POTENTIAL EFFECTS OF EMISSION TAXES ON CO_2 EMISSIONS IN THE OECD AND LDCs

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Foreword

Increased research effort is being directed worldwide toward formulating appropriate measures and policies for reducing energy-related sources of global warming. In view of the scientific uncertainties, a consensus is emerging that such measures and policies must be based on precautionary actions to limit and ultimately reduce future sources of greenhouse gases. This involves both the reduction of emissions and the reduction of potential impacts and effects of an increased atmospheric concentration of greenhouse gases.

This paper by Sabine Messner and Manfred Strubegger presents an important contribution to this research effort by analyzing the potential consequences of energy-related carbon emission taxes in two world regions – the OECD and developing countries. This comparative analysis is based on the formulation of two alternative scenarios with the energy systems optimization model MESSAGE III. One serves as a reference scenario and is based on market clearing prices and the other introduces carbon emission taxes in the two world regions. The environmental tax is set at $46 per ton of carbon dioxide in the OECD countries but is lower in the developing countries. A 50 percent increase of carbon dioxide emissions compared with 1990 levels in the reference scenario is turned into a near-stabilization of future emissions to 1990 levels by the year 2020 through the introduction of carbon taxes. In the OECD countries the carbon taxes have an almost immediate effect on improving the efficiency of the energy system and causing a shift toward "low-carbon" fossil fuels (natural gas) and carbon-free sources of energy. In the developing countries, a relative reduction is also achieved, but in absolute terms the carbon emissions increase in both scenarios, illustrating that the carbon taxes alone are likely to be an insufficient instrument for achieving global greenhouse emissions stabilization to current levels. The carbon taxes cause a substantial increase in required investment, especially in the developing countries where the need for additional capital would compete with other investments required for growth and development.

The Environmentally Compatible Energy Strategies Project at IIASA is developing an inventory of options and measures for reduction and removal of carbon dioxide and other greenhouse gases (and the related computer database CO2DB). The inventory and its database will facilitate further application of energy models such as MESSAGE III for the assessment of options and measures for achieving stabilization, and perhaps even a reduction, of greenhouse gas emissions.

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POTENTIAL EFFECTS OF EMISSION TAXES ON CO_2 EMISSIONS IN THE OECD AND LDCs

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Abstract—A set of existing optimization models, which represent the energy systems of the OECD and LDCs (less developed countries excluding centrally planned economies) with a time horizon to 2020, has been applied to derive first-order estimates of the techno-economic potential for emission reduction. The driving force for the introduction of reduction measures is a scheme of taxes levied on the emission of six pollutants, including the greenhouse gases CO_2 and methane. The tax levels introduced are based on taxes discussed by the Swedish government: they are the break-even point to test which measures are cost-effective and which emission levels can be reached at these costs.

The regional models include the following alternatives: (i) reduction of final energy demand by supplying the requested services by other means (i.e., conservation); (ii) substitution of new fuels for polluting fuels; (iii) introduction of clean technologies for the same purposes; (iv) additions of pollution-reduction technologies. Alternative scenarios with emission taxes are compared with a base scenario without taxes related to pollutant emissions. The results indicate that an increase in CO_2 emissions in the OECD and LDC regions of 47% over the next 30 yr in the base scenario would be changed to stable levels to 2010 by tax-induced measures. Thereafter, energy-consumption growth in the LDCs reverses this trend.

1. INTRODUCTION

Human activities interfere with the natural environment in many different ways. Some activities, such as agriculture or housing construction, evolved over the history of mankind and changed and reshaped the environment. Others, such as deforestation in the Mediterranean and currently in many LDCs, or the accumulation of chemicals generated by human activities in the atmosphere are side-effects of economic development and industrialization. For most of our history, the consequences of human activities have been confined to local effects which caused, in case of major damages to the environment, change in lifestyle or migrations to other areas. Natural events, such as the Little Ice Age that started some 600 yr ago or major eruptions of volcanos, had consequences of the same order of magnitude as direct human intervention.

Industrialization has led to the capability for large-scale intervention in natural processes: burning of fossil fuels, which are carriers with a high energy density, permits large unit sizes for production processes and a degree of urbanization unknown before. But it has also given rise to a unique threat to our societies: CO_2 is a product of any process burning hydrocarbons and may, together with other chemicals, be responsible for the postulated change in climate generally labeled greenhouse effect or global warming.

The Intergovernmental Panel on Climate Change (IPCC) was set up in 1988 to analyze issues related to man-made climate changes and give advice to policy makers. Working Group I is concerned with the scientific assessment of climate changes and has estimated the contribution of CO_2 to the total radiative effect from 1980 to 1990 to be of the order of 55%.[1] The other contributors are methane (15%), CFCs (24%) and nitrous oxides (6%). The major share (some 75%) of man-made CO_2 emissions is caused by energy-conversion activities, i.e., burning of fossil fuels for electricity generation, in industries, private households and for transport. The remaining quarter of the CO_2 increase relates to deforestation.

If the two important conclusions of the IPCC[2] hold, namely, that (i) the current greenhouse effect has warmed the Earth above normal and (ii) the greenhouse effect is being further augmented by anthropogenic activities, then cost-effective strategies to reduce the emissions of all greenhouse gases will be required to limit global warming.

Technology-oriented energy models are useful in analyzing the effects of potential pollutant emissions connected to various energy-supply strategies. Existing models can be used to assess the effects of no-regrets policies as postulated by White.[3] Such options will reduce CO_2 emissions while entailing additional benefits or being readily available and economically viable. They include energy conservation, efficiency improvements, substitution of NG for coal and oil or oil for coal, and investments in non-fossil energy sources (nuclear or solar energy).

In our analysis, we use a set of energy-optimization models that encompass the OECD and LDC (excluding centrally-planned LDC countries like China)† that can be used to estimate the potential for reducing the emissions for CO_2 and other pollutants by introducing a tax on all activities related to emissions of these chemicals. Other pollutants such as SO_x, NO_x and methane are included in the analysis in order to obtain a balanced picture of energy-related environmental issues. In the developing regions, air-pollution problems may be expected to increase in significance over the coming years, mainly due to short-term planning horizons and financial shortages in most of the developing economies.

