A General Equilibrium Analysis of the Effects of Carbon Emission Restrictions on Economic Growth in a Developing Country

by

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I. Introduction

The consequences of environmental damage spread beyond the sectors in which they originate and have repercussions beyond their immediate impact. The same is true of policies designed to deal with environmental traumas. Computable general equilibrium models are particularly appropriate for the analysis of such issues as they make it possible to trace both the consequences of environmental damage and of proposals to deal with these effects.

This paper is intended as a demonstration of the potential uses of a multisectoral, intertemporal, programming model embodying significant non-linearities in production and consumption to analyze the effects of environmental policies. The particular application chosen to illustrate the approach is an analysis of the effects on economic growth of the regulation of carbon emissions. Other applications to the analysis of environmental issues could be treated analogously.

The model used was not originally designed for the present purpose and the setting of the model is rather special.[1] For these reasons, the numerical results should be interpreted as illustrative, rather than definitive, with respect to the relationships involved. Nonetheless, the results have some characteristics which, we will claim, have general validity.[2]

As a by-product of the particular application, the methodology may also be considered as representing a means of incorporating external economies in computable general equilibrium models. This may be of particular interest now as some types of externalities play an important role in the growth theories that have appeared in recent years.

The particular type of emission that will be analyzed is that of carbon generated by the use of petroleum and natural gas fuels. This leaves out other sources of carbon emission, other sources of "greenhouse" effects and other types of pollutants. The focus should not be interpreted as a judgment on the dangers, actual or incipient, of a "greenhouse" effect, on which no position is taken here.

II. Energy, the environment and the economy

Many, though by no means all, of the assaults on the environment are associated directly or indirectly with the use of energy sources of various types. The creation of "acid rain" is traced to the burning of high sulfur coals in thermoelectric facilities. The generation of urban smog is related to automobile emissions of methane, nitrous oxides, methane, sulfur dioxide and particulates from gasoline and diesel fuels. Plastic trash, ground water pollution from leaking underground storage facilities and oil spills, all can be related directly or indirectly to fossil fuel inputs. The argument that there is a global warming danger is related mainly to the generation of carbon dioxide, methane and nitrous oxide from burning of all types of fossil fuels.[3]

These obvious relations have led to many simplistic proposals for the reduction in use of fossil fuels. They are simplistic, not because they are not good-hearted or, not necessarily, because they have an incorrect association of direct causes and effects, but because they do not have a correct assessment, if any assessment, of indirect causes and effects and the overall costs and benefits. Assessing causes and effects is, of course, difficult. In part the difficulties are due to inadequate understanding of the science involved in the physical and chemical interactions in the environment. Part of the difficulties are due to lack of adequate data to project the spatial distribution of physical and chemical consequences of processes that may be well understood.

Part of the difficulties is in the lack of adequate methods for evaluating the overall economic effects of environmental change and environmental policies, including in the evaluations the reactions that will take place throughout the economy to particular kinds of changes and policies that may be confined to only a few sectors. These latter issues are the province of the economist and the profession should react to the challenge.

The reactions, so far, with a few important exceptions, have been rather limited in their sophistication. They have relied on simple extrapolations of pollutants in relation to fuel inputs or on econometric estimates of energy demands and on extrapolations using energy/gross national product ratios. Input-output models have been used in which there is no possibility of substitution of inputs by producers or of substitution of commodity purchases by consumers, both in reaction to changes in relative costs.

One major exception, as might be expected, is in the modeling of the greenhouse effect associated with Alan Manne[4]. Manne (1989) also focuses on the trade-off between reduction in the generation of pollutants and the overall performance of the economy. In estimating the costs of a carbon emissions limit, a growth model is used in conjunction with a process analysis model for the energy sector. The integrated model, called ETA-MACRO, simulates a market economy through a dynamic nonlinear optimization process. The model is intertemporal in nature and alternative carbon emission scenarios are evaluated in terms of their impact upon present and future levels of consumption for the United States.

