# ECONOMICS OF A GLOBAL STRATEGY FOR REDUCTION OF CARBON EMISSIONS

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# Foreword

Policies for addressing the mitigation and impacts of climate change face a number of formidable challenges. Due to the complexity of the processes that lead from anthropogenic sources of greenhouse gases to possible damages, large uncertainties surround any conventional cost-benefit analysis. Even if costs and benefits were quantifiable in an unambiguous way, the geographical and distributional differences would remain, resulting in many unresolved issues and problems. Identification of alternative, stepwise, adaptive, and iterative approaches is one way to tackle these challenges, given the enormous size of the tasks, the uncertainties, and the need for global and multidisciplinary analyses.

This paper addresses the question of cost-effective strategies to reduce energy-related emissions of greenhouse gases. To cover a range of possible future developments, two alternative global energy scenarios are proposed; each contains a number of change cases. Together they consider a wide range of global $CO_2$ emissions, from about 2 GtC to more than 14 GtC in 2050, compared with 6 GtC in 1990.

This study finds that energy efficiency improvements and conservation are the most effective measures to reduce $CO_2$ emissions. Furthermore, the author argues that a number of these measures on the energy-supply side are also cost-effective. Nevertheless, some mitigation measures in the scenarios would impose a heavy financial burden on developing countries, making $CO_2$-abatement policy in these regions hardly affordable. To alleviate this situation, the author calculates the consequences of a hypothetical policy that transfers energy tax revenues raised in developed countries to developing countries requiring assistance in transforming their energy systems. The author theorizes that such transfers from developed to developing countries would accelerate progress in less developed countries, and would partially return to donors in the form of new opportunities for industrial goods and services in global markets. The author finds that this concept of global cooperation could make global $CO_2$-abatement policy attractive for both developed and developing countries.

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# Economics of a global strategy for reduction of carbon emissions*

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**Abstract:** The evolution of natural systems that feed and sustain human populations, and indeed the evolution of modern society, has occurred in the context of a moderate and stable climate. Therefore, recent trends in climate change, most likely caused by increasing concentrations of carbon dioxide and other radiative trace gases in the atmosphere, and the expected consequent global warming, are now a major concern. Carbon emissions from energy systems are considered one of the major contributors to climate change and are the focus of all studies on the prevention of climate changes and adaptation strategies. Two global energy scenarios (each with several options) are analysed in this paper: from a dynamic-as-usual concept to a more advanced concept with the goal of stabilizing carbon dioxide concentrations in the atmosphere (equivalent to about a 60% reduction of carbon emission compared with today's level). It is shown that the stabilization approach will require dramatic changes in energy systems: the share of non-carbon fuels will increase to about three quarters of the total primary energy consumption, which will itself grow by a factor of two by the middle of the next century. Surprisingly, the implementation costs turn out to be approximately the same for all scenarios (taking into account possible errors in the cost appraisals for several decades ahead). However, the cost distributions between energy production and use are quite different. Globally, these costs are 3–4% of the GNP, but for developing countries the share of energy investments is, on average, about 7–8% of the GNP, which is cause for concern and will greatly hamper economic and social progress in the Third World. The introduction of energy taxes or carbon taxes in developed countries and the raising of 'global energy funds' could help developing countries to overcome these difficulties. It is supposed that such a policy would stimulate economic growth in developing countries and, as a feedback, overlap the GNP losses in developed countries. The paper attempts to evaluate an optimal strategy for reducing carbon emissions for the next couple of decades, when large uncertainties surround global warming, and to show ways of establishing 'no-regret' policy.

**Keywords:** carbon dioxide emissions, cost/benefit analysis, energy demand, energy strategy, energy supply, global warming.

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## 1 Introduction

There is a consensus that further environmental pollution and climate changes could be prevented if emissions from energy systems are significantly reduced. Scientists and politicians worldwide are studying ways of making the transition from fossil (carbon-based) fuels to systems based on non-carbon fuels and inexhaustible resources. The majority of studies agree that the following features roughly describe future energy systems:

- Energy consumption will increase mainly in developing countries;
- Energy savings and conservation in all areas of energy demand and supply will become increasingly important;
- Strong constraints will be implemented on nuclear energy (especially over the next couple of decades) unless a new generation of nuclear reactors is developed and proves its safety and economic viability;
- Contributions of renewable energy technologies will be limited (at least, over the next several decades) because of poor economics, unreliability, and the impact on the environment because of high consumption of materials for their construction.
- Fossil fuel resources will continue to play a leading role in the world energy balance in the next century, although environmental and climate constraints can restrict the use of these fuels worldwide or in some regions;
- Environmental and climate issues and priorities will become increasingly important when selecting energy technologies.

The climate change issues are the central point of all current debates around energy systems because $CO_2$ emissions, of which around two-thirds are from energy systems, are the major contributor to greenhouse gases from all anthropogenic activities. There are many known ways to prevent $CO_2$ emissions from energy systems. However, preliminary analyses have shown that the costs of all these measures vary from tens of dollars per ton of carbon to hundreds or even thousands of dollars, depending on the area of application. Taking into account the very long lifetime of energy technologies (several decades) and the low maturity of some prospective technologies (or their low efficiencies such as in the case of the renewable energy technologies), the transition to new energy systems will probably be spread out over the next century. Because of the large capital intensiveness of energy systems, this transition period will put a heavy burden on all economic systems. Therefore, when compiling long-term energy strategies, the prime task is to find an optimal development path, effective from the point of view of climate change as well as associated costs. The situation becomes more complicated because the solution of many social and economic problems in developing countries inevitably requires the growth of per capita energy consumption. This means that, with the expected population growth, world energy demand will increase. For example, according to many estimates, world energy demand will grow to at least two or three times today's level by the middle of the next century despite energy conservation measures. At the same time, the share of developing countries in the world energy demand will expand from 28% today to about 50% or more in 2050. This new situation will shift the burden of global energy problems from developed to developing countries, creating new international tensions.

The solution to these problems requires global and multidisciplinary approaches based on a deep understanding of changes taking place in such multidimensional systems as the energy sector, on the economics of available and projected measures to save energy and reduce negative impacts on the environment, and on the level of uncertainty associated with the scope of climate changes and their impacts on natural systems and human activities.

The aims of this paper are to outline the major points of global energy projections for the next several decades, and to try to evaluate the most effective and no-regret global strategy of how to cope with climate change problems, given the large associated uncertainties.

## 2 Global energy and carbon emissions in the 21st century

### 2.1 Analytical framework

Two major scenarios with different energy conservation policies were selected for the detailed analysis of energy demand: (A) *Dynamics-as-usual Scenario*, in which the rate of social, economic, and technological changes worldwide stays the same over the whole time horizon and the competition between fuel and energy forms is based primarily on market mechanisms; and (B) *Enhanced Efficiency and Conservation Scenario*, in which special regulatory measures in addition to the conditions specified in Scenario A are applied to promote and improve energy efficiency in all regions and economic sectors.

Several options within each scenario, reflecting structural changes in primary energy supply, were chosen for detailed analysis. Three options were available for the Scenario A: (A1) *Base Case*, with no special constraints on energy systems development, and modest introduction of nuclear energy and renewables; (A2) *Nuclear Moratorium Case*, with a freeze on nuclear energy at the level projected for the period 2005–2010, *i.e.* assuming that all nuclear power plants currently under construction will be finished but no new constructions will be allowed except the replacement of old and obsolete plants; and (A3) *Supply-side Measures Case*, in which efforts in energy conservation are applied primarily to the supply side.

