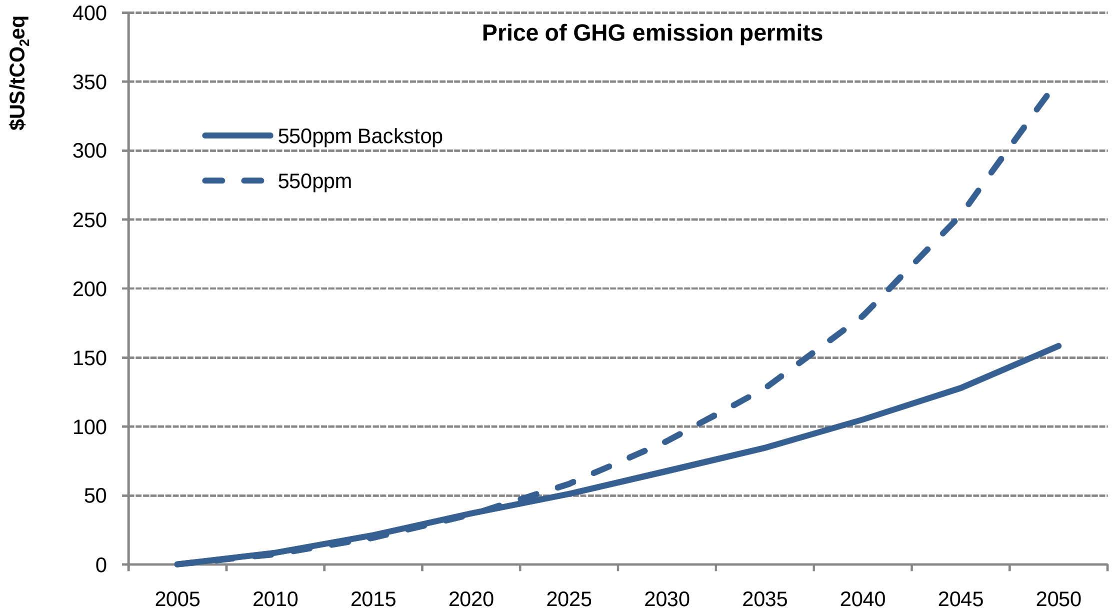


1. Emissions of non-CO_2 gases are not covered by the model used in this analysis and are therefore excluded from these simulations. The 550ppm greenhouse gas concentration stabilisation scenario run here is in fact a 450 ppm CO_2 only scenario and greenhouse gas prices are CO_2 prices. Stabilisation of CO_2 concentration at 450ppm corresponds to stabilisation of overall greenhouse gas concentration at about 550ppm.

Source: WITCH model simulations.

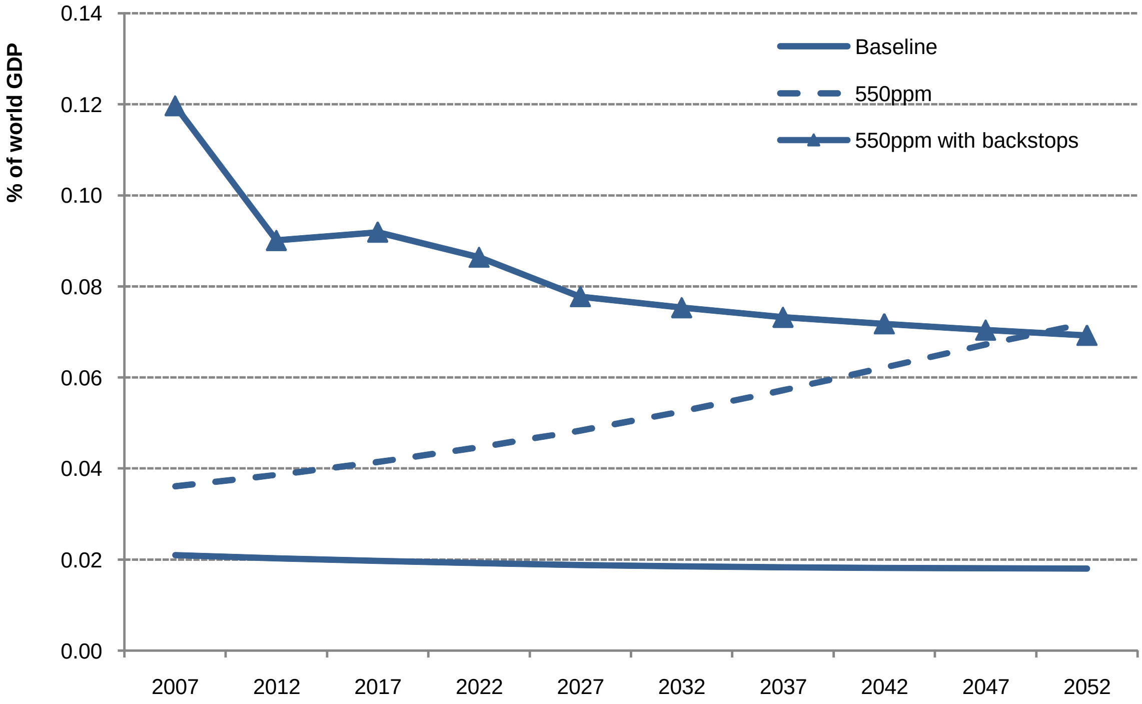
Figure 4.7. Projected world GDP costs and GHG emission price levels under 550ppm GHG concentration stabilisation scenario, with and without backstop technologies [1]





1. Emissions of non-CO_2 gases are not covered by the model used in this analysis and are therefore excluded from these simulations. The 550ppm greenhouse gas concentration stabilisation scenario run here is in fact a 450 ppm CO_2 only scenario and greenhouse gas prices are CO_2 prices. Stabilisation of CO_2 concentration at 450ppm corresponds to stabilisation of overall greenhouse gas concentration at about 550ppm.
Source: WITCH model simulations.

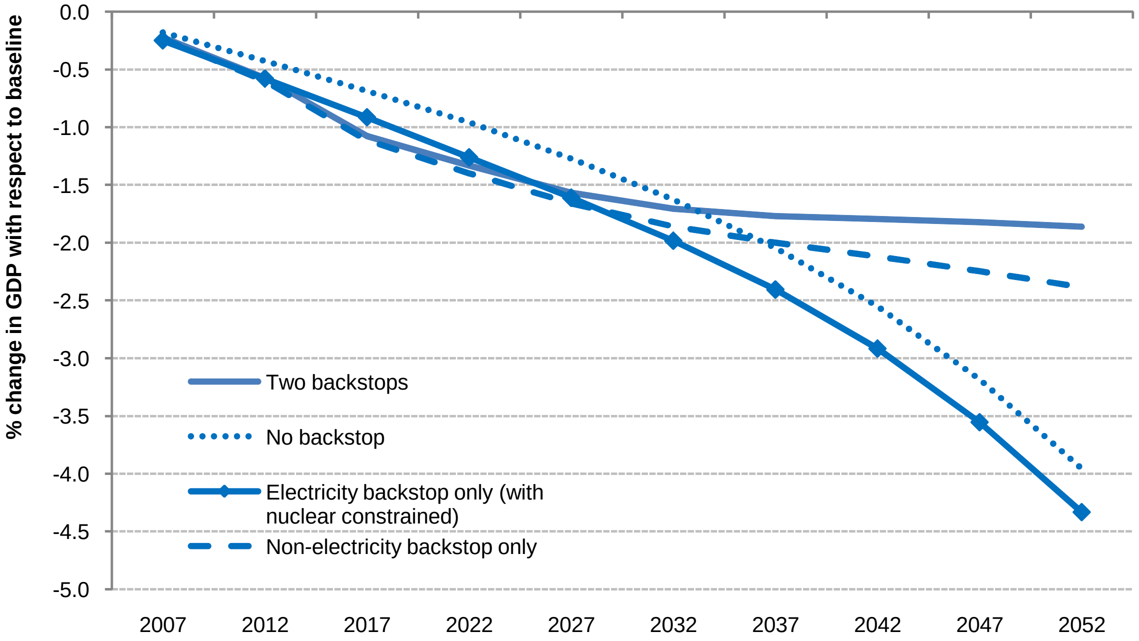
Figure 4.8. Projected energy R&D investments under 550ppm GHG concentration stabilisation scenario, with and without backstop technologies [1]



1. Emissions of non-CO_2 gases are not covered by the model used in this analysis and are therefore excluded from these simulations. The 550ppm greenhouse gas concentration stabilisation scenario run here is in fact a 450 ppm CO_2 only scenario and greenhouse gas prices are CO_2 prices. Stabilisation of CO_2 concentration at 450ppm corresponds to stabilisation of overall greenhouse gas concentration at about 550ppm.