The methodology is extremely useful in tracing the complex energy economy and environmental interactions over time. Its major limitation is its highly aggregative nature. Outside of the energy sector all of the non-energy sectors are treated as a single aggregate. The model is not intended to capture the interactions between the different sectors of the economy as they affect energy supply and usage or sectoral adjustments to emission constraints. These are potentially significant since emissions rates differ among the various types of inputs and outputs and overall emissions are, therefore, sensitive to changes in the sectoral pattern of growth. Thus the environmental and macro consequences of alternative pollution abatement strategies cannot be evaluated adequately within the above framework.

Another major exception to the rule of simple approaches is the sophisticated analysis in Jorgenson and Wilcoxen (1989). It is designed to estimate the tradeoff between pollution abatement and economic growth in the United States. The characteristics of the model will be summarized very briefly here as a means of contrasting it with the model that we will present.

The strengths of the Jorgenson-Wilcoxen study are in its careful and detailed econometric modeling of the production and consumption processes for each of the thirty-five commodity groups into which the economy is disaggregated. The costs of pollution abatement are also calculated carefully. In these respects the analysis appears to be the most advanced available.

The intertemporal results are calculated from steady state solutions of the model. In the base case pollution controls are in effect. Then, in order to determine the overall economic effects of environmental restrictions, the growth path of the US economy is simulated in the absence of regulatory measures. This step is taken by first estimating pollution abatement cost shares. These costs are then subtracted from production costs in the base case and economic growth in the model is simulated again. This gives a comparison of growth performance with and without pollution abatement costs.

There are, however, some features of the model that are not well-suited to its purposes. One of those is the assumption that capital is fully mobile among sectors. That is certainly not a realistic characterization of the economy except in the very long term. However, it is necessary for the way in which economic growth is realized in the model, through the calculation of steady state growth and a transition toward that path.

III. An economy-wide and intertemporal environmental model with substitution possibilities

The model to be presented below, however, is in the same spirit as Alan Manne's approach. Focusing on a single country and demonstrating a general methodology, it is more elaborate in a number of respects than would have been warranted in Manne's first environmental modeling research. In contrast with Manne's approach, our framework proposes a more disaggregated multi-sectoral model to evaluate the consequences of alternative pollution control strategies.

The basic structure of the model is well-known from previous work by the authors and many others. The complete mathematical structure of the model is presented in an appendix and only those features that are particularly important for its present application will be described here. It is a multisector, intertemporal optimizing model with some distinguishing features. The model was originally constructed for the analysis of energy policy in Egypt. It was adapted to the analysis of environmental issues since it is relatively detailed with respect to the sources and uses of energy, which, as noted above, is one of the primary sources of environmental offense.

For many purposes of environmental analysis, a country based analysis is the correct one. With some exceptions, as, for example, the Montreal agreement on the control of fluorcarbon emissions and regulation of the quality of the Rhine river, environmental policies are now national, rather than international.

Economic policies, with only a few exceptions, are, likewise, national rather than international. For large countries, national analysis is often appropriate, with important qualifications for border areas.

Nonetheless, some apologies are required for respecting national boundaries that are, for environmental purposes, often quite artificial. First, the local effects of some kinds of environmental pollution are the most important and averaging over a larger area is misleading. Second, transnational effects may be not be confined only to border areas. With these apologies, a national model will be presented, but also with the belief that the methodology is generalizable and extendable.

The model has a 25 year time horizon, divided into five periods of five years each. This somewhat artificial pacing makes it possible to avoid a more detailed formulation of year-by-year interactions and dynamic processes while still generating a close temporal approximation of growth conditions. Results are reported for five, evenly-spaced years.

The economy is divided into ten sectors, six of which are non-energy sectors: agriculture, manufacturing, construction, transportation, services and non-competing imports. There are four energy sectors: crude oil, natural gas, petroleum products and electricity.

The economic variables determined by the model are investment, capital capacity and production by each sector, household consumption by sector, energy demand and supply, imports and exports and relative prices, all calculated for each of five evenly spaced, periods that are, in turn, five years apart.