The models used in our analysis minimize costs. Therefore, they should provide a consistent, cost-optimized path to supply the desired energy. All economical means to reduce CO_2 emissions under a chosen tax regime will be used. The regional models include the options listed by White[3] with the exception of nuclear energy, which, considering present public resistance, will probably only contribute a limited share of electricity.

Options exogenous to the energy system (e.g., adding carbon sinks or afforestation) are not represented in the present versions of the models. Such additional options may be introduced during the next century, when conventional methods will not suffice to yield acceptable CO_2 concentration levels. Presently and probably for a long time to come, CO_2 levels and emissions of greenhouse gases are the focus of scientific debate. Consequently, there is no defined target. For this reason, we chose to study the effects of taxing on emissions.

2. METHODOLOGY AND MODEL STRUCTURE

The energy demand, population and GDP are related to the sectoral energy intensities and lifestyle parameters. They are converted into energy requirements or demand. This demand is one of the driving forces of the energy model used. The second important set of input parameters are the prices of internationally-traded energy carriers. A consistent set of parameters concerning energy demand and energy import/export prices must be defined for the reference case. This scenario is consistent with respect to both regional energy demand and international energy prices. Consistency was assured by using market prices for individual energy carriers. In sensitivity analyses, the regional energy models incorporate options to adapt demand to price changes or other forces driving consumption down. These options may be interpreted as price-elasticity or conservation from investments (e.g., better insulation, more efficient equipment at higher cost, etc.).

The technologies and costs in the energy models change over time. The potential impacts of scenario assumptions (e.g., cost reductions for solar technologies due to enhanced improvements) are exogenous to the model. Hogan and Jorgenson[5] have noted that the modeling assumptions for exogenous technological change become progressively less tenable over the long term, which is equally valid for our techno-economic approach. In further analyses of long-term CO_2 reduction strategies, technological change must be included as a parameter.

2.1. *The energy optimization model*

The computer model used for the regional models, MESSAGE III,[6] is a dynamic linear programming model optimizing a given objective function (in this application, the sum of the

†The set of energy-optimization models was developed and used recently for a global analysis of the competitive situation of OPEC oil in international energy markets.[4]

discounted costs of supplying energy over the next 30 yr). It is a techno-economic model covering all physical energy flows, capacity requirements (including peak production and back-up requirements in the electric system) and conservation measures with a high degree of detail. Investment decisions and fuel choices are based on cost-effectiveness, long-term demand and requirements for replacing old capacities.

Structurally, each of the regional models covers the total energy system from domestic resource extraction and energy imports via central conversion, transport, transmission, and distribution of energy to the final consumption in various sectors of the economy, for transport and in private households. The energy demand is given in terms of useful energy for all thermal processes, in ton- or person-km for transport and as final energy for the remaining, non-substitutable uses of energy (mainly coke in steel production and electricity for non-thermal uses). The model is used to choose an optimal strategy for application of the available sources of energy and corresponding technologies based on the existing structure of the energy system, costs of energy supply, and requirements for infrastructure. It will seek the optimal path for introducing new technologies and phasing out uneconomical or unsustainable supply options. Since energy utilization and conservation are included in the optimization, optimal strategies are obtained for the overall energy system and include optimizing the structure and level of final energy consumption. Environmental and socio-political components of energy supply and consumption are also included in the model structure. The regional models account for emissions of some of the important pollutants and also include abatement measures for SO_x and NO_x, as well as clean technologies such as fluidized-bed combustion of coal as alternatives. Emissions of the following chemicals are accounted for in all conversion steps of the energy chain: CO_2, CO, CH_4, NO_x, SO_x, and non-methane volatile organic compounds (NMVOCs).

Examples of socio-political constraints include limits on the introduction of nuclear energy and on the share of domestic energy consumption covered by imports.

3. BASIC SCENARIO ASSUMPTIONS

The analysis is based on a set of models describing the energy system of six world regions including the OECD and the LDCs.† The time horizon starts in 1990 and extends to the year 2020.

3.1. *Economic development and energy demand*

Table 1 shows the historical development and assumptions for the future growth of population, GDP and the resulting growth of GDP *per capita* for the OECD region and the LDCs.

The figures on population growth are taken from the UN Data Bank and the GDP development is based on an IIASA scenario.[4] GDP growth for the LDCs is assumed to be

Table 1. Annual growth of population, GDP and GDP *per capita* in %/yr (1900–2020).

%/yr	Population		GDP (real)		GDP/capita	
	OECD	LDCs	OECD	LDCs	OECD	LDCs
1900–1950	0.88	2.20	2.28	2.77	1.38	0.55
1950–1973	1.15	2.46	4.72	5.32	3.52	2.80
1973–1987	0.76	2.50	2.52	4.41	1.74	1.87
1987–1990	0.54	2.52	3.47	3.07	2.91	0.54
1990–1995	0.53	2.42	2.07	3.94	1.53	1.49
1995–2000	0.48	2.29	1.64	3.96	1.15	1.63
2000–2010	0.36	2.04	1.99	4.11	1.63	2.02
2010–2020	0.17	1.42	2.69	4.22	2.51	2.75

†The following regions were modeled separately: North America, Western Europe, OECD Pacific, Latin America (excluding OPEC members), OPEC and other developing countries but excluding centrally-planned economies.

Table 2. Final energy use *per capita* and per unit of GDP (1987–2020).

Year	Final energy use per capita [kW/cap]		Final energy use per unit of GDP [kWh/US$(87)]	
	OECD	LDCs	OECD	LDCs
1987	4.30	0.56	2.53	6.06
1990	4.54	0.57	2.46	6.10
1995	4.52	0.59	2.27	5.86
2000	4.37	0.60	2.07	5.51
2010	4.23	0.67	1.70	5.02
2020	4.45	0.79	1.40	4.53

greater than in the OECD, i.e., the OECD economies are assumed to grow at an average rate of 2.2%/yr, whereas growth in the LDCs is assumed to be 4%/yr. On a *per capita* basis, the growth in the LDCs is only 0.3%/yr greater than in the OECD (2.11 vs 1.83%/yr in the OECD). The scenario is based on the expectation that, in the immediate future, economic growth will be relatively moderate and, compared with historical rates, will decline with a reversion of this trend after the turn of the century.