Source: WITCH model simulations.

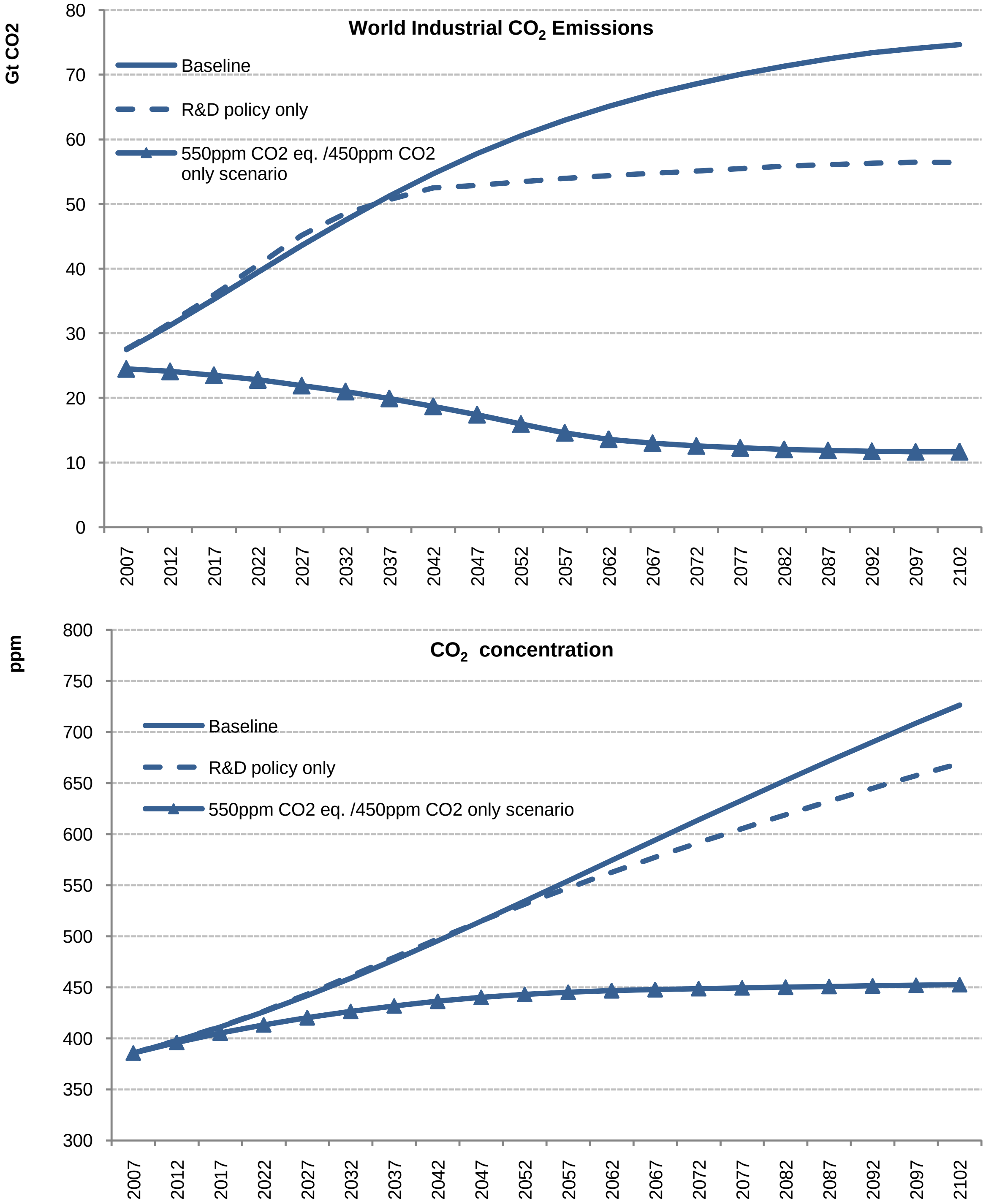
Figure 4.9. Projected world GDP costs under 550ppm GHG concentration stabilisation scenario, with electricity backstop or non-electricity backstop only[1]



1. Emissions of non-CO_2 gases are not covered by the model used in this analysis and are therefore excluded from these simulations. The 550ppm greenhouse gas concentration stabilisation scenario run here is in fact a 450 ppm CO_2 only scenario and greenhouse gas prices are CO_2 prices. Stabilisation of CO_2 concentration at 450ppm corresponds to stabilisation of overall greenhouse gas concentration at about 550ppm.

Source: WITCH model simulations.

Figure 4.10. Projected CO_2 emissions and concentration under a global R&D policy only [1]

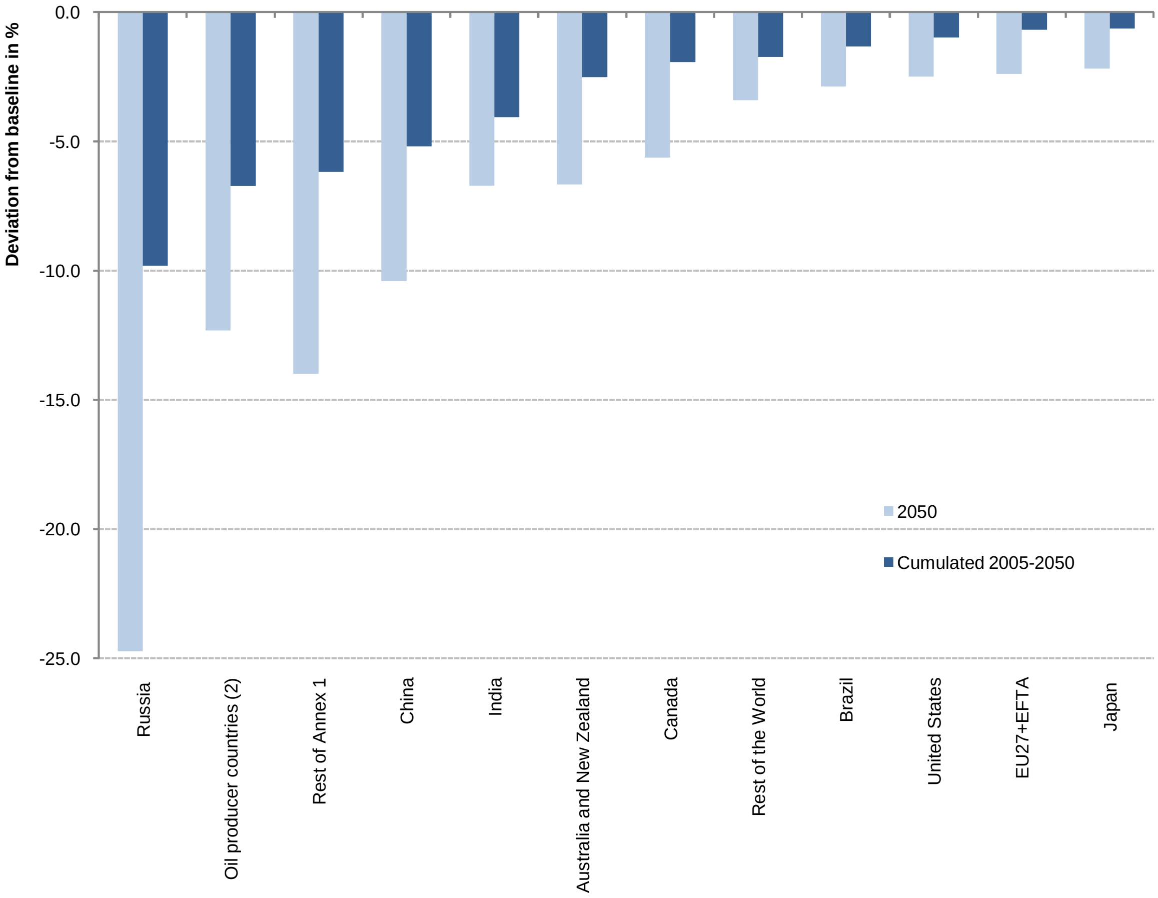


1. Emissions of non-CO_2 gases are not covered by the model used in this analysis and are therefore excluded from these simulations.