As noted, the model focuses only on the generation of carbon emissions due to fuel use, although the methods are completely adaptable to other types of emissions associated with the use of any input or to the output of particular goods with specific technologies. The carbon emissions are calculated for each sector, as well as in total, for each period.

As an optimizing model, it maximizes an objective or welfare function which is the discounted sum of aggregate consumer utility over the model's horizon. The utility of the representative consumer in each time period is a weighted logarithmic sum over all goods of the difference between its consumption of each type of good and a parametrically fixed consumption level. Individual utility is multiplied by the projected population to obtain aggregate utility. This formulation is identical to simulating the market behavior of a representative consumer modeled as a linear expenditure system. It should be noted, in the present context, that environmental conditions do not enter the consumer's utility function directly. However, the consumer's choice of goods in the consumption basket will depend on relative prices and income levels, which are determined within the model, and those can be expected to be affected by environmental policies.

The usual material balance constraints, which require that the aggregate uses of output can be no greater than the aggregate availabilities, apply in each period. Availabilities depend on domestic production and imports, where the latter is feasible.

One of the most significant features of the model for the purposes of assessing the environmental impacts of economic activity is that, in general, production of each good can be carried out by alternative technologies, or, "activities," with different input patterns. The total output of each sector is the sum of the production from each of the technologies. Thus, there is the possibility of substitution among inputs in production processes. The substitution takes place endogenously, in response to the relative prices of inputs and outputs, which are also determined endogenously. This is important for the analysis of environmental policies that either directly or indirectly affect the cost of inputs.

The potential alternative requirements for production in each sector are, with one exception, specified exogenously, as if they were taken from engineering specifications. The exception is in the demand for fuels, where, in effect, the BTU requirements per unit of output are specified, but the requirements can be met by using either natural gas or petroleum. Here, again, the choice will be made endogenously, depending on relative prices and any constraints that affect those prices.

Only three primary energy sources are distinguished: hydropower, crude oil and natural gas.[5] Production of each is constrained by availability. Crude oil is produced from petroleum reserves and the creation and use of these and of natural gas reserves is modeled to reflect the fact that the level of reserves is a function of the rate as well as the quantity of use of the resources.and outputs to producers and consumers.

Production also requires labor inputs, whose unit requirements are also specified exogenously, but differently, for each technology or activity in each sector. There is an overall constraint on labor availability and, separately, a labor constraint in the agricultural sector intended to reflect limited rural-urban labor mobility and the tightness of the rural labor market over the past decade or so.

As is customary in such models, and different from the Jorgenson/Wilcoxen model, capital is specific to each sector and, here, it is specific as well to the particular technology that it embodies. Capital formation in each period in each sector requires that investment be undertaken in the previous period. Depreciation rates are specified exogenously for the capital stock used by each technology in each period.

Foreign trade is confined to the tradable goods sectors: agriculture, manufacturing, transportation, other services, crude oil and petroleum products. As an approximate way of recognizing limited flexibility in the response of exports and imports to changes in relative prices, the rate of change of each of these is constrained, although within wide bounds.

The overall balance of payments constraint, that limits imports to what can be paid for from exports and foreign exchange resources, must also be met. Foreign borrowing is allowed, within moving upper bounds.

The problems of establishing initial and terminal conditions in a model of this sort are well-known. Here they are, largely, finessed. The sectoral levels of investment in the initial period are constrained not to be greater than those actually achieved in 1987. The sectoral levels of investment in the terminal period are determined by the condition that they be adequate to sustain an exogenously specified rate of growth of output in the sector in the post terminal period. The terminal conditions, in particular, create some anomalies in the final periods of the model's time horizon. Since that horizon is relatively long, these have only modest effects on the intermediate years, for which results are reported.