Three options were also analysed for Scenario (B): (B1) *Demand-side Measures Case*, in which efficiency improvements are applied primarily to energy end-users; (B2) *Nuclear Moratorium Case*, as for A2; and (B3) *Accelerated $CO_2$ Abatement Case*, with enhanced restructuring of energy systems. The last case (enhanced energy conservation and a whole range of $CO_2$ abatement measures) assumes $CO_2$ emission reductions by 2050 of about 60% of the current level, which is what is required to stabilize concentrations[1]. This case supposes anthropogenic releases of $CO_2$ at levels close to the sustainability state and no further increases in $CO_2$ concentration after the middle of the next century.*

Ten world regions were selected for final energy demand estimates. These were aggregated into two groups (developed and less developed countries) to evaluate primary

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* The earlier this state is achieved, the less the projected global temperature increases. This means that postponing policy actions to prevent global warming for some time in the future will result in the concentration of $CO_2$ stabilizing at a higher temperature.

energy production and trade. The time horizon of the study was divided into three periods: first, 1980–1990 for models calibrations and verifications; second, 1990–2010 with two 10-year subperiods to provide more detailed mid-term projections; and third, 2010–2050 with two 20-year subperiods to understand better the long-term trends and policy measure responses. Two simulation-type models were used in the study: the MEDEE-2 model[2] generated the final energy demand projections, which were then supplied to the LEAP model[3] for the analysis of energy transformation sectors and primary energy productions and trade. An energy/$CO_2$ abatement policy was developed with a special model using elements of dynamic programming and combinatoric analysis (for a modified version of this model see ref. 4).

## 2.2 *Long-term energy projections*

Table 1 contains the summary of world primary energy projections. World energy consumption is expected to increase from 8.6 gigatonnes of oil equivalent (Gtoe) currently to about 10 Gtoe in 2000 and 10–12 Gtoe in 2010. With smaller efforts in efficiency improvements, the projected consumption will amount to 18–24 Gtoe by the middle of the next century. But enhanced efforts in energy savings could reduce primary energy demand to only 12–17 Gtoe.** Most remarkable is the fact that the share of developing countries, which is about 30% today (including non-commercial fuels), will reach 55%–65% in the long-term future. This means that over the next several decades the burden of the world energy problems will shift from developed to developing countries. The consequences of this shift should be evaluated well in advance to avoid complications and tensions regarding energy resources and severe environmental degradation in the future. The projected structure for the primary energy mix is summarized in Table 2.

Until recently, fossil fuel resources and their availability were considered the main factor in long-term energy strategies at national and international levels. Today, however, the decisive role for shaping energy development is that of energy conservation as well as environmental implications, and resource availability is no longer so significant. Energy-production costs, safety and emissions are of much greater importance now than the absolute amount of energy resources because in the long term only relatively cheap deposits of fossil fuels or potential renewable energies will be of practical interest (*i.e.* only this part of resources will be capable of competing with ever-expanding achievements in energy savings).*

** The Nuclear Moratorium Case shows lower energy demand because of the constant conversion factor used for nuclear equal to 0.33 over the time horizon of the study (the cause is one of the limitations of the LEAP model) compared with changing (and improving) efficiency of coal-fired power plants which are assumed to replace nuclear energy. The same reason is behind the higher primary energy demand projections for other cases, in which a larger percentage for nuclear and renewables (enhanced by a higher share of electricity in final energy to reach $CO_2$ reduction goals) results finally in higher primary energy demand for these cases compared with others in the study.

* Moreover, in reality there exists a clear reverse interdependence between the deposit volume and the resource extraction cost with all other factors being equal.

**Table 1** Primary energy projections (Mtoe).

| Scenario/region | 1980 | 1990 | 2000 | 2010 | 2050 |
|---|---|---|---|---|---|
| *Dynamics-as-Usual Scenario* | | | | | |
| Base Case (A1) | 7004 | 8580 | 10 025 | 12 015 | 18 795 |
| • Developed countries | 5379 | 6196 | 6910 | 7385 | 8715 |
| • Developing countries | 1625 | 2384 | 3145 | 4630 | 10 080 |
| Nuclear Moratorium Case (A2) | 7004 | 8580 | 10 025 | 12 060 | 18 995 |
| • Developed countries | 5379 | 6196 | 6910 | 7340 | 8570 |
| • Developing countries | 1625 | 2384 | 3145 | 4720 | 10 425 |
| Supply-side Measures Case (A3) | 7004 | 8580 | 10 025 | 12 675 | 24 025 |
| • Developed countries | 5379 | 6196 | 6880 | 7885 | 11 915 |
| • Developing countries | 1625 | 2384 | 3145 | 4790 | 12 110 |
| *Enhanced Efficiency and Conservation Scenario* | | | | | |
| Demand-side Measures Case (B1) | 7004 | 8580 | 9825 | 10 490 | 12 325 |
| • Developed countries | 5379 | 6196 | 6680 | 6475 | 5245 |
| • Developing countries | 1625 | 2384 | 3145 | 4015 | 7080 |
| Nuclear Moratorium Case (B2) | 7004 | 8580 | 9825 | 10 385 | 12 105 |
| • Developed countries | 5379 | 6196 | 6680 | 6385 | 5095 |
| • Developing countries | 1625 | 2384 | 3145 | 4000 | 7010 |
| Accelerated $CO_2$ Abatement Case (B3) | 7004 | 8580 | 9825 | 10 760 | 17 235 |
| • Developed countries | 5379 | 6196 | 6680 | 6660 | 7145 |
| • Developing countries | 1625 | 2384 | 3145 | 4100 | 10 040 |

Total *crude oil* production is projected to increase slightly, reaching 3600 Mtoe by 2000 (3500 Mtoe in 1990). But after 2000, two marginal projections are considered here: one for the case with moderate efforts (Base Case A1), in which a stabilization or further slow growth in crude oil production is expected, and the other with enhanced changes (Case B3) in which after 2000 crude oil production is projected to decline to that about half today's level by the middle of the next century. In all cases, crude oil production in developed countries will decrease from 1362 Mtoe today to 250 Mtoe in 2050. Therefore, developed countries will remain net importers over the whole period, and it is expected that crude oil imports will even increase over several decades because domestic crude oil production will decline faster than demand. Only beyond the year 2025 will imports of crude oil begin to decrease as liquid fuels are replaced by cheaper substitutes. It is expected that the Middle East will keep its position as a leader in the world crude oil export over the time horizon of the study.