Source: WITCH model simulations.

Figure 6.1. Regional costs from stabilising long-run GHG concentration at 550 ppm[1]

(% of GDP)



1. Scenario "550ppm-base" (Scenario A), see table 3.1. " 2050" denotes the cost as a per cent of GDP in 2050 relative to baseline. "Cumulated 2005-2050" denotes the cumulated costs over 2005-2050 and represents the gap (in per cent) between the (undiscounted) sum of annual GDPs over 2005-2050 in the "550ppm-base" scenario and the corresponding sum in the baseline scenario.

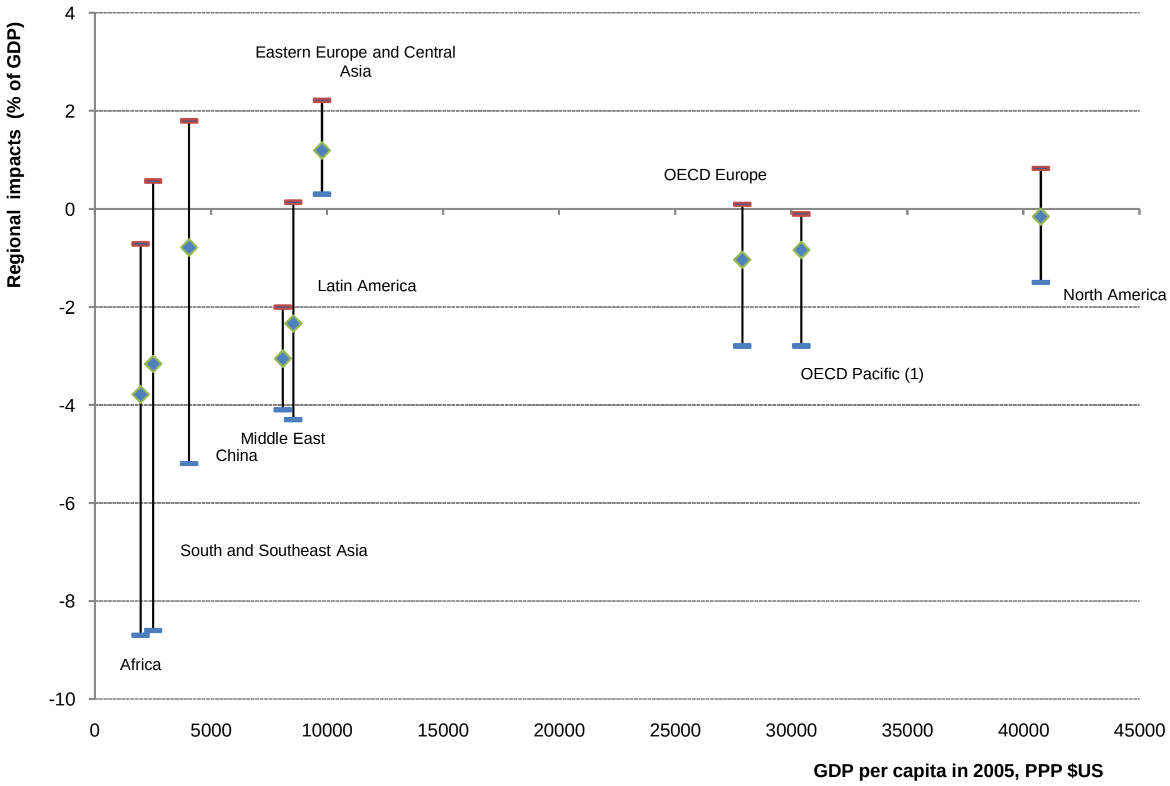
2. The region includes the Middle East, Algeria-Libya-Egypt, Indonesia, and Venezuela

Source: OECD ENV-Linkages model

Figure 6.2. Regional economic impacts

(% of GDP)

Dispersion of long-run impacts across countries of a 2.0-2.5°C increase in temperature above its pre-industrial level



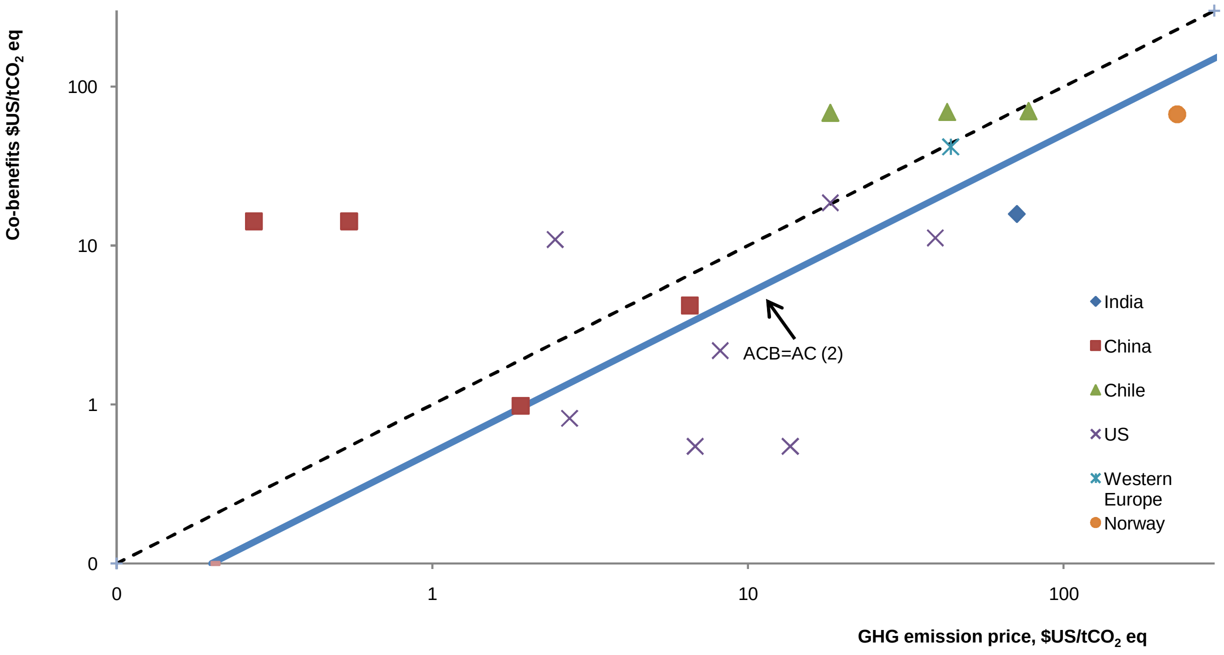
Note : Estimates come from different sources that are not entirely comparable. Those by Mendelsohn (2000) and Nordhaus and Boyer (2000) represent the annual GDP impact (relative to a no-climate-change scenario) observed at the time when a +2.5° increase in temperature is reached (i.e. in 2100 in both exercises). They are not entirely comparable to first-generation estimates surveyed by IPCC (1995), which are static estimates representing the annual GDP impact of a +2.5°C rise in temperature based on 1990 economic structures. The figure should be read as follows: For example, for Africa, the impacts of a warming of 2-2.5°C is expected to fall within the range of -1% to -9% of GDP according to existing estimates, with an average value of about -4% of GDP.