The scenario includes more energy conservation than in the past. While historical trends show that the primary energy consumption per unit of GDP has declined by 1%/yr,[7] our scenario assumes stronger decoupling for the OECD region, rising from a reduction of energy use per unit of GDP of 1.6%/yr between 1990 and 1995 to 1.9%/yr after 2010 (see Table 2). The LDCs are assumed to follow the 1%/yr energy/GDP decline rate. These assumptions are based on the expectation of increasing social awareness concerning global environmental problems resulting from energy consumption in the developed world.

Table 2 highlights discrepancies in the North–South perspective and shows the relative inefficiencies of the developing economies in terms of energy use per unit of GDP (nearly 2.5 times that used in the OECD). We also note the extremely low (by a factor of 7) energy use *per capita*. Because of anticipated high population growth, even the favorable economic growth assumptions made in the scenario do not allow a reduction of the gap between the developing and developed world. On a *per capita* basis, OECD citizens still consume 5.6 times more energy than the population of the LDCs in 2020.

An analysis of the *per capita* GDP in the two regions shows another aspect of this problem: historically, the discrepancy between the developed and the developing world has grown with time (see Table 3). The assumptions in the scenario reverse this trend and assume moderate narrowing of the gap: a difference of a factor of nearly 20 today is reduced to a factor of 18 by 2020.

3.2. *International energy prices*

Assumptions concerning the international market clearing prices for globally-traded energy carriers are consistent with low energy demand-growth expectations: From the low price at the

Table 3. Development of *per capita* GDP in absolute terms (1900–2020).

Year	OECD	LDCs	factor
	US$(87)/cap		OECD/LDCs
1900	2.65	0.25	10.6
1950	5.26	0.33	16.0
1973	11.67	0.62	18.8
1987	14.87	0.81	18.4
1990	16.20	0.82	19.8
1995	17.48	0.88	19.8
2000	18.51	0.96	19.4
2010	21.76	1.17	18.6
2020	27.88	1.53	18.2

Table 4. International market clearing prices in 1987 U.S.$/barrel of oil equivalent.

Fuel	US$/boe					
	1987	1990	1995	2000	2010	2020
Crude oil	18.1	16.0	18.2	20.1	25.8	25.8
Natural gas	14.1	12.0	13.7	14.1	18.1	18.1
LNG	16.2	14.4	16.4	15.1	19.4	19.4
Coal	9.4	8.0	9.1	9.0	12.3	11.6

beginning of 1990, there is an increase to roughly U.S.$26(87)/boe in 2010, stabilizing thereafter (see Table 4).

The prices of hard coal, NG imported via pipeline and LNG are the result of a market-clearing mechanism of these prices vs the price of crude oil. It is noteworthy that NG and LNG cannot reach oil parity (the gap between the prices increases slightly). This result is a consequence of the moderate demand growth in the scenario, for which competition between energy carriers are strong.

4. MODEL RESULTS

We first limit the description of the energy-related results of the structure of primary energy consumption. Thereafter, environmental aspects are briefly discussed for the pollutants, with a detailed analysis of CO_2. Finally, the impacts on investment requirements are discussed.

4.1. Base scenario

The primary energy consumption in the OECD reflects the envisaged pattern of economic development: after a period of moderate growth to the turn of the century, consumption growth accelerates after 2010 (see Fig. 1). The contribution of coal increases to 20 million barrels of oil equivalent per day (mbpd) by 1995 and then stabilizes at this level. Crude oil and oil products contribute more than 40% to 1995. Thereafter the oil share declines by 30% by 2020, being increasingly confined to transportation requirements. The gap left by declining oil use is filled by nuclear energy and NG, with gas covering an additional 5 mbpd by 2020 and nuclear energy growing from the present 7 mbpd to over 15 mbpd by 2020. The contributions of hydroelectric energy and other renewable sources of energy grow moderately at rates of 0.7 and 1.3%/yr, respectively.

Primary energy use in the LDCs grows from 31 mbpd in 1987 to 86 mbpd in 2020, at an average annual rate of 3.2%. Coal and crude oil market shares are constant over the whole horizon, while NG use is increased from 12 to 18% in 2000 and 20% in 2020. Nuclear energy grows moderately to 5% of primary energy in 2020, while hydropower and the other renewable sources of energy lose market shares; in absolute terms, they grow from 9.5 mbpd today to 15.3 mbpd in 2020, i.e. at an average annual growth rate of 1.6%.

Figure 2 shows pollutant emissions for the base scenario in terms of applicable values for the first year of the analysis. Emissions in the OECD are relatively stable due to moderate growth in energy use and stringent emission standards for SO_x and NO_x. Only methane emissions increase slightly, while CO_2 emissions remain at current levels as the result of substitution for oil products by NG and nuclear energy. All other pollutants decrease below present emission levels (CO by 16%, SO_x by 21%, NO_x by 9%, and the NMVOCs by 21%).

The situation in the LDCs is far less favorable. Emissions of pollutants grow. The minimum increase is 28% within 30 yr for CO (0.9%/yr), while other pollutants increase at rates between 2 and 4%/yr. The largest increase occurs for SO_x (by 2020 to more than three times the current level). Pollutant emissions associated with energy conversion and use are assumed to meet present standards in the modeled regions,† which means that no abatement measures are

†The emission data are based on the emission data bank compiled by the Parliamentary Inquiry Commission on "The Protection of the Atomsphere" of the Fed. Rep. Germany.