**Table 2** Primary energy consumption by fuel type (Mtoe).

| Scenario/region | 1990 | 2000 | 2010 | 2050 |
|---|---|---|---|---|
| *Dynamics-as-Usual Scenario* | | | | |
| Base Case (A1) | 8580 | 10 025 | 12 015 | 18 795 |
| • Coal | 1970 | 2370 | 2815 | 5455 |
| • Oil | 3540 | 3630 | 3765 | 4030 |
| • Gas | 1660 | 2235 | 3015 | 3995 |
| • Nuclear | 483 | 655 | 970 | 2045 |
| • Renewables | 552 | 705 | 1040 | 2940 |
| • Non-commercial | 375 | 430 | 410 | 330 |
| Nuclear Moratorium Case (A2) | 8580 | 10 025 | 12 060 | 18 995 |
| • Coal | 1970 | 2370 | 3160 | 7020 |
| • Oil | 3540 | 3630 | 3765 | 4030 |
| • Gas | 1660 | 2235 | 3015 | 3975 |
| • Nuclear | 483 | 655 | 670 | 705 |
| • Renewables | 552 | 705 | 1040 | 2940 |
| • Non-commercial | 375 | 430 | 410 | 325 |
| Supply-side Measures Case (A3) | 8580 | 10 025 | 12 675 | 24 025 |
| • Coal | 1970 | 2370 | 2355 | 1340 |
| • Oil | 3540 | 3630 | 3715 | 3795 |
| • Gas | 1660 | 2235 | 2910 | 2690 |
| • Nuclear | 483 | 655 | 1995 | 7665 |
| • Renewables | 552 | 705 | 1365 | 8380 |
| • Non-commercial | 375 | 430 | 375 | 155 |
| *Enhanced Efficiency and Conservation Scenario* | | | | |
| Demand-side Measures Case (B1) | 8580 | 9825 | 10 490 | 12 325 |
| • Coal | 1970 | 2300 | 2205 | 2970 |
| • Oil | 3540 | 3545 | 3325 | 2400 |
| • Gas | 1660 | 2200 | 2660 | 2615 |
| • Nuclear | 483 | 655 | 950 | 1660 |
| • Renewables | 552 | 695 | 970 | 2435 |
| • Non-commercial | 375 | 430 | 385 | 245 |
| Nuclear Moratorium Case (B2) | 8580 | 9825 | 10 385 | 12 105 |
| • Coal | 1970 | 2300 | 2465 | 3730 |
| • Oil | 3540 | 3545 | 3325 | 2405 |
| • Gas | 1660 | 2200 | 2595 | 2615 |
| • Nuclear | 483 | 655 | 650 | 675 |
| • Renewables | 552 | 695 | 965 | 2435 |
| • Non-commercial | 375 | 430 | 385 | 245 |
| Accelerated $CO_2$ Abatement Case (B3) | 8580 | 9825 | 10 760 | 17 235 |
| • Coal | 1970 | 2300 | 2150 | 125 |
| • Oil | 3540 | 3545 | 3185 | 1955 |
| • Gas | 1660 | 2200 | 2665 | 2025 |
| • Nuclear | 483 | 655 | 1170 | 6280 |
| • Renewables | 552 | 695 | 1250 | 6850 |
| • Non-commercial | 375 | 430 | 340 | 0 |

A further strong growth in *natural gas* production and international trade based on the available resources of conventional and non-conventional methane is anticipated. Production will increase from about 2000 billion $m^3$ in 1990 to 2700 billion $m^3$ in the year 2000 and to 3000–3600 billion $m^3$ in 2010. If no stringent measures in energy conservation are implemented, then a further strong growth will be inevitable, practically more than doubling current levels by 2050. However, efficiency improvements in parallel with enhanced energy system restructuring might result in decreasing production growth rates and even a decline in production (however, this decline will be much lower than the decline for other fossil fuels because of much higher environmental benefits from using natural gas instead of solid or liquid fuels). Natural gas interregional trade is projected to increase 2.5–4.5 times, reaching 370–680 billion $m^3$ per year compared with about 145 billion $m^3$ today. It is expected that this expansion will be achieved by the further development of dry gas supply systems using pipeline technologies and by liquefied natural gas transportation in liquefied natural gas (LNG) tankers.

World *coal* production is projected to grow at least during the first third of the next century under Scenario A, reaching almost 3500 Mtoe compared with 2800 Mtoe today. Thereafter, a decrease in coal production is expected, which will be even more enhanced in the second part of the century when new energy technologies with less environmental impact will appear on the market. In the other extreme case, Case B3, coal production reductions commence much earlier (immediately after 2000) to reach the goal of drastic coal consumption reductions by the middle of the next century. One way of achieving a 60% $CO_2$ emissions reduction is to greatly decrease, or even eliminate, the wide use of coal. However, the application of efficient carbon absorption and disposal technologies could eliminate this problem and keep the share of coal in future energy supply at a much higher level than projected. To steer coal consumption in such a drastic direction seems extremely difficult to implement. Therefore, Case B3 should be considered as an illustration rather than a realistic forecast of efforts required for reaching the $CO_2$ abatement goal, at least until 2050.

Table 3 shows the projected depletion of fossil fuel resources up to 2050.

**Table 3** Extraction of fossil fuel resources between 1990 and 2050[a]

| Scenario | Coal (Gtce) | Oil (Gt) | Natural gas (trillion $m^3$) |
|---|---|---|---|
| *Dynamics-as-Usual Scenario* | | | |
| Base Case | 270 | 200 | 215 |
| Nuclear Moratorium | 300 | 210 | 225 |
| Supply-side Measures Case | 150 | 155 | 170 |
| *Enhanced Efficiency and Conservation Scenario* | | | |
| Base Case | 215 | 180 | 205 |
| Nuclear Moratorium plus Demand-side Measures Case | 230 | 190 | 215 |
| Accelerated $CO_2$ Abatement | 150 | 150 | 160 |

[a] Fossil fuel recoverable resources are as follows: coal (<\$75/t), 3000 Gtce; oil (<\$30/bbl), 380 Gt; natural gas (<\$30/bbl) 295 trillion $m^3$.

*Source:* ref.12.

Table 3 shows that, by the middle of next century, about half of the currently estimated crude oil resources will be extracted. However, the extraction rate for conventional natural gas is expected to be even higher, meaning that industrial methods for unconventional natural gas production should be developed and introduced on a broad scale in the near future. The cumulative extraction of coal resources will be comparable with those of other fossil fuels, but because of coal's much higher availability its depletion within the time horizon of the study is not considered.

World *electricity* generation will increase at an average rate of 2–2.5% annually over the time horizon of the study, reaching 40 000–45 000 TWh in 2050 (11 150 TWh in 1990). The structure of the generating technologies strongly depends on the scenario applied. In Base Case A1, renewable energy technologies could contribute not more than one-third of the electricity required by the middle of the next century. On the other hand, $CO_2$ emission constraints in Case B3 will not allow for more than 10% of fossil fuel use, of which most will be based on natural gas. Therefore, the difference (about 55%) should be met with non-carbon technologies (*e.g.* nuclear or renewable sources). Of course, the changes are much less for Scenario A, in which the share of non-carbon technologies will increase only to one-third by 2050 (with only 15% coming from renewable sources).

The future of *nuclear energy* is one of the most controversial points in all energy projections. Therefore, several options related to nuclear energy have been analysed in the study (Table 4).

**Table 4** Nuclear installation requirements (GWe).

| Case | 1980 | 1990 | 2000 | 2010 | 2050[a] |
|---|---|---|---|---|---|
| *World* | | | | | |
| A1 | 135 | 327 | 385 | 440 | 1210 |
| B3 | – | – | – | 460 | 3235 |
| *Developed countries* | | | | | |
| A1 | 133 | 310 | 355 | 400 | 905 |
| B3 | – | – | – | 415 | 1440 |
| *Developing countries* | | | | | |
| A1 | 2 | 17 | 30 | 40 | 305 |
| B3 | – | – | – | 45 | 1795 |

[a] Average annual increment, 2010–2050 (including replacements): case A1, 30 GWe; case B3 80 Gwe. This compares with approximately 20 GWe/yr in the 1980s (31 GWe/yr only in 1985).

Nuclear energy will not only play one of the key roles in the marginal Case B3 but also be a hurdle to be overcome in the Base Case (A1). Table 4 shows the calculated requirements of nuclear generation capacity installations in the two cases. The Dynamics-as-Usual Scenario (Base Case, A1) assumes steady but declining growth rates for nuclear energy in the time horizon of the study. The Nuclear Moratorium Cases (A2 and B2) are based on practically freezing nuclear energy after the completion of all nuclear power plants under construction and no further projects (after 2005). In the Supply-side Measures Case (A3), the necessity for nuclear energy is determined by reaching the $CO_2$ emissions target. Prospects for this energy source over the next 15–20 years are extremely uncertain: on the one hand, risk and safety issues make nuclear energy unpopular in many countries that have this technology, on the other hand, the idea that environmental damage could be mitigated by replacing fossil fuels, especially coal, with nuclear energy is becoming more and more popular. In all scenarios without limits for nuclear energy, the share of this energy will increase from 5.4% in 1990 to 6.3% in 2000 and 6.3–8% in 2010. However, the development of nuclear energy after 2010 will depend on improvements being made in the technology and the recognition that nuclear energy is an alternative to reduce the risk of global warming: by 2050 the share of nuclear energy in total energy demand may rise slowly to 11% (Base Case, A1) or even to more than one-third if constraints on $CO_2$ emissions are imposed to achieve a 60% $CO_2$ emissions reduction (B3) by 2050.