1. The OECD Pacific region includes Japan, which could not be featured separately due to the geographical aggregation of the underlying models. However, a few available estimates point to costs for Japan alone of -0.1 to -0.5% .

Source : Nordhaus and Boyer (2000), Mendelsohn et al. (2000) and IPCC (1995).

Figure 6.3. Review of existing regional estimates of the co-benefits in 2010 at different GHG emission prices

($US/ton of CO_2 eq[1])



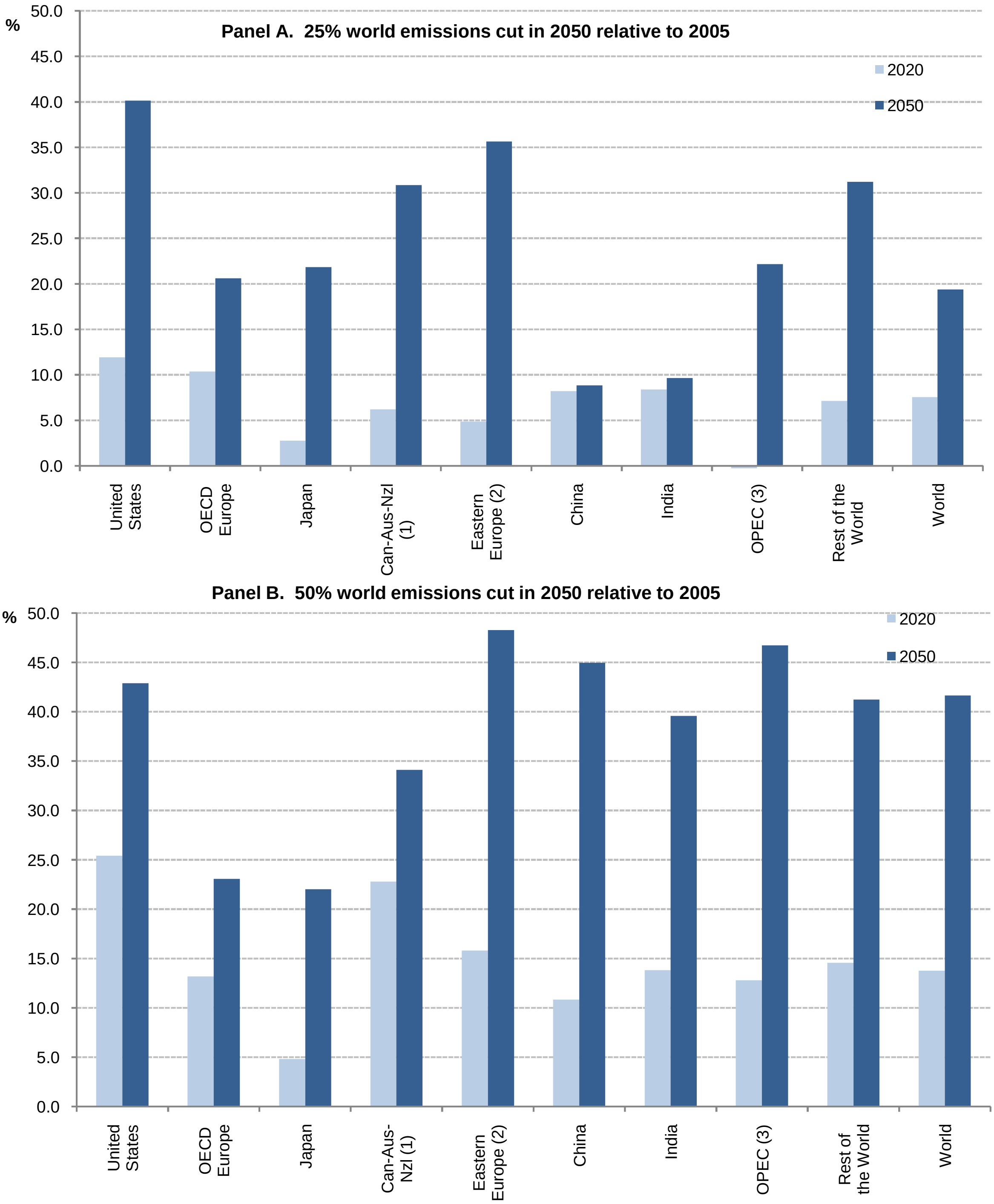
1. For each country, observations represent estimates from various studies and/or for various carbon prices. The base year for estimates is 1996 or the latest available year.

2. The line ACB=AC" indicate situation where the average co-benefit is equal to the average cost of abatement. It assumes that abatement costs are a square function of emission reductions; average costs can then be computed as one half of marginal costs (i.e the carbon price). Points above this line indicate situations where the average co-benefit is higher than the average cost.

Source: OECD

Figure 6.4. Avoided premature deaths from reduced local air pollution through GHG mitigation policies[1]

(Differences from the baseline in %)

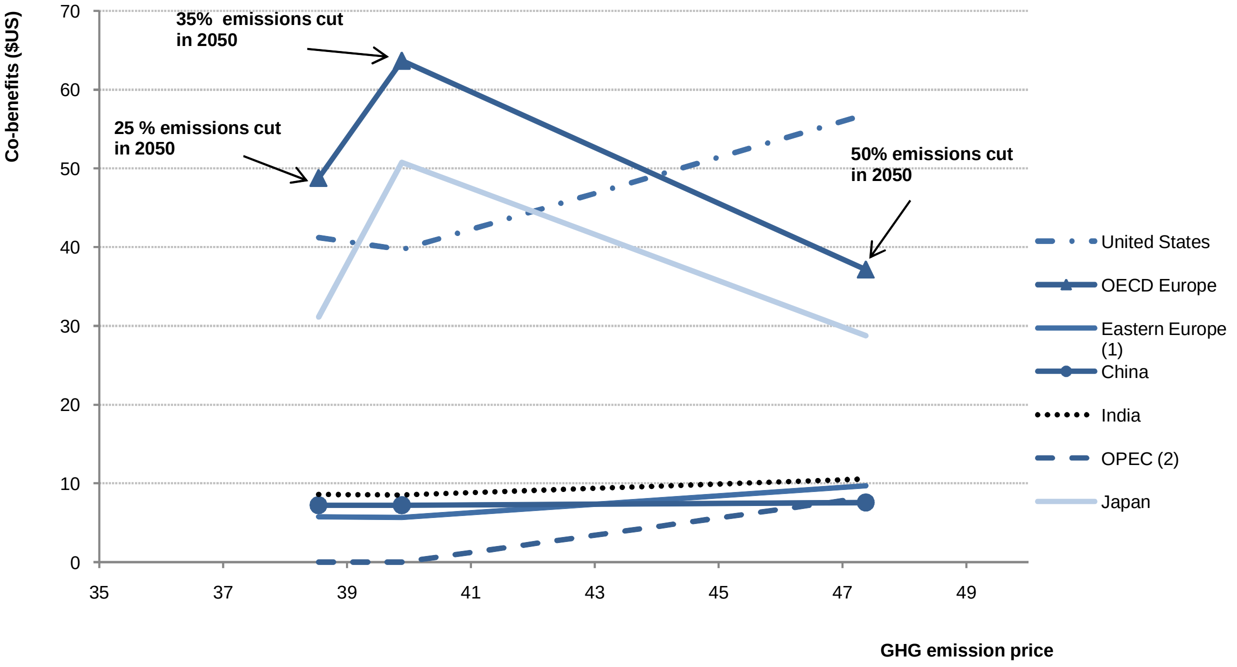


1. Canada, Australia and New Zealand are in the same geographical area in the MERGE model.
2. Including Russia.
3. Including Mexico.

Source: Bollen *et.al* (2008).