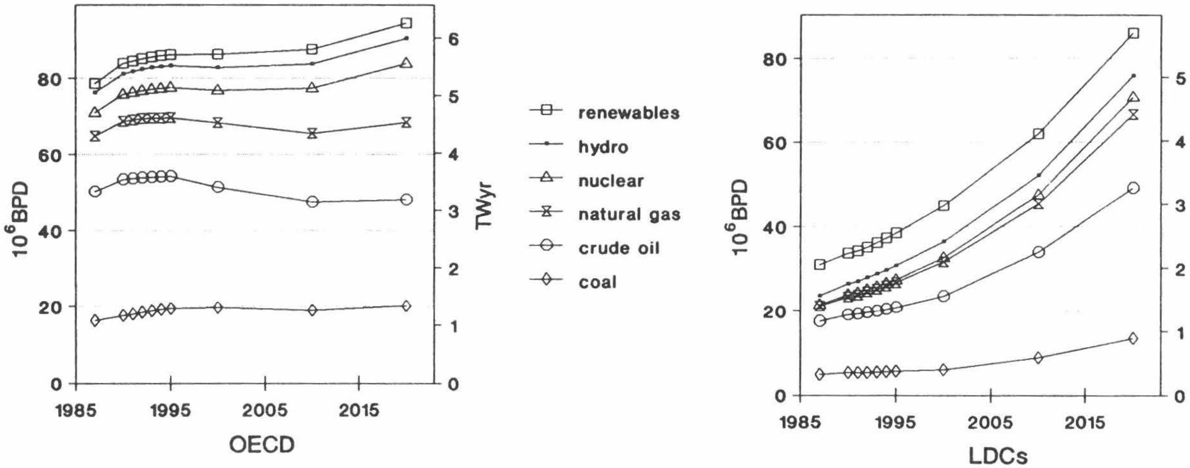

Fig. 1. Primary energy consumption for the base scenario in 10^6 bbl/day for the OECD and the LDCs.

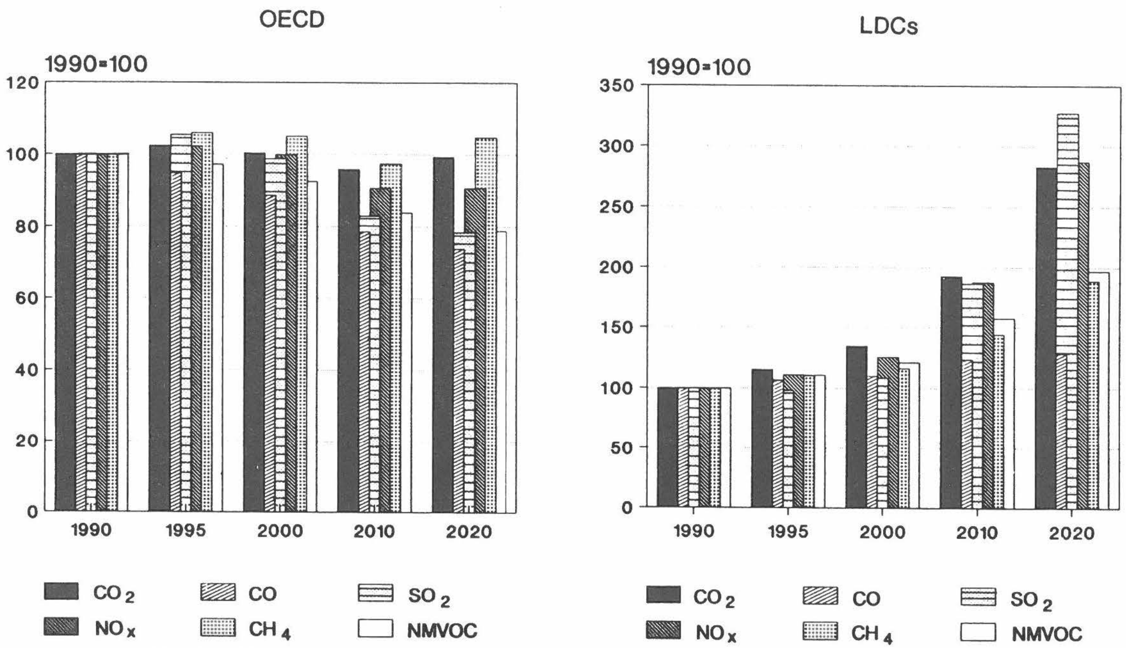

Fig. 2. Pollutant emissions for the base scenario for the OECD and the LDCs (1990 = 100).

included for the LDCs. For calculations with environmental taxes, separate technologies representing desulfurization and denoxing in the power-generation sector and for industrial consumers are included. These are selected in the optimization procedure if they are cost-effective as compared with taxes on emissions.

4.2. Environment taxes

The base scenario served as reference for studying the effect of introducing emission taxes in an optimizing, rational environment. The taxes adopted for the OECD are based on those considered by the Swedish government administration (see Table 5). For the LDCs, these values were divided by two to account for the stress such taxes place on developing economies, with lower environmental standards and higher emission levels for some of the pollutants.

In their analysis based on the Global 2100 Model, Manne and Richels[8] determine a long-run equilibrium tax of \$250/ton of carbon, which is equivalent to \$68/ton of CO_2, while Nordhaus[9] calculates shadow prices for greenhouse gases for various damage functions and comes up with \$3–37/ton of CO_2 equivalent.† We used a tax of \$46/ton of CO_2 in our model analysis.

Compared to the base scenario, the primary energy mix for the OECD reflects greater awareness with respect to environmental problems: overall energy use is about 15% lower as a result of conservation measures and the contribution of coal is reduced to roughly 5% of primary energy by 2020 (see Fig. 3). The use of liquid fuels is slightly lower than in the base scenario, while NG use is increased by 2 mbpd. The contribution of nuclear power is not increased. Hydroelectric power and other renewables contribute over 15% of primary energy by 2020, as compared with 11% in the base scenario.

Due to the lower charges for pollutant emissions and the lower elasticity of energy consumption in the LDCs, total primary energy use is only 12% below the base scenario. The contribution of coal is reduced to half the value for the base scenario but there remains growth from 4.8 to 6.1 mbpd in 2020. With 8% of primary energy use in 2020, the contribution of coal is also greater than in the OECD. Much less crude oil is used, while the contributions of hydro-power and nuclear energy are increased slightly in our scenario. The major increase occurs for the use of NG: 29 mbpd compared with 17 mbpd in the base scenario by 2020, which implies an increase of consumption and build-up of associated infrastructure of 6.5%/yr over 30 yr. It is questionable if the LDCs will be able to afford this necessary capital expenditure without assistance. Figure 4 compares the annual investment requirements in the LDCs for the base scenario and with emission taxes. The cumulative investments required between 1990 and 2020 are 3400 billion U.S.\$(87) in the base scenario vs 5900 billion U.S.\$(87) with emission taxes. By 2020, NG use in the LDCs would be twice the present level of use in the OECD.