With this description of the basic model in place it is possible now to turn to the features that deal with the environment, which can, in fact, be described quickly. The quantity of carbon, V, that is generated by the use of a particular fuel, i, in a technology, k, in a particular sector, j, in period, t, is V_{ikjt}. So the total amount of carbon generated by the use of a particular fuel in the sector is obtained by summing over all technologies:

$$V_{ijt} = \sum_k V_{ikjt}$$

In addition carbon emissions are generated directly by consumption. The carbon emitted by a use of a fuel, i, in consumption, V_{ict} is related to consumption of that fuel, C_{it}, by a coefficient v_{ict}:

$$V_{ict} = v_{ict} C_{it}$$

The total amount of carbon generated by the use of the particular fuel in all sectors and in consumption is:

$$V_{it} = \sum_j V_{ijt} + V_{ict}$$

The generation of carbon is related to the use of the particular fuel in the sector by a coefficient, v_{kijt}. I.e.,

$$V_{kijt} = v_{kijt} V_{kjt}$$

where the V_{ik}'s are understood to refer only to the fuel inputs.

The simple relationships are the conventional ones used in projecting the generation of environmental agents. Now, however, that generation is a matter of endogenous determination in a complete model. So calculation of the generation of environmental agents is completely consistent with the calculation of the other features of the model, including its growth path.

Although the issues analyzed here are the consequences of carbon emissions constraints for economic growth, the model can be turned to other questions, for example, the environmental consequences of an increase in the efficiency of energy use in consumption. With modest modification of the consumer's utility function to make some types of consumer durables complementary with specific fuels, the implications of <u>requiring</u> the use of a particular fuel could be investigated.

In studying the trade off between the generation of carbon emissions and overall economic performance, two alternative forms of quantitative restrictions will be analyzed. The first is a constraint on the generation of carbon emissions by the use of a particular fuel, i, in particular sectors, j. The constraint would be of the form:

$$V_{ijkt} \leq \bar{V}_{ijkt}$$

It will be recalled that capital is committed to a particular technology in a particular sector. So it is quite possible that an "old" technology will continue to be used in a sector, because its capital has not depreciated, while a new technology with different capital is being adopted. This constraint, therefore, makes it possible to investigate the consequences of essentially banning particular technologies.

The second type of restriction is a constraint on the total amount of the particular agent generated by a particular sector. This would take the form:

$$V_{it} \leq \bar{V}_{it}$$

This discriminatory regulation of particular sectors is also a kind of environmental regulation that is frequently discussed. It may have a certain rationale in that there may be differences among sectors in the degree to which regulations can be enforced effectively.

The third type of restriction is a constraint on the total amount of the particular agent generated by two or more sectors. It would take the form:

$$\sum_i V_{it} \leq \bar{V}_t$$

This type of restriction can be used to reflect the idea of "bubble" regulation. It is, essentially, regulating the total output of an environmental agent by a complex of industries so as to permit the individual industries to choose, themselves, the most efficient means of meeting the overall target.

Each of these types of restrictions can be applied with greater severity, to investigate the trade-offs between reduction eneration of carbon emissions and overall economic per-

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rn e perspectives in the use of the model

izing model has some advantages and disadvantages in application to which it is put here. In the analysis pplication of a particular policy to an economy questions ys asked as to the assumptions made about the character djustment to the policy. Is the adjustment an efficient o individuals and firms adapt ineffectively? In this adjustment is optimal, in terms of the maximization of ctive function. Moreover, it is done with perfect over the model's time horizon. The implicit assumption agents in the economy act efficiently to maximize their vith perfect foresight. A single solution of the model therefore, what must be regarded as an optimistic on of what can be achieved in terms of the maximand, endowments, the opportunities and constraints that are ted in its framework.

s customary in such modeling, a particular solution is nterest than the comparisons among solutions, which pro- ghts into problems and opportunities. In the applica- rted on here, the comparison will be between economic with and without carbon emission controls. In both solution is one that is dynamically efficient with o the objective function. Therefore, it is less clear, ase, that the results with respect to the effects of emission constraints should be interpreted as "optimistic," since the basis for the comparison is also an optimal result.