Figure 6.5. Co-benefits per ton of CO_2 equivalent and GHG emission prices

2020, $US per ton of CO_2 eq



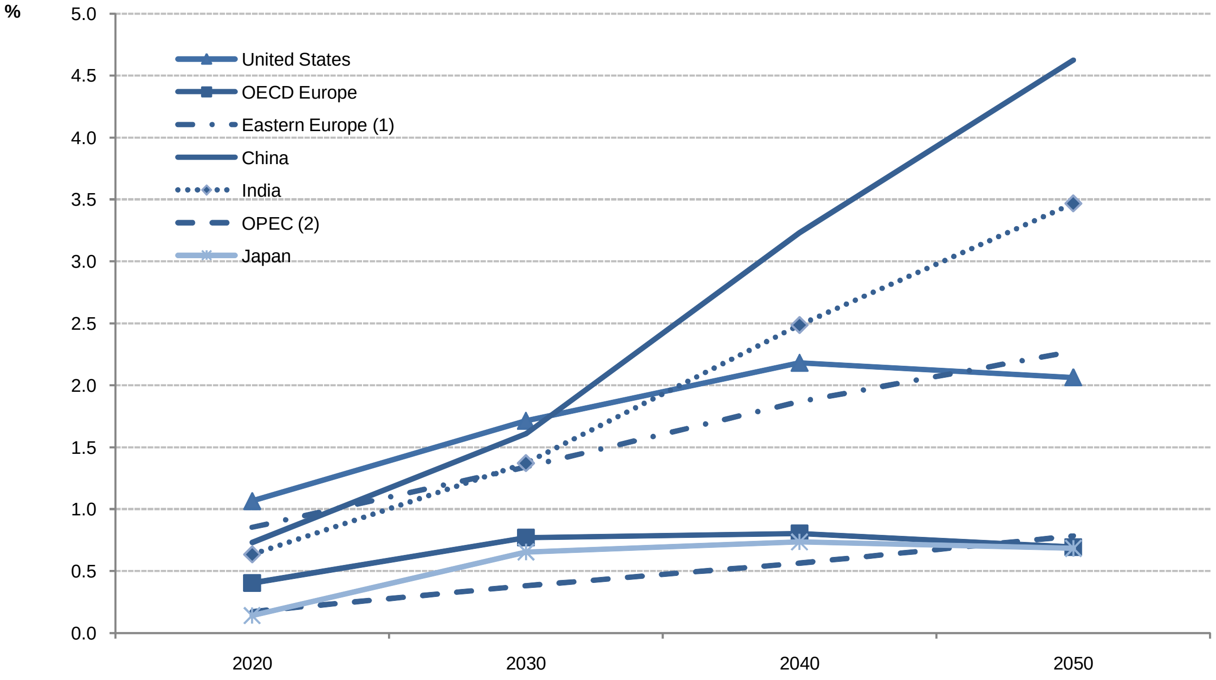
Note: Co-benefits per ton of CO_2 eq reflect an average co-benefit while the carbon price reflects the marginal cost of abatement, which exceeds the average cost. Therefore, their values are not directly comparable.

1. Including Russia.
2. Including Mexico.

Source: Bollen et.al (2008).

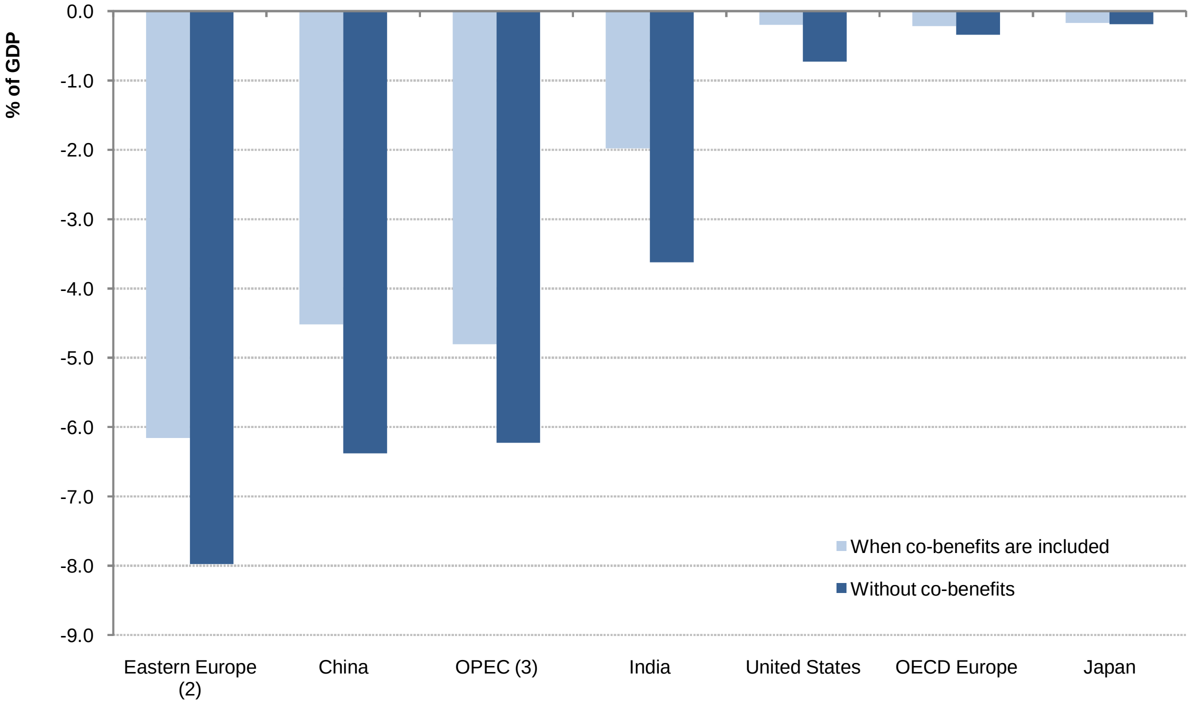
Figure 6.6. Co-benefits of reducing GHG emissions by 50% in 2050

(% of GDP)



1. Including Russia.
2. Including Mexico.
Source: Bollen *et.al* (2008).

Figure 6.7. GDP impact of participating in a global climate change agreement to reduce GHG emissions by 50% in 2050 : with and without co-benefits from local air pollution control[1]