The conditions under which the necessary infrastructure could be developed will have to be investigated further. The models of the LDC regions include present technology for gas transmission and distribution. They account for the fact that new grids in newly-built areas are relatively cheaper and the initial investments are lower than for the addition of low-density areas to an existing system. Other effects, such as reductions in pipe-laying costs due to newly-developed and as yet unavailable technologies are not included in the analysis. Such

Table 5. Emission taxation in U.S.\$(87)/kg of pollutant emitted for the OECD.

Pollutant	Tax on emission US\$(87)/kg
Carbon dioxide (CO_2)	0.046
Carbon monoxide (CO)	2.3
Sulphur dioxide (SO_2)	2.3
Nitrous oxides (NO_x)	2.3
Methane (CH_4)	0.23
Non-methane volatile organic compounds (NMVOCs)	0.23

†Nordhaus includes *all* greenhouse gases in his analysis, which is not possible in purely energy-related models, which do not include CFC emissions and abatement measures.[9]

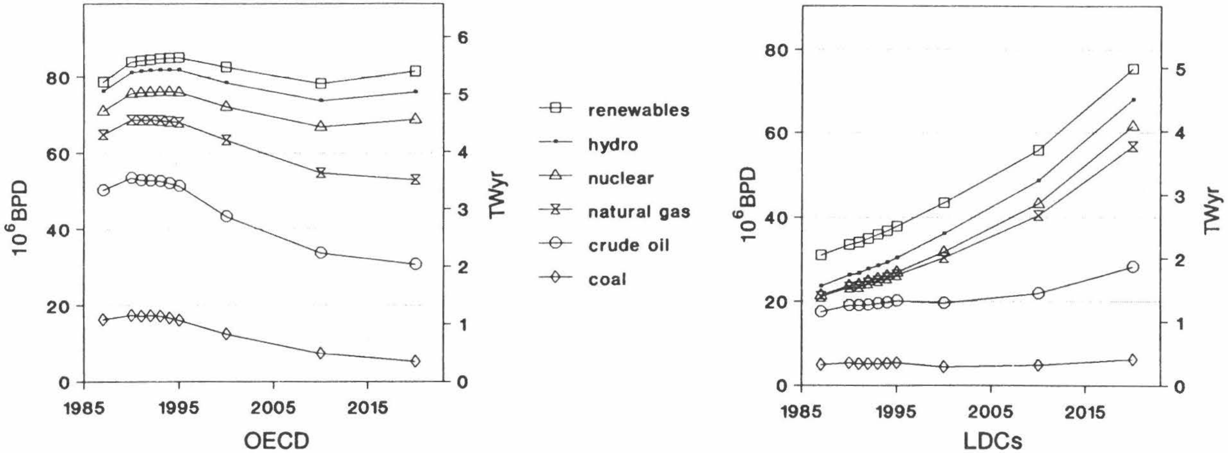

Fig. 3. Primary energy consumption for the emission-taxation case in 10^6 bbl/day for the OECD and the LDCs.

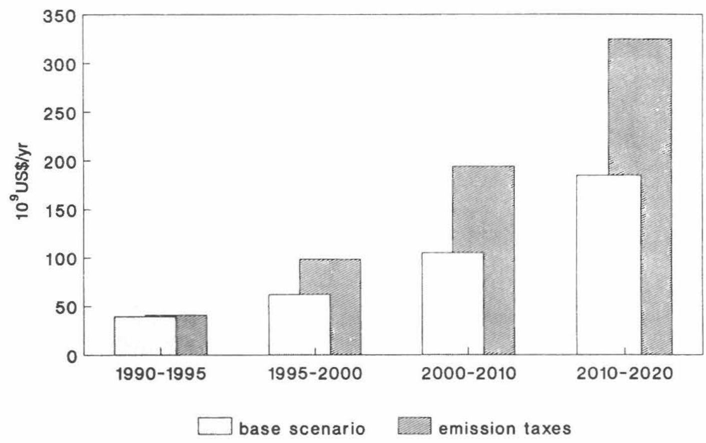

Fig. 4. Investments in gas infrastructure in 10^9 U.S.\$(87/)yr for the LDCs.

measures will be needed to avoid the extremely high investment figures derived in the model run with emission taxes.

Pollutant emissions in the OECD countries can be reduced considerably below the values for the base scenario: the level of SO_x emissions is one-quarter of the present level and the reductions of CO_2 and NMVOCs amount to 35% by the year 2020. For all of the other pollutants, the reduction is between 40 and 50% (see Fig. 5).

For the LDCs, the picture is completely different. Only CO and SO_x can be reduced to levels lower than in 1990. The emissions of NO_x increase by 17%, NMVOCs by 55%, methane by 30% and, worst of all, CO_2 is more than doubled compared to the level of 1990!

4.3. Comparison of carbon dioxide emissions

Figure 6 compares total emissions of CO_2 for the two model runs: in the base scenario, CO_2 emissions in the OECD are stabilized and the overall growth of 1.3%/yr over the next 30 yr is contributed by the LDCs. In the run with environment taxes, CO_2 emissions in the OECD area are considerably reduced, but this reduction is accompanied by growth of CO_2 emissions in the LDCs. The overall level of CO_2 declines slightly to 2010 but, by 2020 and as the result of increased economic growth, a level greater than in 1990 is reached again.

Figure 7 shows a comparison of the annual CO_2 emissions in the two model runs with the 1990 figures for the OECD, LDCs and the sum for the two regions. Stable CO_2 emissions in the base scenario in the OECD countries become a reduction of 35% by 2020 as the result of the environment taxes, while the increase by a factor of 2.8 in the LDCs is reduced to a more moderate increase of a factor of 2.1. In total, the CO_2 emissions for the combined two regions grow by nearly 50% by the year 2020 in the base scenario; environmental taxes lead nearly to stabilization to 2010, followed by increases later on.