There are alternatives to the structure presented above for building preferences for lower emissions into a model of the sort presented. Emissions could be introduced into the objective function being maximized, with a negative sign. Or reductions in emissions could be put into the objective function with a positive sign. Solutions could then be found with different weights on the emissions variables in the objective function and the consequences traced out, just as we will trace out the consequences of different levels of constraints.

We believe that this approach would provide less insight than the direct application of emission constraints. That is partly because policy is often discussed in just these terms: constraining emissions. Then the question is asked: what is the cost? That question can be answered directly from the results of this type of model.

The first consideration will be the coverage of the constraints. The objective is usually stated in terms of reduction of total emissions. However, the debate often quickly turns to reducing emissions from particular sources or particular types of activities, e.g. emissions from thermal-electric generating plants or emissions from automobiles. In the model to be presented, both types of constraints will be imposed, in separate sets of solutions: first, a constraint on total emissions; second, constraints on emissions by each sector.

The different types of constraints correspond to the analogous differences between emission constraints on individual plants or an emission constraint on a "bubble" covering a set of plants. The latter approach has been advocated and applied by environmental agencies in some instances to other types of emissions.

The next issue is the base to which emission reductions are related. Perhaps the approach that receives the most publicity is the stipulation of reductions in absolute amounts of emissions, or, what is the same thing, percentages of a fixed base level of emissions. For example, goals are often articulated in terms of a reduction of emissions to a fraction of what they were in some base year.

Even without actually solving the model we know what the general nature of the results must be, if additional restrictions in the form of lower emissions are imposed. If the constraints are binding, and it is expected that they will be, economic performance measured in terms of the objective function and the related output and income levels will suffer. Only on the assumption that there are costless ways of adjusting to the constraints could the results be different. While it is often argued that increases in efficiency in the use of various fuels would reduce emissions, hardly anyone believes that would be costless.

It is plausible for advanced countries that they should think of adjustments and sacrifices, if necessary, in their material living standards in order to gain the benefits, which are hard to quantify but which may be important, of lower absolute levels of emissions. It is just as plausible that developing countries, which are not close to the levels of living in industrialized countries, would resist a goal formulated in terms of absolute reductions in emissions.

If developing countries are going to be involved in the debate over reduction in carbon emissions, a more plausible basis for comparison is a reduction in emissions relative to what they would have been, if the country had been following a growth path that was not constrained by emissions reduction. This is the objective that is investigated here. It is, of course, different from targets related to the absolute levels of emissions at some original point in time.

V. Data Base and Parameterization

Data requirements of economy wide general equilibrium models of this nature are quite rigorous since they require an extensive set of estimated parameters and exogenous projections.[6] The data needs can be classified into four broad categories: technological relationships, behavioral relationships, miscellaneous exogenous or predetermined variables, and initial conditions. The estimation of these relationships and parameters is described in Blitzer, et al (1989). However, since substitution among energy inputs in production and consumption has a central role in this model, the methods used to provide the necessary data will be described briefly.

The principal source of primary data on the inter-industry structure of the Egyptian Economy is a 37 sector transactions matrix for 1983/84 obtained from CAPMAS.[7] The 37 sector matrix is aggregated into a ten sector classification, adjusted and updated to represent our base year transactions matrix of 1986/87. This transaction matrix provided much of the data for the implementation of the model.

The model is formulated to use one or more technologies to produce each good or service. The specific number of alternatives depends on sectoral characteristics. The alternative production technologies, k, are divided in two categories. The first, encompasses the implicit technologies implied by the transactions matrix in 1986/87. The second category of technologies are the alternatives to the initial technology. In general, the alternatives allow for substitution between fuels, electricity, labor, and capital. The alternative technologies were derived using a small program which has as inputs: i) the initial technology, ii) the own-price elasticity of energy for the sector; and iii) the sectoral elasticities of substitution between labor and capital, between labor and energy, between capital and energy, and between electricity and fuels. The model takes the unit demand for fuels as fixed for each technology, but this demand can be met by using either natural gas or petroleum products. At the same time, there are limits placed on the degree to which natural gas and petroleum products can be substituted for each other.