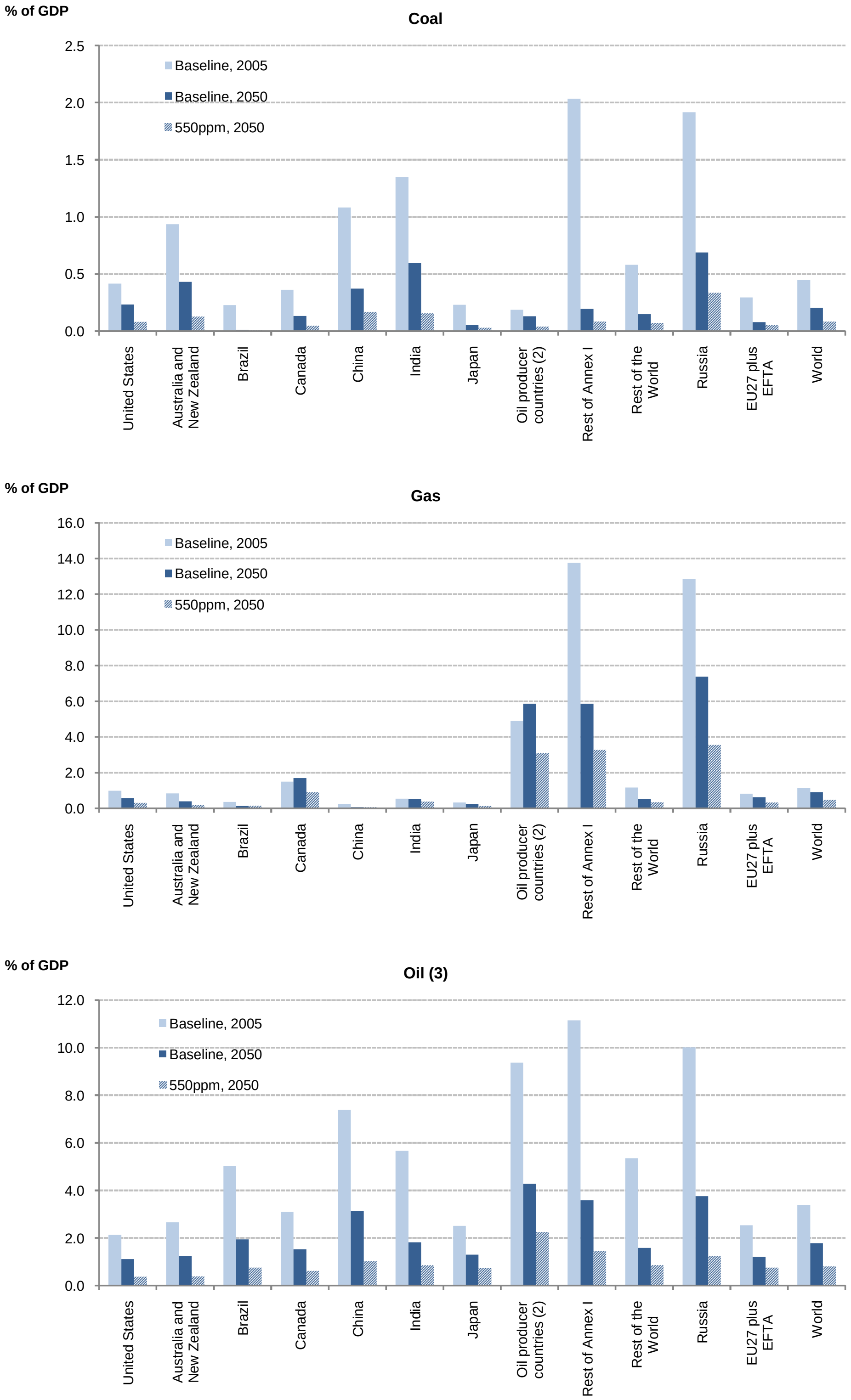
1. "Without co-benefits" is the return from GHG mitigation policy when co-benefits are not included, or the difference between the benefits in terms of avoided global climate change and the cost of mitigation policy. "When co-benefits are included" is the return from GHG mitigation policy when co-benefits are included, *i.e* the difference between the benefit in terms of both avoided global climate change and local air pollution and the cost of mitigation policy to which the opportunity gain of not having to achieve the same level of LAP reduction through direct policies is then added.

2. Including Russia.

3. Including Mexico.

Source: Bollen *et.al* (2008).

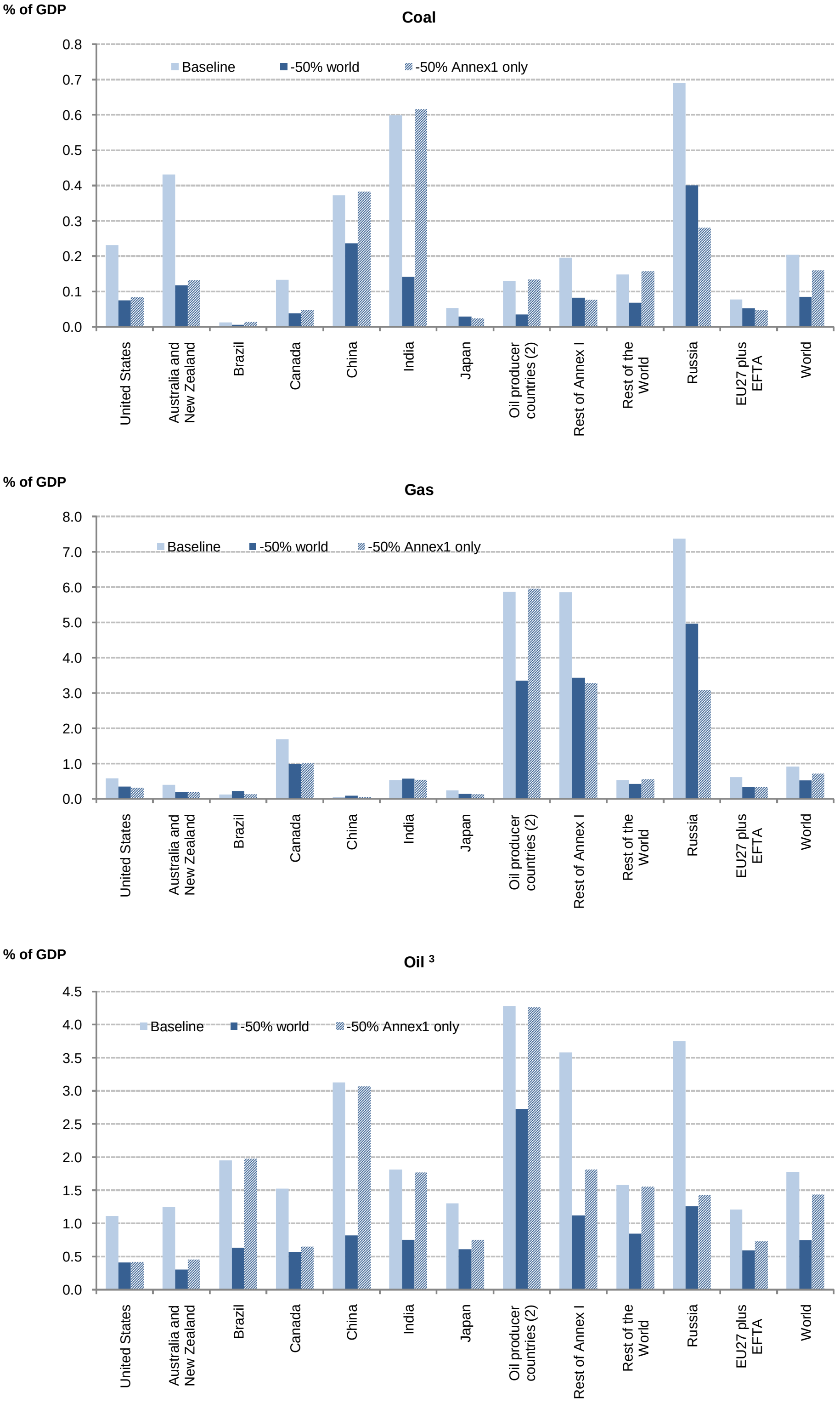
Figure 6.8. Projected fossil fuel intensities in world regions under baseline and 550ppm GHG concentration stabilisation scenarios[1]



1. Energy intensity, defined as Domestic demand as a % of GDP in 2050.
2. The region includes the Middle East, Algeria-Libya-Egypt, Indonesia, and Venezuela.
3. Refined oil only.

Source : OECD ENV linkages model.

Figure 6.9. Projected fossil fuel intensities in world regions under different mitigation policy coverages[1]