4.4. Sectoral carbon dioxide emissions

The contributions of the different sectors to the emissions of CO_2 is displayed in Fig. 8. We show CO_2 emissions from resource extraction, central conversion of energy and energy use in the residential and commercial sectors, in industry and for transport, for both the base scenario and the case with environmental taxes. Generally, the largest share of CO_2 is accounted for by central conversion, mainly power generation (around 40%). The transport sector is the next largest producer of CO_2 with 27% in 1990, followed by the industrial and the residential/commercial sectors with roughly 15% each.

In the base scenario, the major trend is a reduction of the contribution of the transport sector from the present value of 27–24% by 2020, which is caused by the increasing hydrogen content of the fuels when aviation accounts for a larger share of passenger and freight

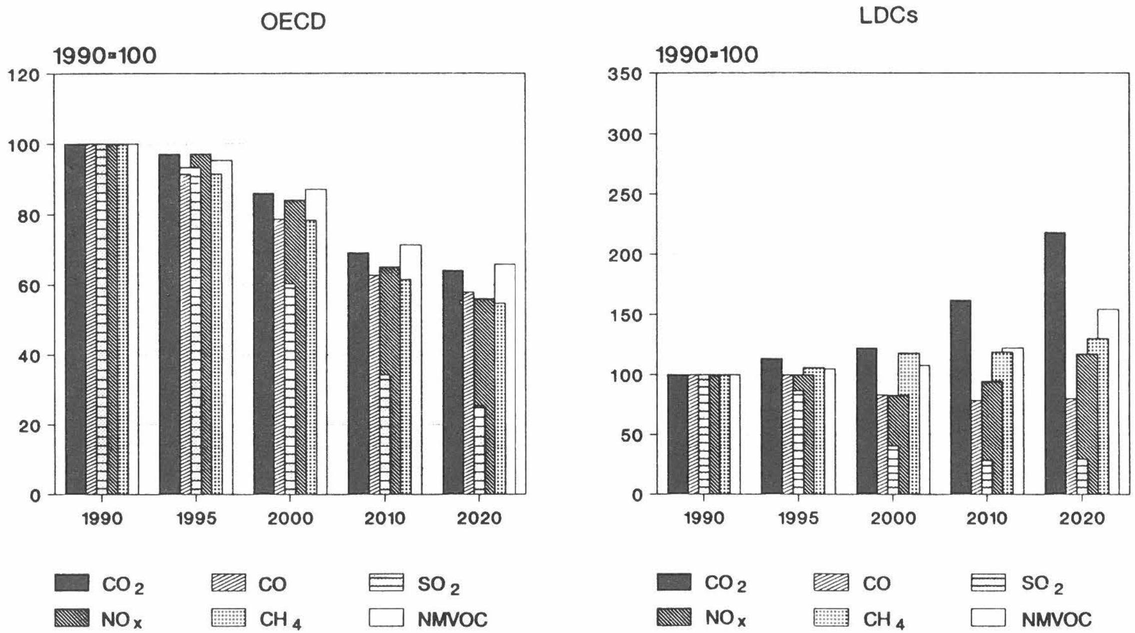

Fig. 5. Pollutant emissions for the emission-tax case for the OECD and the LDCs (1990 = 100).

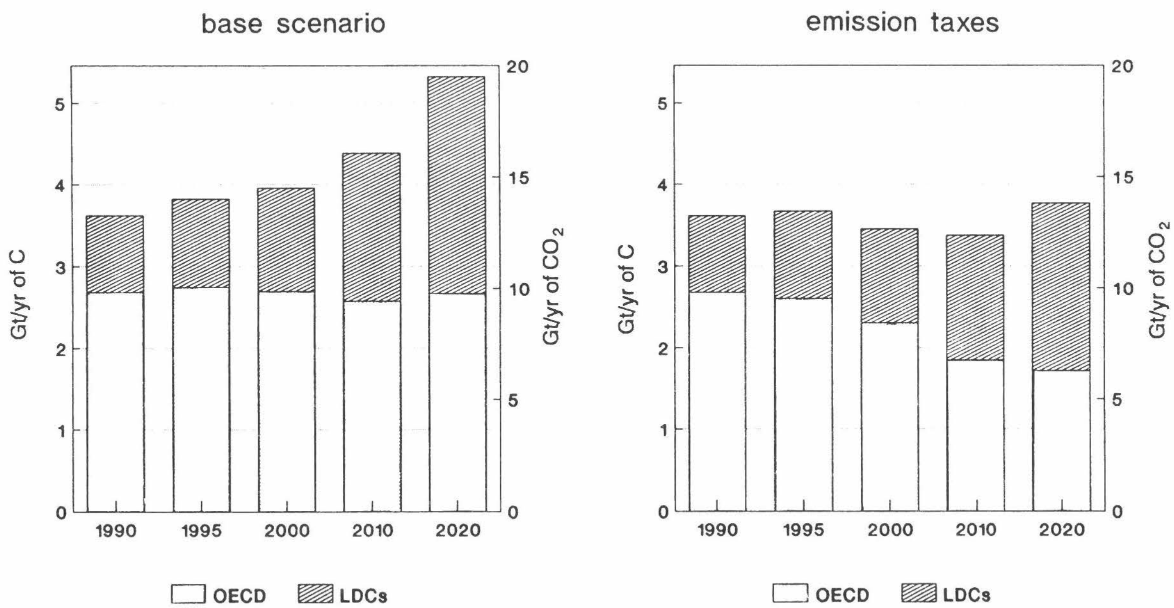

Fig. 6. Comparison of emissions of CO_2 in billions of tons/yr.