The total installed capacity of nuclear power plants will have to increase from 318 GWe today to almost 400 GWe in 2000 and 1200–3200 GWe in 2050. In Case A1, the required average annual increment of nuclear generation capacity is approximately 30 GWe worldwide, while it is roughly 80 GWe in Case B3. In Case B3, the generation capacity has to be larger in the developing regions than in the developed regions. The average nuclear generating growth in the 1980s was approximately 20 GWe per year globally, with a peak in 1985 when 31 GWe of nuclear power plants started operation. This was the last year to exceed 30 GWe. To achieve the Base Case, the maximum construction capability of current nuclear industries must be maintained for many years. However, for the Accelerated Abatement Case, the installation requirements of about 80 GWe per year may be difficult to fulfil without a comprehensive revitalization of the world's nuclear industry, possibly with some sorts of advanced nuclear reactors which would allow, for example continuous production in factories.

The extended use of projected nuclear installations for the two cases (A1 and B3), as shown in Table 4, will result in a large contribution to the total energy supply in developing countries. The share of this region in today's nuclear-installed capacity is less than 6%; it will reach 7% in 2000, 25% in Case A1 in 2050, and 60% in Case B3 in 2050.*

Technical solutions using known *renewable energy* resources could physically (or theoretically) supply practically all energy consumers with the required quantities and qualities of energy. Table 5 contains a summary of the global potential of renewable energy resources. According to these very speculative and conservative estimates, the global realizable potential is equal to a minimum of 11–15 Gtoe per year, about twice as much as current world primary energy consumption.** However, with respect to energy economics, only certain areas may be considered most promising for the next several decades, especially in the production of low-temperature heat or electricity. From this point of view, the best prospects are biomass, hydro, geothermal, and wind technologies. They all have remarkable potential; and have been successfully developed in some regions with favourable economic conditions. Energy costs for these technologies will remain higher than for conventional ones over the long term.

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* In addition to a revitalization of the nuclear plant construction industries, there will be several prerequisites for nuclear power in creating environmentally sound energy systems: completion of the nuclear fuel cycle, in which reprocessing and waste disposal should be of crucial importance; issues related to plutonium utilization, especially non-proliferation and safeguards; advanced concepts and measures to improve safety and reliability of existing and planned reactors.

** These estimates are very close to those made by IIASA[5] in 1981, where the technical potential was assumed to be about 11 Gtoe and the realizable potential was only 7 Gtoe.

**Table 5** World renewable energy potential (sources: refs. 13–18).

| Renewable energy | Energy potential: In natural form | Energy potential: Gtoe | Current use (approx.) |
|---|---|---|---|
| *Hydro (economic potential)* | | | |
| Developed countries | $6 \times 10^{12}$ kWh | 1.3 | $1.3 \times 10^{12}$ kWh |
| Developing countries | $6.5 \times 10^{12}$ kWh | 1.3 | $0.6 \times 10^{12}$ kWh |
| *Geothermal (without dry rock)* | | | |
| Electricity | | | |
| Developed countries | $2 \times 10^{12}$ kWh | 0.3–0.4 | $14 \times 10^{9}$ kWh |
| Developing countries | $5 \times 10^{12}$ kWh | 1.3–1.7 | $1 \times 10^{9}$ kWh |
| Heat supply | | | |
| Developed countries | 700 GW(t) | 0.3–0.4 | 3 Mtoe |
| Developing countries | 700 GW(t) | 0.3–0.5 | 0.3 Mtoe |
| *Solar* | | | |
| Electricity | | | |
| Developed countries[a] | $300 \times 10^{9}$ kWh | 0.1–0.15 | $2.2 \times 10^{6}$ kWh |
| Developing countries | $1.1 \times 10^{12}$ kWh[a] | 0.15–0.25[a] | |
| | $4.8 \times 10^{12}$ kWh[b] | 0.7–1.0[b] | |
| Heat supply | | | |
| Developed countries[c] | | 0.15–0.2 | 10–17 Mtoe |
| Developing countries[d] | | 0.8–1.2 | 1.5–3.5 Mtoe |
| *Biomass* | | | |
| Managed forests | | | |
| Developed countries | | 0.8–1.0 | |
| Developing countries | | 1.7–2.0 | |
| Agricultural wastes (biogas production) | | | |
| Developed countries | | 0.15 | |
| Developing countries | | 0.2–0.3 | |
| Reforestation (at 10% of desert territories) | | 0.15 | |
| *Wind* | | | |
| Developed countries[e] | $8 \times 10^{12}$ kWh | 0.4–0.5 | |
| Developing countries[f] | $12 \times 10^{12}$ kWh | 1.3–1.7 | |
| *Ocean (wave or tidal energy, OTEC, etc.)*[g] | | | |
| Developed countries | $600 \times 10^{9}$ kWh | 0.07–0.15 | |
| Developing countries | $13 \times 10^{12}$ kWh | 0.4–0.5 | |
| *Total (rounded)* | | 11–15 | |
| Developed countries | | 3.5–4.0 | |
| Developing countries | | 7–11 | |

*Notes for Table 5*

[a] Photo-voltaic (PV) decentralized systems.

[b] PV centralized systems in desert areas (1% of desert territories).

[c] Assuming that only 35% of the population lives in areas suitable for solar applications and with approximately 5 $m^2$ of solar collectors per person at annual fossil fuels savings equal to 50 kg of oil equivalent per square metre per year.

[d] Assuming that 50% of the population lives in areas suitable for solar applications with approximately 2 $m^2$ of solar collectors per person at annual fossil fuels savings equal to 75 kg of oil equivalent per square metre per year.

[e] 25% of theoretical potential.

[f] 50% of theoretical potential.

[g] 15% of theoretical potential.

The general strategy for the use of renewable energy for the next several decades consists primarily in phasing out decentralized and less efficient conventional systems, especially those in remote and rural areas and using wood and liquid fuel as major fuels. This will save liquid fuel and improve the economic situation for nations with large and ever-growing foreign debts. It will also reduce the use of wood as a fuel, resulting in declining deforestation, and provide access for the population in developing countries to effective energy forms (chiefly electricity), which is a major prerequisite for social progress. Supplying electricity to certain areas will require large investments, but this seems to be the most effective way to solve many social, technical, and ecological problems. This is of even greater importance for the less developed areas, where energy remains a driving force for social, economic, and cultural transformations and changes. The progress of humanity in the near future will almost entirely depend on addressing the problems of developing countries. The use of renewable energy sources can effectively contribute to solving this problem. Renewable energy sources will hardly be dominant in the world energy balance over the first half of the next century; however, from a social point of view, they are one of the most important development areas.

## *2.3 $CO_2$ emissions*

The expected levels of $CO_2$ emissions produced by energy systems all over the world over the next several decades are presented in Figure 1. By definition, the Accelerated Abatement Case (B3) goes along with the IPCC Accelerated Policy Scenario, toward 2.7 Gt of carbon per year in the year 2050. To see how this will be achieved, we compare the Supply-side Measures Case (A3), which stabilizes global emission at 6.6 Gt of carbon per year in 2050, and the Demand-side Measures Case (B1), which shows 7.0 Gt of carbon per year. In the year 2010, however, the Case B1 reaches 7.0 Gt of carbon per year, which is lower than the 7.9 Gt reached in Case A3. Generally, it is difficult or even impossible to separate explicitly the effectiveness of supply-side and demand-side measures in analyses using macro models like the ones used here. The demand-side measures can play a practical and effective role in controlling the global carbon emission in the short term (*e.g.* until 2010). Meanwhile, supply-side measures, such as widespread development and use of nuclear energy and accelerated introduction of renewable energy sources, will need a couple of decades to demonstrate their powerful abatement abilities. The practical approach to carbon emission control, therefore, will be to steadily advance R&D of non-carbon technologies, while carrying out enhanced conservation and efficiency improvements.