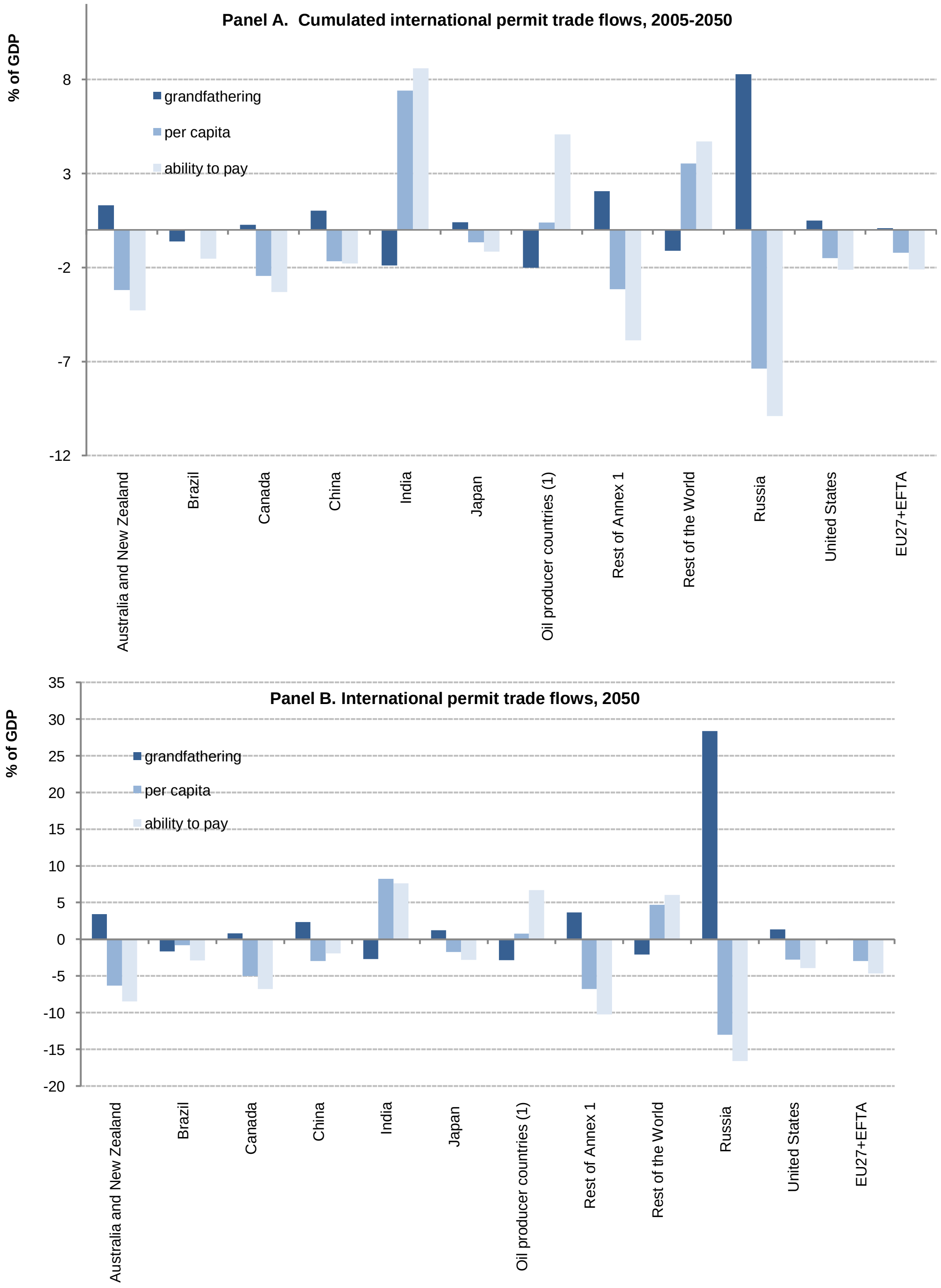


1. Energy intensity, defined as Domestic demand as a % of GDP in 2050.
2. The region includes the Middle East, Algeria-Libya-Egypt, Indonesia, and Venezuela.
3. Refined oil only.

Source : ENV linkages model.

Figure 6.10. International permit trade flows under alternative permit allocation rules

(550ppm GHG concentration stabilisation scenarios)

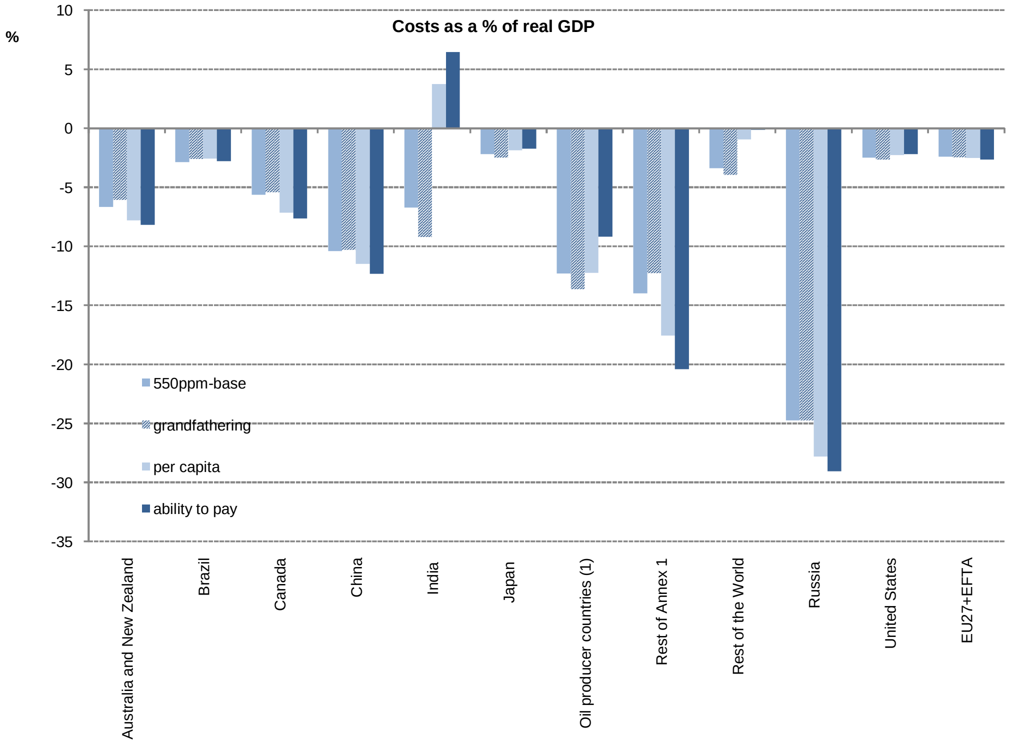


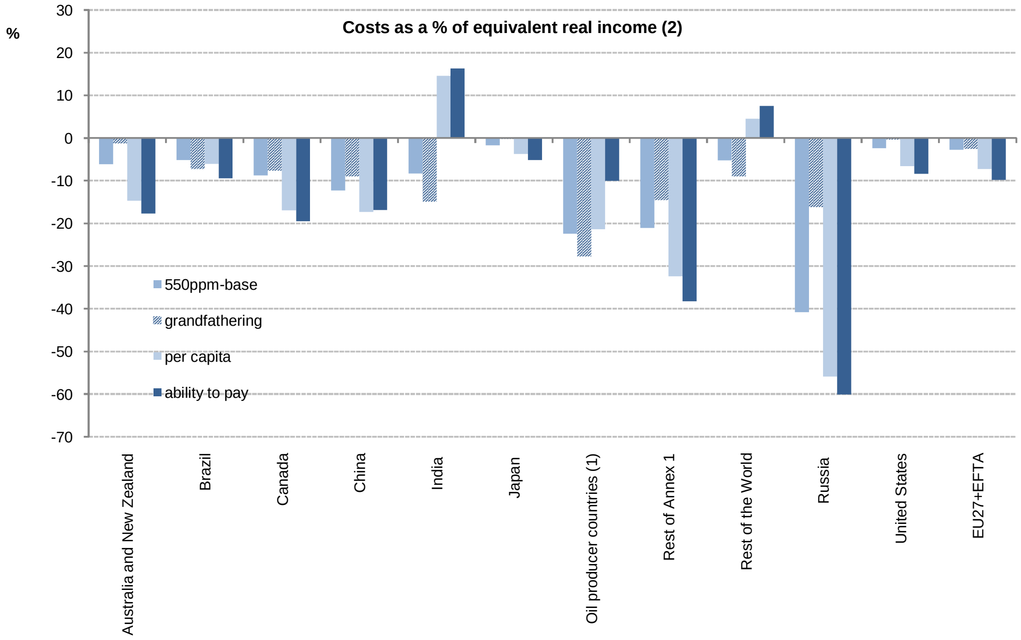
Note: Exports (imports) of permits lead to GDP gains (losses). Under "grandfathering", for the same emissions pathway, permits are allocated according to emissions in 2012. Under a "per capita" allocation rule, for the emissions pathway target, permits are allocated each year according to population. Under an "ability to pay" allocation rule, permits are allocated each year to each individual worldwide in inverse proportion to the gap between this individual's GDP per capita and average world GDP per capita (in PPP terms).