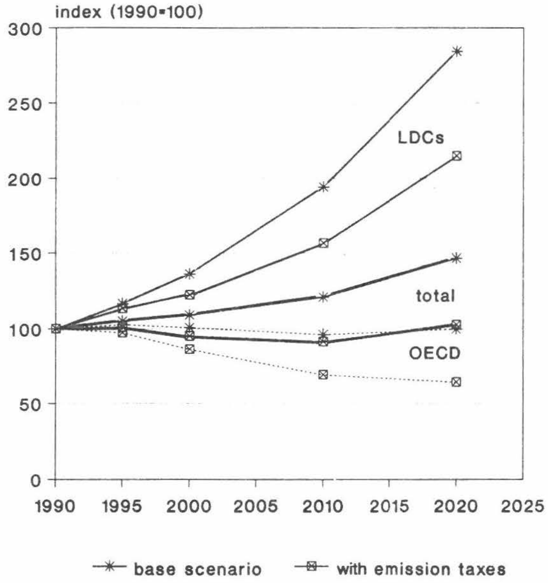

Fig. 7. Comparison of emissions of CO_2 (1990 = 100).

transport;† in the residential/commerical sectors, 27% less CO_2 is emitted in 2020 than in 1990. Final energy use in the residential/commercial sectors grows at an annual average rate of 0.4%/yr. The reduction of CO_2 emissions is caused by changes in the energy carriers used: coal is nearly phased out and the contribution of liquid fuels is reduced from 25% in 1987 to 10% in 2020. The use of NG remains constant, with the remaining gap covered by electricity, district heat and renewable sources of energy.

CO_2 emissions from central conversion grow slightly over the model horizon; the increase in overall electricity production is offset by the growing contribution of nuclear energy and the use of combined heat and power production. The major growth of CO_2 emissions comes from the industrial sectors, which, in 2020, emit one-third more than today. Besides growth in final industrial energy use, there is increased use of heavy oil products (which are no longer used for electricity generation), a slight increase in the use of coal and a reduction in the use of renewable sources of energy.

In the model run with emission taxes, the overall CO_2 emissions are reduced by 35% by 2020 (22% in 2005). The major reductions come from central conversion and the residential/commerical sectors, in which emissions of CO_2 are reduced by roughly 50% by 2020. Emissions in the transport sector are reduced slightly compared to the base scenario; industries emit 16% less CO_2 than today or 37% less than in the base scenario in the same year.

The LDC CO_2 emissions show exponential growth for the base scenario, from 3.4 billion tons presently to 5.6 billion tons by 2005 and to 7.3 billion tons by 2020, an average growth rate of 2.6%/yr (see Fig. 9). The industrial-sector share increases due to increased coal use and a much lower share of electricity in the fuel mix; considerably less CO_2 is produced from central conversion because of lower consumption of electricity. CO_2 produced during fuel extraction is greater than in the OECD because of OPEC oil and gas production. Over the next 30 yr, all sectors show considerable growth. The greatest increases come from central conversion (an effect of electrification) and from industry (due to a three-fold increase in final industrial energy use), which increases by a factor of three. Emissions from extraction double and the residential, commercial and transport sectors emit roughly 2.8 times more CO_2 than today.

†Final energy use for transport purposes is constant in the scenario. Increases in passenger- and ton-km are offset by efficiency improvements in the equipment used.

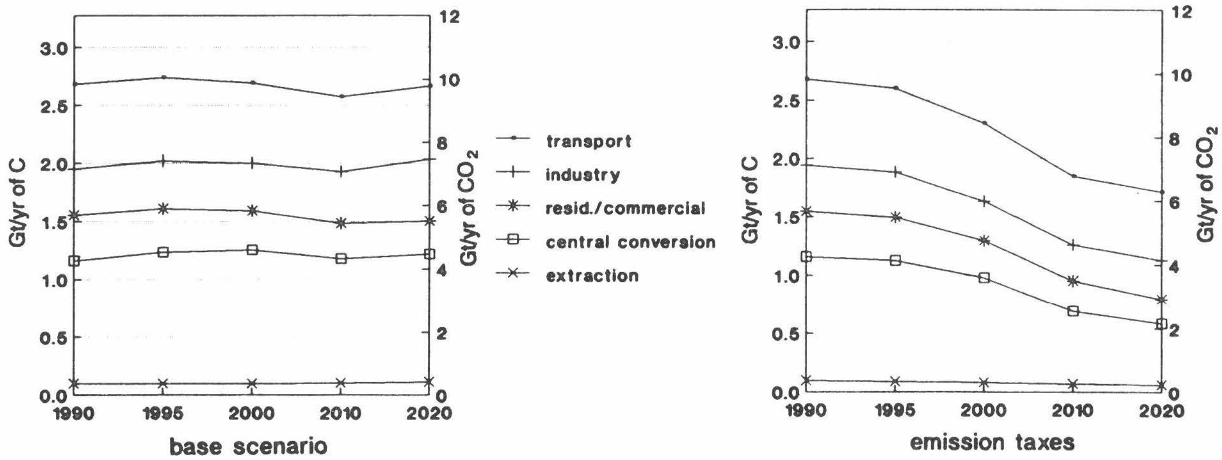

Fig. 8. Comparison of sectoral CO_2 emissions in billions of tons/yr for the OECD.

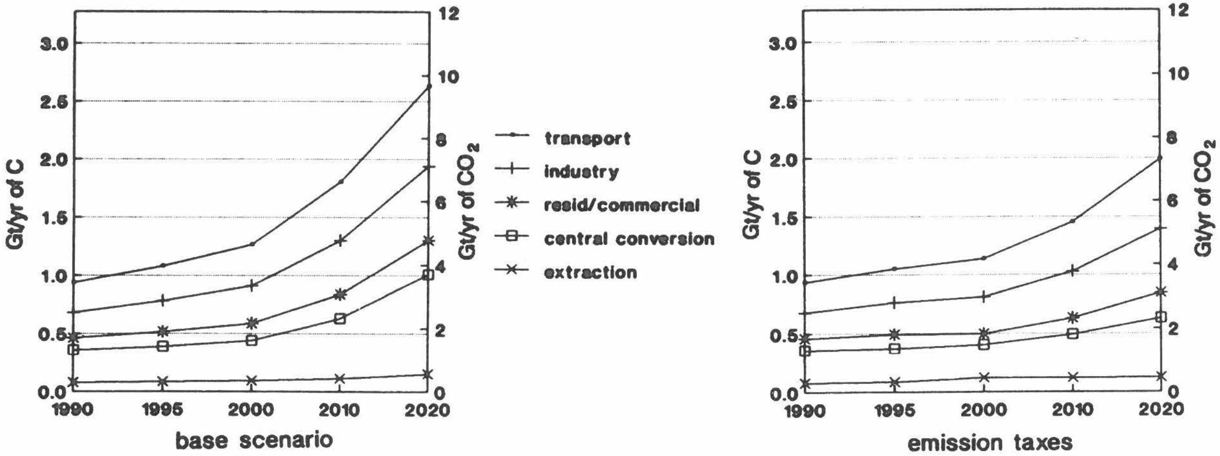

Fig. 9. Comparison of sectoral CO_2 emissions in billions of tons/yr for the LDCs.