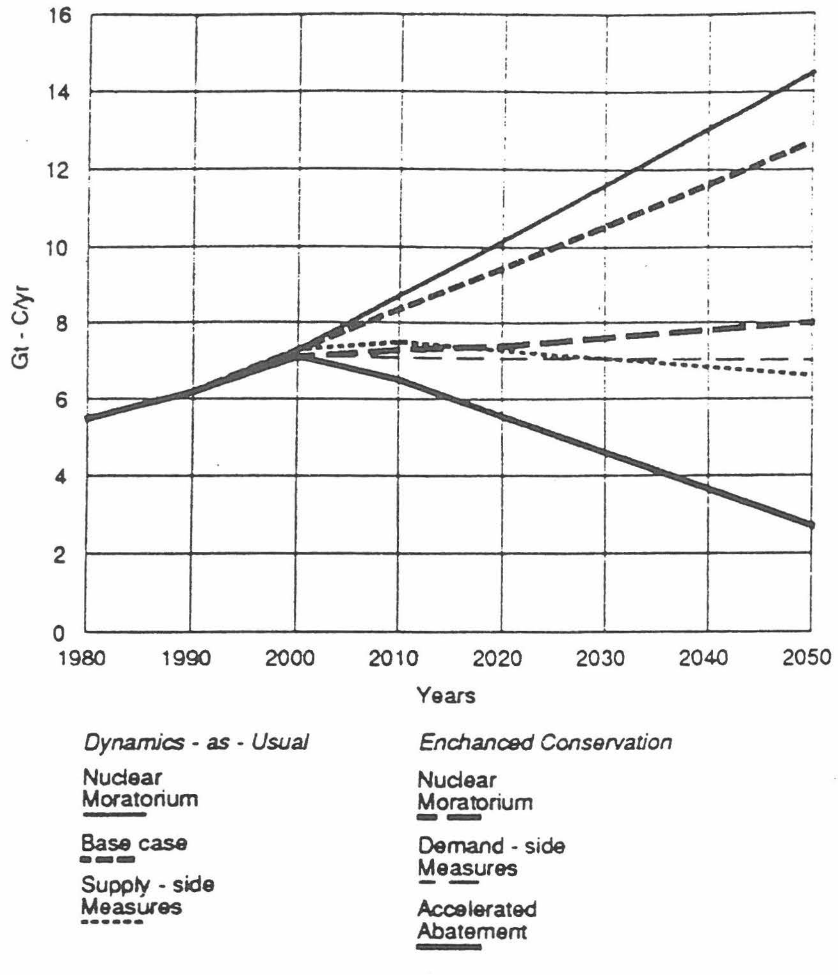


**Figure 1** $CO_2$ emissions by global energy systems.

The influence of a nuclear moratorium varies depending on the final demand structure. In Case A2, the carbon emission in 2050 is evaluated at 14.5 Gt per year, which is 15% higher than the Base Case A1; the Case B2 (8.0 Gt per year) shows an 11% increase from the Case B1 (7.0 Gt per year.) The enhanced conservation and efficiency improvements in Scenario B are expected to mitigate the impacts in the case where the nuclear moratorium policy is put into practice, compared with those based on the Scenario A. The degree of softening of the impact, however, is too small to offset the increase in the emissions. However, the efforts of the end-users are not enough, and we anticipate that the implementation of the nuclear moratorium policy on a global scale will result in a 10% or more increase in emission.

$CO_2$ concentration assessments were made by calculating the $CO_2$ accumulation in the atmosphere, taking into account the world energy balance described by the scenario applied. It was assumed that only 60% of carbon released from emissions remains in the atmosphere as airborne concentration.* The results of these rough calculations are summarized in Table 6. The results show that, in spite of large efforts in energy conservation and changes in the primary energy mix to transfer to $CO_2$ energy-sustainable systems by the middle of the next century (60% $CO_2$ reduction compared with currently observed levels), a further increase in $CO_2$ atmospheric concentration will take place over the time horizon of the study. Quite naturally, a nuclear moratorium will lead to maximum concentration increases; however, they will be insignificantly higher in this case than in the base cases because, at the time of its introduction (somewhere around 2005–2010), nuclear energy's contribution to the total world energy balance will still be at the level of several percent. Meanwhile, concentrations are projected to increase by 1.3–1.5 times until 2050 in Scenario A and by 1.25–1.35 times in the Scenario B. This means that concentrations will be at least 100 ppm higher than today's level, even when applying very severe measures in energy conservation and the primary mix change. If we assume that $CO_2$ contributions to global warming remain at only 50% over the time horizon of the study as is observed today, then a doubling of the $CO_2$ concentrations will be observed around 2050.

If, parallel to enhanced energy systems restructuring, reforestation were introduced on a broad scale, then global warming would be substantially reduced. A simplified calculation shows that, if reforestation in suitable areas were to occur until the middle of the next century, then the quantity of carbon accumulated in the atmosphere could be reduced by 25–40%.** Although the effect of reforestation is very uncertain, and the appraisals are based on a simplified approach, it is hoped that reforestation may partly compensate for the negative effects of $CO_2$ accumulation in the atmosphere.

Because of the large uncertainties surrounding global warming, the priority for an energy $CO_2$ strategy should be given to flexibility rather than to a directly anticipated outcome. The most radical measures applied to the energy systems will not stop the process of carbon accumulation in the atmosphere (at least, the period of doubling $CO_2$ concentrations will be extended beyond 2050 for a couple of decades). Parallel efforts in other spheres of human activity are required (urgently stopping deforestation and starting enhanced restoration of forests, especially in tropical zones, and reducing other greenhouse gases emissions which contribute not less than 50% to global warming; these

* According to $CO_2$ concentration records from 1860 to the early 1970s, and estimates of the cumulative fossil fuel consumption over this time period, it follows that approximately 40% of the carbon released has remained in the atmosphere. However, more precise instrument observations provided in the period 1959-1973 have shown that the airborne part was equal to 56% (see ref.6). Today, the majority of climate models estimate this share at 60%. The last estimate is used in our approach for the evaluation of $CO_2$ concentration changes in the long-term future. However, there are expectations that the value of $CO_2$ sinks by nature will strongly depend on the temperature increases and biomass expansion followed by natural processes as well as afforestation.

** Total estimated area available for reforestation is about 865 million ha (ref. 7). If we assume that the carbon fixation rate in growing trees is equal to 5 t-C/ha/year (managed and tropical forests) and the growing time is 20 years (see, e.g., ref.8), then growing biomass can absorb about 80 Gt of carbon over the next 50-75 years, which corresponds to about 40% of carbon accumulated in the atmosphere as in the Accelerated $CO_2$ Abatement Case or much lower values for the other cases. Of course, we must take into account the large difficulties in the reforestation process, including those areas in inferior condition. Even under favorable conditions, there is a kind of competition between reforestation and food production when considering that all favorable land may belong to developing countries where a large population expansion is expected. Therefore, this calculation is an illustration of a measure that requires further detailed research.

amounts are much lower than $CO_2$ emissions and seem to be much easier to handle). Research on the impact of global warming on humans and the environment should start now to help in selecting the optimal (or at least most reasonable) path for global energy development.