1. The region includes the Middle East, Algeria-Libya-Egypt, Indonesia, and Venezuela

Source : OECD ENV linkages model.

Fig 6.11. The impact of permit allocation rules on the distribution of mitigation costs across countries, 2050





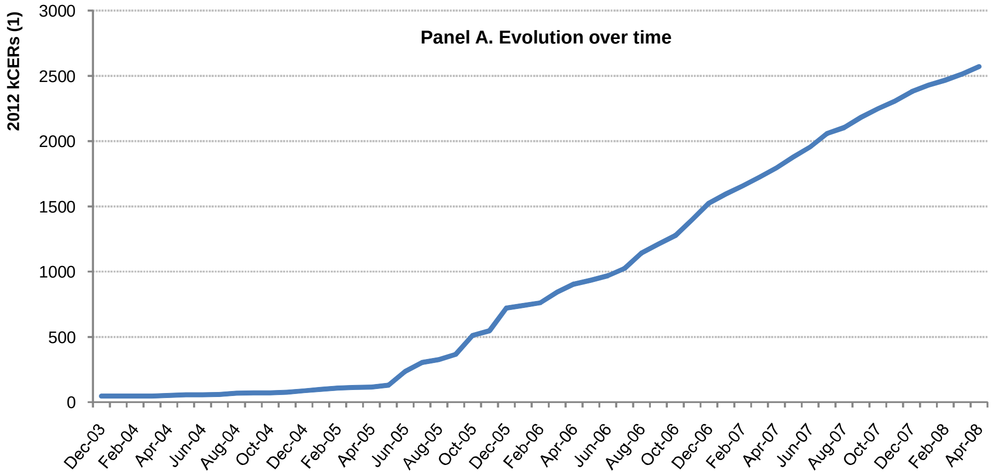
Note: The "550ppm-base" (Scenario A in table 3.1) scenario is the reference case, where a carbon tax is imposed to achieve long-run stabilisation of GHG concentration at 550 ppm CO_2 eq. Under "grandfathering", for the same emissions pathway, permits are allocated according to emissions in 2012. Under a "per capita" allocation rule, for the emissions pathway target, permits are allocated each year according to population. Under an "ability to pay" allocation rule, permits are allocated each year to each individual worldwide in inverse proportion to the gap between this individual's GDP per capita and average world GDP per capita (in PPP terms).

1. The region includes the Middle East, Algeria-Libya-Egypt, Indonesia, and Venezuela

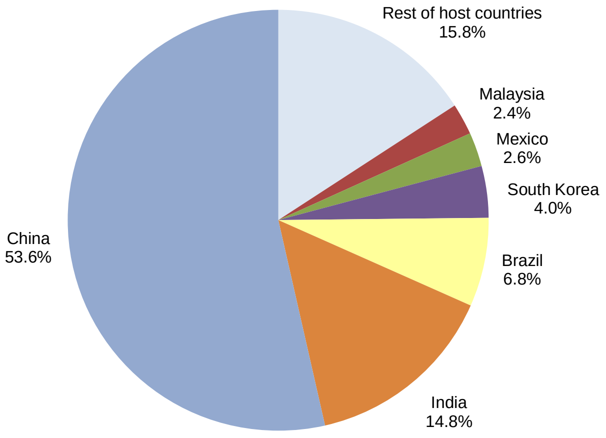
2. Hicksian “equivalent real income variation” defined as the change in real income (in percentage) necessary to ensure the same level of utility to consumers as in the baseline projection.

Source : OECD ENV linkages model.

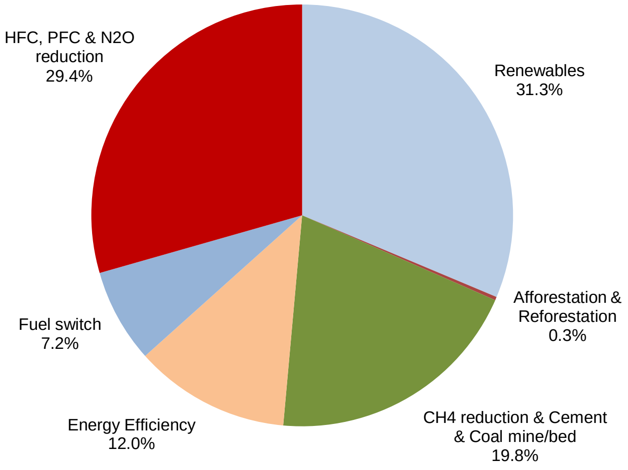
Fig 6.12. CDM development, host countries and allocation across sectors



Panel B. Geographical distribution



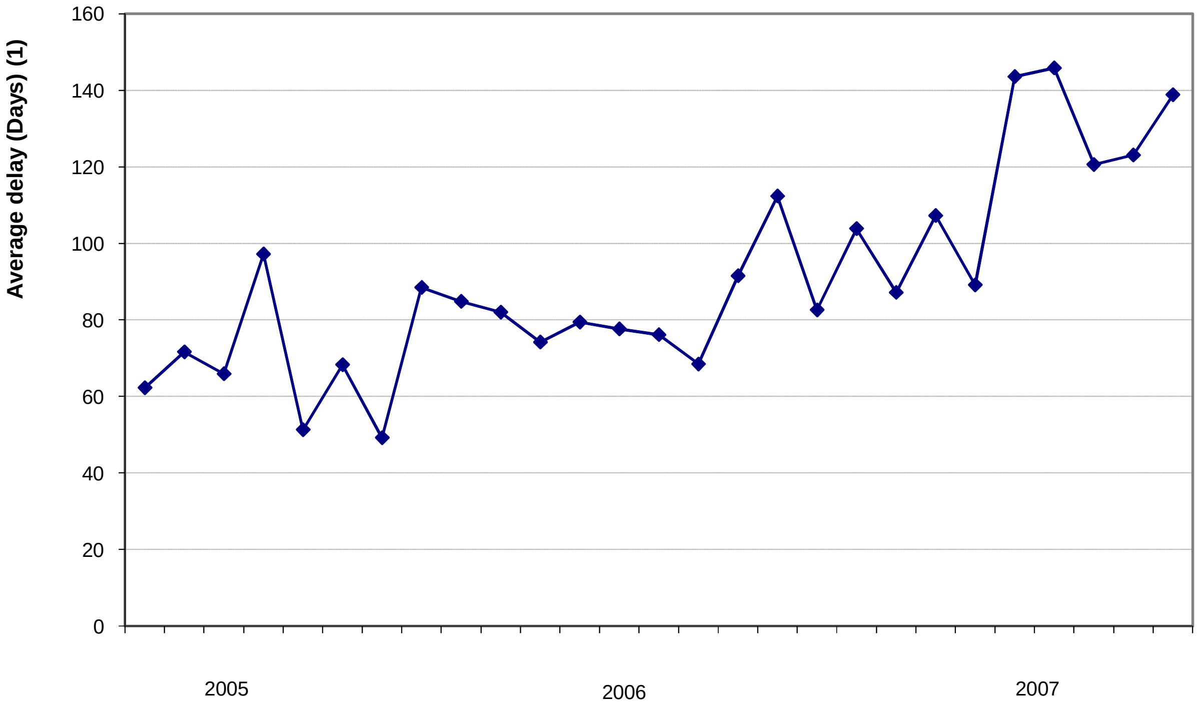
Panel C. Sectoral distribution



1. Expected Certified Emission Reduction (CER) accumulated until end 2012, expressed in 1000 tons of CO_2 eq.

Source: UNEP Risoe Center, Capacity Development for the Clean Development Mechanism.

Figure 6.13. Bottlenecks associated with checking the "addionality" criterion



1. Days elapsed between registration request and registration by the CDM Executive Board.
Source: UNEP Risoe Center, Capacity Development for the Clean Development Mechanism.

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