Environment taxes change the picture: by 2005, 38% more CO_2 is emitted than today (compared with 63% in the base scenario); by 2020, emissions grow by a factor of 2.1 (compared with 2.8). However, the tendency towards exponential growth is preserved, although with a less steep slope. A relatively high reduction can be reached in central conversion (40% less than in the base scenario), followed by the residential/commercial sector (24% less). All other sectors reach a uniform reduction of about 15% compared to the base scenario.

4.5. *Investments*

Stabilization of total CO_2 emissions in the OECD plus LDCs at present levels to 2020 (compared to an increase of 50% in the base scenario) can be reached through measures justified by tax levies of U.S.$46/ton of CO_2 (equivalent of U.S.$170/ton of carbon) in the OECD area and half that value in the LDCs, in conjunction with taxes on other pollutants. However, such measures require an enormous investment. Figure 10 shows the annual investments in the two regions† for the case with emission taxes and for the base scenario.‡ While the base-scenario investments in both regions grow steadily between 1995 and 2020 (1.6% annually for the OECD and 5%/yr for the LDCs), emission taxes disrupt this development. Starting in 1995, investments increase considerably. Between 1995 and 2000, investments with emission taxes are 35% higher than for the base scenario for the OECD. In the LDCs, the increase occurs more gradually, starting with 14% around 1995 and growing to 70% by 2000. One of the causes for the large increases in the LDCs is that, in addition to measures taken in the OECD such as substitution of clean fuels for coal or investments in conservation measures, technologies for reducing SO_x and NO_x emissions, which are already widely applied in the OECD, must also be introduced. Emission taxes lead to reductions of all pollutants considered. At present, environmental standards in the LDCs are not severe. Therefore, cheap measures are available, which will be applied even at the lower tax level chosen for the LDC regions, thereby increasing investments considerably in a transition period.

After 2000, the total investments in both regions are reduced to levels below the base scenario. This change is attributed to generally lower energy-consumption levels and could well be offset by higher investments in more efficient equipment or conservation measures, which are not included in the investment figures.

In the long run, changes in investments in energy supply remain low for the OECD (a reduction of 2% to 2010 and 4% to 2020). The 15% reduction of energy consumption roughly

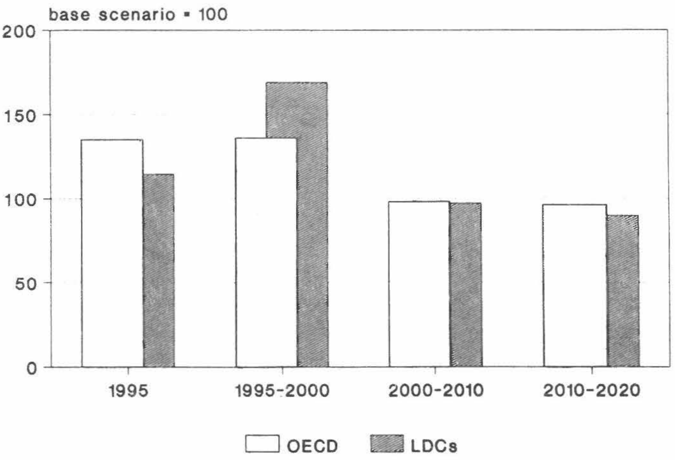

Fig. 10. Comparison of annual investments (base scenario = 100).

†The figures for OPEC were omitted from the analysis because oil trade and construction of new oil-production infrastructures distort the picture.

‡The figures include all investments in the energy conversion chain from resource extraction to energy utilization by various users. They do not include investments in conservation or restructuring measures to reduce useful energy consumption.

offsets the investments required for cleaner energy supplies. The LDCs show more substantial reductions in investments: 3% to 2010 and 10% to 2020. The supply of 12% less primary energy, together with investments in emission reductions induced by the tax level of U.S.$23/ton of CO_2 (CO_2 emissions are 25% below the base scenario compared to a 35% reduction in the OECD) seem to be feasible with 10% lower investments after an extraordinarily costly transition time.

5. FINAL REMARKS AND OUTLOOK

According to Shell,[10] carbon emissions from fossil-fuel use amounted to 5.5 Gt (1 Gt = 1 gigaton = 10^9 tons) of carbon in the year 1987, which is equivalent to 20.4 Gt of CO_2. Of this amount, 48% was emitted in the OECD, 16% in the LDCs and 36% in the centrally planned economies (CPEs). The Toronto target of reducing overall emissions of CO_2 by 20% compared to 1988 levels by the year 2005 seems to be infeasible, given the results of our analysis and keeping in mind the current energy situation in the world. For example, the Soviet Union faces severe problems in oil production and decreasing public acceptance of nuclear energy, resulting in the necessity to at least maintain the present levels of coal use in the U.S.S.R. At the same time, there is an expressed policy of enhanced coal use in the People's Republic of China.

Another problem relates to the likely unwillingness of the industrialized nations to contribute their share to the reduction measures. While Fed. Rep. Germany, one of the leading industrialized nations, has decided on a target of 25% reduction of CO_2 emissions by 2005,[11] other industrialized nations such as the U.S.A., Japan and the U.K. seem to be unwilling to implement the required measures to reduce their CO_2 emissions.[12] According to responses to a letter sent by IEA to all governing board members, these countries are still examining the need for or the scope of actions to deal with the greenhouse-gas problem.

The analytical tool applied to the analysis described in this paper could be instrumental in evaluating potential paths to reach given emission levels for different pollutants. Additional technologies to reduce net emissions by extracting chemicals from the atmosphere and the use of improved technologies should be allowed for. Evaluation may be made of tradable permits for CO_2 emissions, including inter-regional transfers, especially between the OECD and the LDCs.

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