**Table 6** Atmospheric accumulation of $CO_2$ in 2050.

| | GtC | ppm |
|---|---|---|
| *Dynamics-as-Usual Scenario* | | |
| Base Case (A1) | 345 | 530 |
| Nuclear Moratorium Case (A2) | 355 | 535 |
| Supply-side Measures Case (A3) | 225 | 470 |
| *Enhanced Efficiency and Conservation Scenario* | | |
| Demand-side Measures Case (B1) | 240 | 480 |
| Nuclear Moratorium Case (B2) | 275 | 495 |
| Accelerated $CO_2$ Abatement Case (B3)[a] | 200 | 460 |

[a] 60% annual $CO_2$ reduction by 2050.

## 3 Cost of $CO_2$ reduction strategies

It is quite natural to assume that the transition from a 'normal' development to one characterized by accelerated $CO_2$ abatement will require different efforts. For simplicity, we can assume that these efforts could be measured by the fraction of GNP spent on energy systems, including cumulative investment in energy production, conversion, transportation and distribution, and end-use over the time horizon of the study. Table 7 lists the summarized results of the cost calculations. Comparing the total expenditures by scenarios/options and regions, the efforts can be summarized in the following way. Total investments required by energy systems strongly depend on efforts in energy conservation and efficiency improvements. As a rule, the Enhanced Efficiency and Conservation policies are about one-third less capital intensive than the Dynamics-as-Usual policies, in spite of the common belief that a $CO_2$ abatement policy will inevitably result in increased costs for society.* However, within the scenarios the cases differ by 10–15% in favour of policies requiring less effort in the restructuring of energy systems. As a result, the investments in the Base Case (A1) and Accelerated $CO_2$ Abatement (B3) differ by only about 15% in favour of the latter.

* The investments are expressed in US dollars in 1980 and summed without discounting. In this assessment, all direct expenditures in the energy sector are taken into account without, however, any of the indirect measures required for changing the attitudes toward more energy-efficient and conserving lifestyles and societies, such as education, advertisement, and incentive-inducing policies. If these measures are incorporated in the calculation in an appropriate way, then strategies for stronger abatement will have increasing expenditures, as shown here.

**Table 7** Investments required for the energy scenarios and cases, 1980–2050, in billions of US dollars in 1980.

| | Developed countries | Developing countries | Total |
|---|---|---|---|
| *Dynamics-as-Usual Scenario* | | | |
| Base Case (A1) | 38 600 | 53 400 | 92 000 |
| Production | 10 150 | 25 820 | 35 970 |
| Conversion | 23 915 | 21 915 | 45 830 |
| Final use | 4535 | 5665 | 10 200 |
| % of GNP | 2.2 | 8.0 | 3.9 |
| Nuclear Moratorium (A2) | 37 950 | 53 370 | 91 320 |
| Production | 10 200 | 25 820 | 36 020 |
| Conversion | 23 300 | 21 900 | 45 200 |
| Final use | 4450 | 5650 | 10 100 |
| % of GNP | 2.2 | 8.0 | 3.9 |
| Supply-side Measures (A3) | 46 830 | 56 620 | 103 450 |
| Production | 8560 | 16 620 | 25 180 |
| Conversion | 32 750 | 32 000 | 64 750 |
| Final use | 5520 | 8000 | 13 520 |
| % of GNP | 2.6 | 8.5 | 4.4 |
| *Enhanced Efficiency and Conservation Scenario* | | | |
| Demand-side Measures (B1) | 30 360 | 37 790 | 68 150 |
| Production | 8300 | 16 000 | 24 300 |
| Conversion | 19 100 | 17 450 | 36 550 |
| Final use | 2960 | 4340 | 7300 |
| % of GNP | 1.7 | 5.6 | 2.9 |
| Nuclear Moratorium (B2) | 30 200 | 38 580 | 68 780 |
| Production | 8420 | 16 390 | 24 810 |
| Conversion | 18 800 | 17 850 | 36 650 |
| Final use | 2980 | 4340 | 7320 |
| % of GNP | 1.7 | 5.8 | 2.9 |
| Accelerated $CO_2$ Abatement (B3) | 33 900 | 45 260 | 79 160 |
| Production | 7520 | 12 515 | 20 035 |
| Conversion | 22 480 | 27 145 | 49 625 |
| Final use | 3900 | 5600 | 9500 |
| % of GNP | 2.0 | 6.8 | 3.3 |

In general, total global investments spent on the reconstruction of energy systems over the next several decades will keep, on average, within 3–4% of global GNP produced over the time period. However, in dynamics the share is expected to decline for all regions as a result of steady progress in efficiency improvements. The structure of capital expenditures is strongly dependent on the scenario/option adopted. First, the $CO_2$ accelerated abatement policy in both scenarios requires much more investment in energy conversion (primarily in the electricity sector) for two reasons: a higher rate of electrification and a larger share of non-carbon (but more expensive and less energy effective) technologies. Second, the fraction of total investments spent on fossil fuel production must be markedly reduced, especially if we want to follow a policy of enhanced energy conservation and $CO_2$ accelerated abatement. There is a large difference in the percentage of investments spent on energy systems between regions: 2.5–2.8% of cumulative GNP for developed countries with already existing infrastructures and 6–8% for developing countries. The latter seems alarming because it means that about 30–40% of total capital available in developing countries over the next decades must be invested in energy systems reconstruction, which will be very difficult to maintain over a long time period. Therefore, the main task of industrialized countries is to provide enough assistance and aid to developing countries to make it easier for them to bear this burden and help them in achieving (at a minimum) economic and social development. The only solution to this unpleasant problem is in increased financial aid from developed to developing countries. Unfortunately, foreign aid declines from year to year: only 0.09% of donors' GNP in 1988 compared with 0.13% in 1970 and 0.20% in 1965.[9] Meanwhile, the developing countries need more and more foreign aid. If we assume that the 'normal' proportion of GNP invested into energy systems is about 3% per year as it is seen, for example, in developed countries, then it will be necessary for developing countries to provide a maximum of about 5% of their GNP as foreign aid to ensure that energy systems are developed and reconstructed in line with acceptable economic and social goals.

The funds to stimulate these investments could be raised, for example, by energy/carbon taxes introduced immediately in developed countries. This aid could be returned to donors in the form of increased demand for goods and services produced by developed countries, because the aid will stimulate additional internal investments in the manufacturing and service sectors and local infrastructure, thereby expanding national economies. Therefore, the donors would also benefit from such cooperation.

Currently, the approach to energy tax evaluations is based on running econometric models using some 'production functions', which define energy savings as a response to increased energy prices. The difference between the simulated prices and normal market prices is usually assumed to be equal to the energy/carbon tax, but such an approach is based on a very dubious assumption of the price/demand elasticity, which usually is defined by posterior analysis and is valid more for short-term evaluations than for long-run projections of any dynamic systems, as is the case with global warming studies. The suggestion to introduce this tax for all nations immediately provokes negative reactions from the developing countries. However, in the scenario approach, the taxes can be considered as accumulated funds to be spent on energy demand reductions or energy supply mix changes. The fund should be equal to the subsidized part of required investments in energy systems. Global institutional bodies (the UN, the World Bank, etc.) should control the access to this fund.

According to the above estimates, the investments required by developing countries for the reconstruction and development of their energy systems are about 50–55 trillion dollars over the next 60 years (1990–2050). This corresponds to about 17 trillion dollars until 2010, if we agree that we must start immediately with all measures to stimulate more effective ways of energy development in less developed countries. As mentioned above, such immense investments would require at least 8–9% of the GNP produced in this region to be invested in energy systems, which seems unrealistic in view of the large economic and financial difficulties facing developing countries. The hopes that developing countries will in the near future implement environmental protection strategies on a broad scale are vain. Meanwhile, earmarked foreign aid could substantially reduce this difficulties.