The methodology used in determining the parameters of the utility function in the maximand is based on a linear expenditure system of equations. The parameters of that function were first estimated econometrically, and then adjusted for consistency with the model's base year. The complete system of consumer demand functions has (2n - 1) independent parameters: n - 1 β_i 's and n γ_i 's. Since these equations are highly interrelated, a complete systems approach was used to econometrically estimate the parameters. The database for estimating these parameters was constructed by pooling cross-section family budget data which was available for two time periods, 1974/75 and 1980/81. Maximum likelihood estimates of the entire system were derived using the procedure of "seemingly unrelated regression."

VI. Model results on the effects of restraining carbon emissions

There are a number of potential uses of the model and only a very few will be exemplified here. Perhaps the most important and most obvious is that mentioned above, analysis of the trade-offs between emission restrictions and economic performance. The effect of emissions restrictions will be tested in the two ways indicated: (1) as a global constraint on total emissions from the use of fuel inputs and (2) as constraints on emissions by each sector. The effects of the emissions restrictions will always be calculated as comparisons with model solutions without emissions constraints.

The global constraints on total emissions that are applied in alternative solutions are presented in Table 1, as percentages of the total emissions generated in each period in the unconstrained emissions solution. As will be noticed the emission limits are, in a general sense, increasingly restrictive, over time and in successive solutions.

Table 1

Constraints on Total Carbon Emissions As Percentages of Total Emissions in Unconstrained Solution

	1987	1992	1997	2002	2007	2012
G1	100	0.95	0.90	0.85	0.80	0.70
G2	100	0.95	0.85	0.70	0.70	0.65
G3	100	0.90	0.80	0.65	0.65	0.65
G4	100	0.90	0.80	0.65	0.60	0.55
G5	100	0.85	0.75	0.60	0.55	0.45

When similar constraints were applied on a sector by sector basis, the solution often became infeasible. The infeasibility was located in the emissions constraint in the Services sector. That sector uses relatively little fuel in any case and, when fuel usage was constrained by emissions limitations in the proportions corresponding to the G4 and G5 cases, the model simply could not find a feasible solution, i.e. could not meet other economic constraints. That occurred in part because the substitution possibilities between among fuels and other inputs in the sector were quite limited.

To continue the investigation, the emissions constraints on the service sector were then lifted and the limitations were applied only to the other sectors. Table 2 summarizes the sectoral emissions constraints that were applied. There is an immediate and important lesson from this first result, which is also immediately obvious to an economist: sectoral emissions constraints, if not applied with care, may create serious difficulties for an economy. The flexibility in inputs within the sector and the demands for its outputs may not be sufficient to absorb the constraints without widespread repercussions.

Chart 1 presents the time paths of real GDP in the alternative solutions corresponding to Table 1, with constraints on

Table 2

Sectoral Constraints on Carbon Emissions As Percentages of Sectoral Emissions in Unconstrained Solution

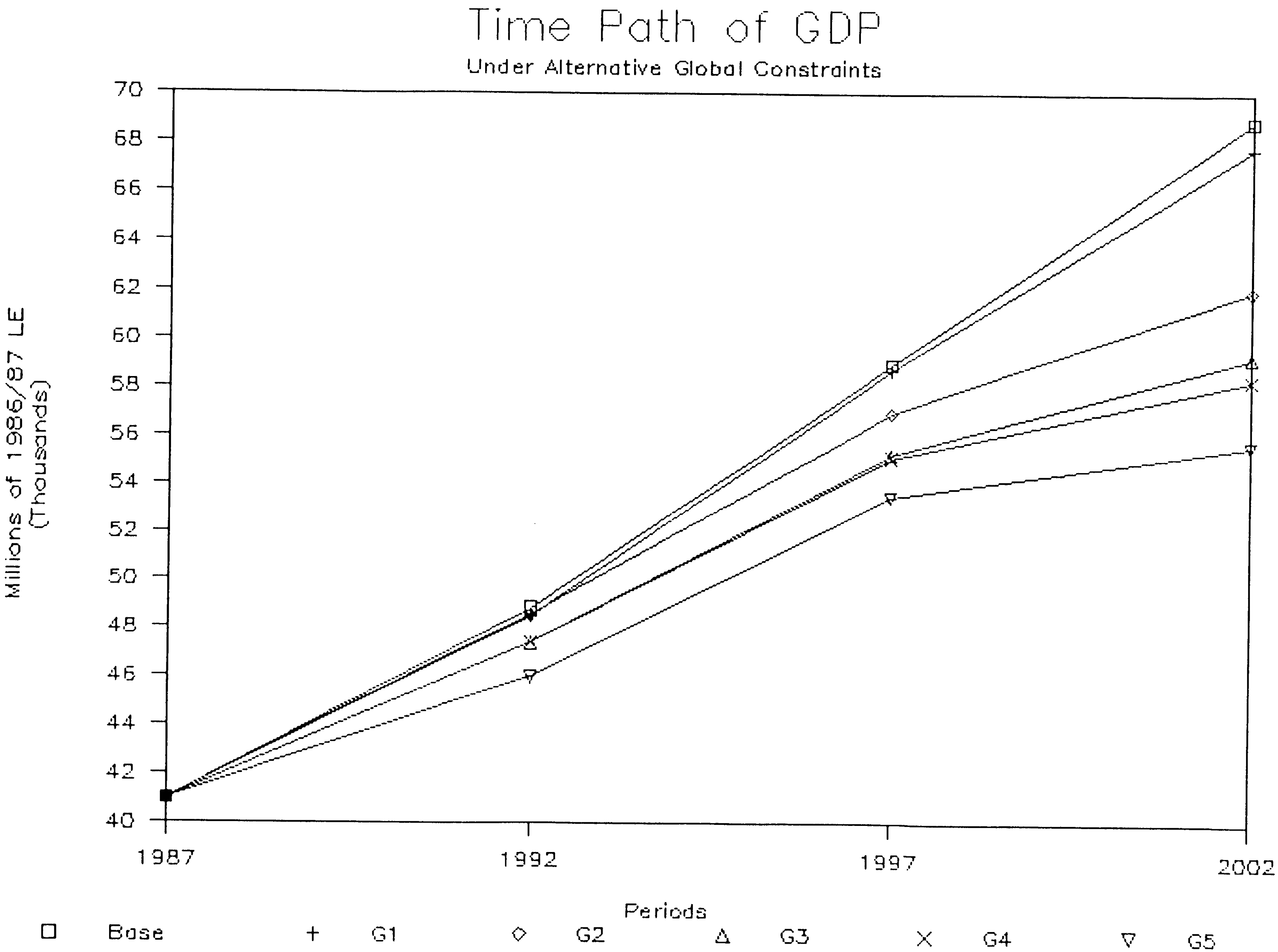
	1987	1992	1997	2002	2007	2012
S1	100	0.95	0.85	0.70	0.70	0.65
S2*	100	0.95	0.90	0.85	0.80	0.70
S3*	100	0.90	0.80	0.65	0.65	0.65

* Emissions in the Services sector are not constrained.

aggregate emissions. It will be noticed that the successive 5 per cent reductions in total emissions in each period are accommodated in the G1 solution without substantial effect on the economy that is being simulated. If 10 or 15 per cent reductions are called for in the first period and later periods, as in the other solutions, the effect on GDP is quite substantial.