The total carbon released in developed countries during the time period under analysis can be used as a basis for energy/carbon tax calculations. The cumulative fossil fuel consumption in developed countries and associated values for carbon released into the atmosphere over the period 1990–2010 are given in Table 8. The table contains estimates for carbon taxes required to subsidize energy system investments in developing countries. The full-scale foreign aid will demand about 3% of the GNP produced in developed countries to be transferred to developing countries to ensure and promote the required changes within the energy systems. The maximum value for a carbon tax is about $100 per tonne of carbon released. Therefore, based on the carbon contents of different fossil fuels, fuel price increases in developed countries under the different subsidization schemes are given in Table 8. It follows that, in the case of maximum subsidies from the global carbon-tax funds, coal prices in developed countries at the mine mouth will practically double, crude oil prices will increase by about 50%, and the natural gas prices by 20%.

**Table 8** Carbon tax to subsidize energy investments in less developed countries over the period 1990–2010

| | % of investments subsidized from the global carbon tax 'fund' | | |
|---|---|---|---|
| | 10% | 30% | 60% |
| Carbon tax ($/t C) | 17 | 50 | 100 |
| % of GNP in developed countries | 0.5 | 1.6 | 3.2 |
| Fuel price increase ($/toe) | | | |
| • Coal | 20 | 60 | 120 |
| • Oil | 15 | 45 | 95 |
| • Natural gas | 10 | 35 | 65 |

It is noteworthy that the carbon taxes calculated by econometric models using quite different approaches are in many cases of the same order of magnitude.[10] Therefore, the carbon tax together with certain abatement targets may be an effective tool for managing $CO_2$ emission reductions and thereby combating global warming.

One general remark should be made here. The global, long-term environmental problems will not be solved by efforts undertaken only in developed countries; there must also be strong involvement of the developing world. However, developing countries faced with many problems will hardly be willing to share responsibilities for environmental degradation with advanced countries (as was seen at the Earth Summit in

Rio de Janeiro). Environmental problems begin to be addressed only after some level of prosperity is reached (above $7000–8000 per capita, which is much higher than the per capita income in developing countries[11]). Of course, with time this threshold should be lowered as our knowledge of the environment improves. Nevertheless, the expected GNP per capita for most of the developing countries will remain below this level until the middle of the next century. Therefore, the only path to the necessary transformations, without waiting for catastrophic and irreversible consequences, lies in helping developing countries as soon as possible to develop in a more environmentally compatible way.

## 4 Optimal energy/$CO_2$ reduction strategy under climate uncertainties

Energy projections and scenarios are especially of interest if they elaborate global strategies for solving the most important long-term problems of human development and progress. As mentioned earlier, one problem that needs to be solved by the worldwide scientific community is the mitigation of global warming and climate changes, which are a result of expanded human activities and are expected to increase. Two factors seems to play a leading role in the reduction of $CO_2$ emissions within the time period selected for the analysis: (1) energy conservation by economic structural changes and efficiency improvements, partly by social behavioural changes; and (2) implementation of cleaner and lower-carbon-content fuels and energy forms.

The central point of this Section is the approach for estimating the energy-savings potential as a major factor in mitigating $CO_2$ emissions over the next 20 years. Several approaches for the evaluation of energy savings can be used, based on comparison with the current status or with a certain base case or with a hypothetical case. We have selected the last approach, assuming that the Hypothetical Case can be calculated for a system under development, but with no changes within energy systems over the time horizon of the study (no efficiency improvements, no changes in fuel mix, etc.). This means that the Hypothetical Case corresponds to the situation in which we apply only existing technologies and management practices to meet the system's expansion. The introduction of any changes in energy systems leads to a decline in energy demand, which can be defined as energy savings. The energy-savings potential is the maximum difference between the Hypothetical Case and other projection cases (in our study the Enhanced Efficiency and Conservation Scenario). Naturally, the real savings are usually less than the potential because of the existence of obstacles preventing the realization of the whole potential.

When identifying energy-savings potentials for different regions, three types of change in energy demand are considered: structural changes, due to shifts in the national economy towards less energy-intensive products and services; technology changes, due to the application of more energy-efficient technologies and tools than currently in use; and social changes, due to alterations in lifestyle goals and priorities, and transitions to less energy-wasting human behaviour.

The cost analysis described in the previous Sections provides a good basis for the optimization.* Figures 2 and 3 illustrate the results of calculating the energy-savings potential for developed and developing countries.

* A special model based on combinatoric analysis and dynamic programming was used to find an optimal $CO_2$ abatement strategy until 2010.

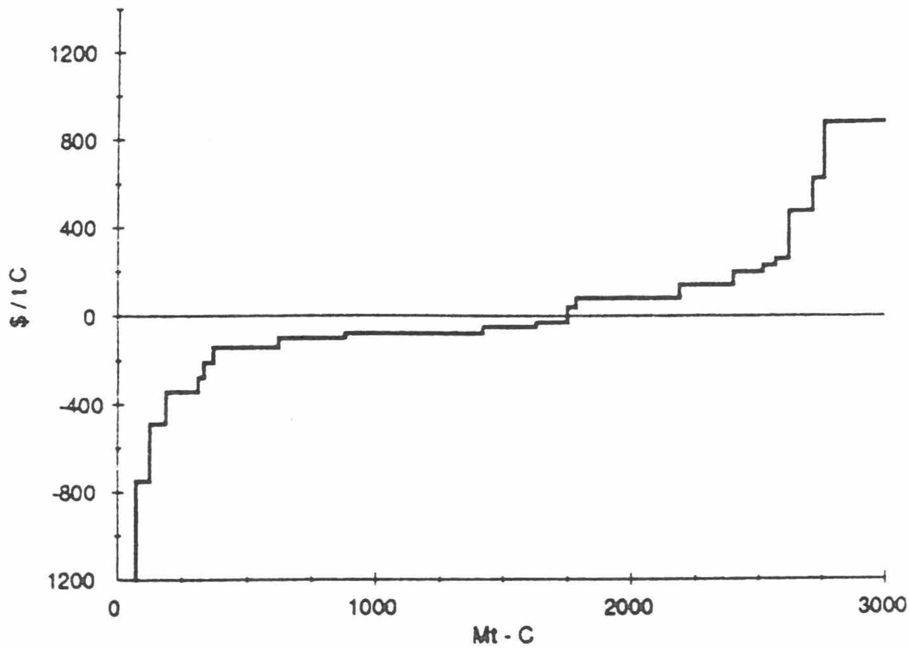


**Figure 2** Cost effectiveness of $CO_2$ reduction measures in 2010 for developed countries.

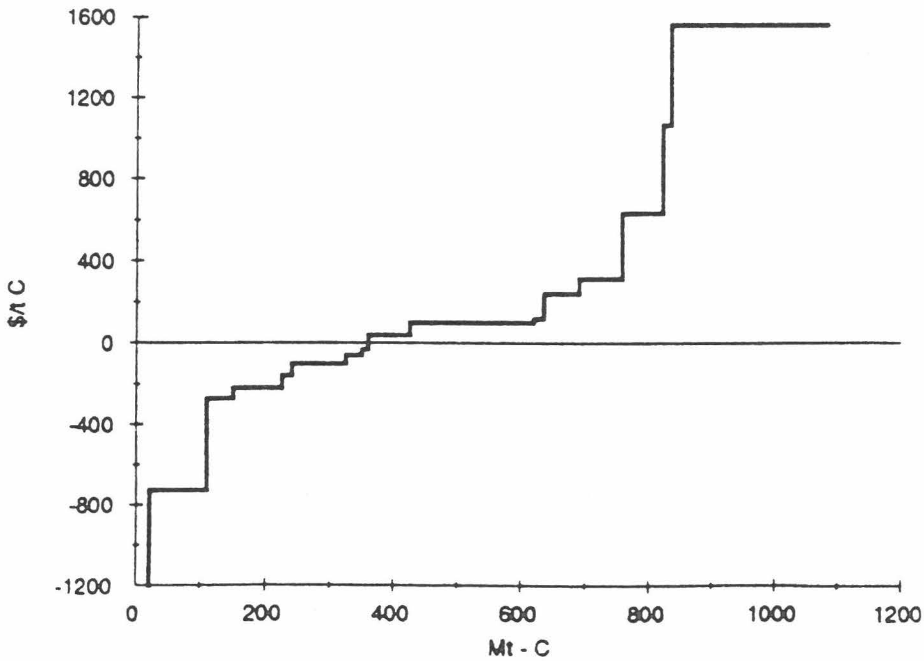


**Figure 3** Cost effectiveness of $CO_2$ reduction measures in 2010 for developing countries.

The analysis for developed countries in 2010 shows that the saving is more than 40% (over 3000 Mtoe) of the hypothetical energy demand in that year. The realization of this potential is from 45% in the case of less energy conservation to almost 100% in the case of energy-efficient ways of development and restructuring. The efficiency of energy-savings efforts in developing countries within the time horizon of the study will be less pronounced because of the lower level of the total energy demand (only 20%, about 400 Mtoe, in the Hypothetical Case). Both potentials are measured relative to the Hypothetical Case. The potential for savings in energy demand by 2010 compared with the Dynamics-as-Usual Scenario is 850–900 Mtoe globally, of which about 75% arises from the developed countries.

In fact, cost evaluations show that the $CO_2$ reduction potential in 2010 in energy systems of developed countries is 11 Gt of $CO_2$ (3 Gt C), or approximately 40% of the $CO_2$ emissions in the Hypothetical Case, of which at least half (or 20%) could be reduced with negative net costs, *i.e.* even with some increases in the GNP growth. The potential in developing countries is several times less, and equal to only 3.7 Gt of $CO_2$ (or 1.0 Gt C) (22% of the $CO_2$ emissions in the Hypothetical Case); 15% can be saved with negative net cost.

Sometimes it is important to present the optimization results relative to the Base Case rather than the Hypothetical Case. Figure 4 provides the possibility for such recalculations with the results summarized in Table 9. As follows from Table 9, switching from the Dynamics-as-Usual Scenario to a policy that is more energy efficient and produces less $CO_2$ will require additional costs, which are equal to 0.2–0.4% of the cumulative GNP produced globally. The Supply-side Measures Case (A3) seems to guarantee the same (or very close) level of expenditure, but with $CO_2$ emissions of more than 5% less than the Base Case. A more effective $CO_2$ abatement policy will require, of course, additional costs in energy conservation and efficiency improvements and changes in the primary energy mix, which in some cases could be overlapped by savings on the expansion of energy production and the use of old and conventional technologies. The maximum $CO_2$ reduction in Case B3 (compared with the Base Case) is expected to be 20% in 2010. However, this reduction can be achieved only by additional expenditure of about \$1.7 trillion, which corresponds to 0.4% of the global cumulative GNP produced over the period 1990–2010. Meanwhile, if implemented, the Accelerated $CO_2$ Abatement Case would result in $CO_2$ emissions in 2010, some 7% higher than today's level.

In conclusion, it seems that there are ways of minimizing the $CO_2$ concentration increases in the next century, mitigating the global warming process, and substantially preventing climate changes. With the uncertainty surrounding the global warming phenomenon, it looks reasonable to follow a no-regret policy, based primarily on the immense potential energy savings in both developed and developing countries. Such a policy could be a real benefit for the world economy, contributing to economic growth and abating carbon emissions.

A global policy will hardly be possible without the active involvement of developing countries. Effective cooperation between developed and developing countries in abating global warming should be established, assuming the direct assistance in their energy systems development. For this, global funds, raised by the introduction of energy/carbon taxes, could be a solution, which would be beneficial for both sides.

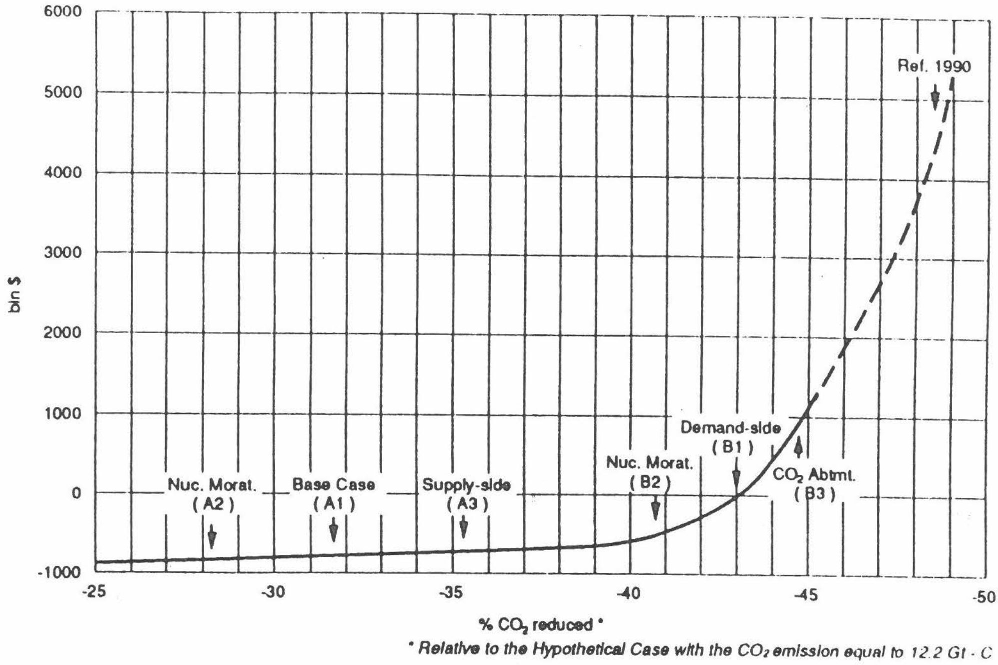


**Figure 4** Annual $CO_2$ emission reduction in 2010.

**Table 9** $CO_2$ abatement strategies relative to the Base Case A1, 2010.

| Strategy/Option | Annual emissions (%) | Primary energy (%) | Additional costs (billion $) | Percentage of GNP[a] |
|---|---|---|---|---|
| *Dynamics-as-Usual* | | | | |
| Base Case (A1) | 100.0 | 100.0 | 0 | 0 |
| Nuclear Moratorium (A2) | 104.3 | 100.4 | –20 | ~0 |
| Supply-side Measures (A3) | 94.4 | 105.5 | +40 | ~0 |
| *Enhanced Efficiency and Conservation* | | | | |
| Demand-side Measures (B1) | 83.0 | 87.3 | +855 | 0.20 |
| Nuclear Moratorium (B2) | 86.4 | 86.4 | +300 | 0.07 |
| Accelerated $CO_2$ Abatement (B3) | 80.2 | 89.6 | +1,655 | 0.40 |

[a] Cumulative global GNP until 2010 is equal to $420 trillion.

A global energy and climate change policy cannot be introduced without obligatory measures at both national and global levels. These measures should address policy actions, marketing guidelines, educational programmes, financial mechanisms, and technology transfer. Environmentally benign energy strategies cannot be developed globally without calling on all available measures in every place and sector. Many questions remain unanswered on the global-warming issue and in finding effective response strategies. Therefore, research into the problem and its links with energy systems will have to continue at the global level as well as at regional and national levels.

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