It is interesting to note that, although the emissions constraints in G3 and G4 are the same for the first three periods after the base year, GDP levels are lower in the G4 solutions because the simulated economy begins to adjust to the prospect of tighter restrictions in the last two period of the model's time

CHART 1

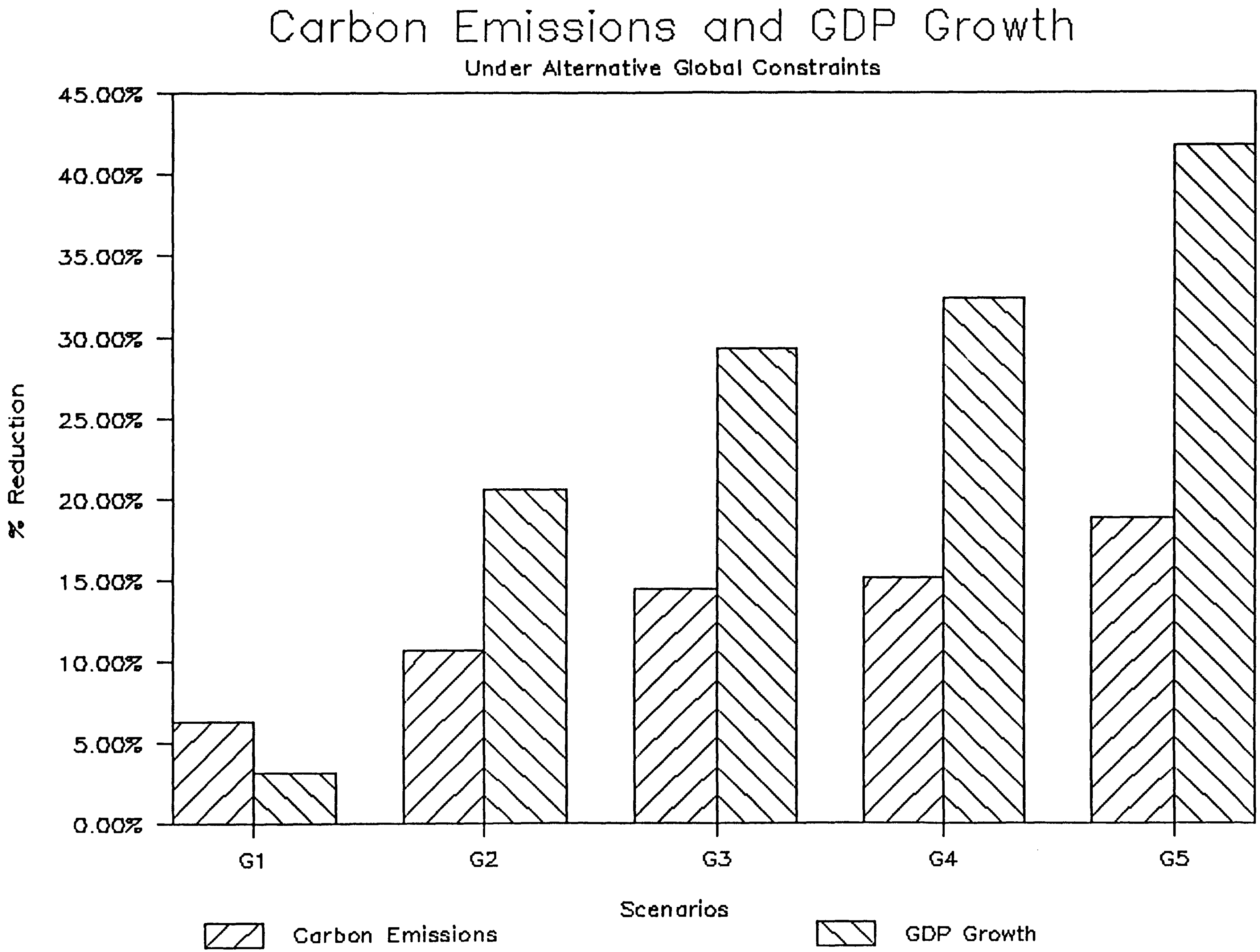

Time Path of GDP
Under Alternative Global Constraints
Millions of 1986/87 LE
(Thousands)
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
1987
1992
1997
2002
Periods
Base
G1
G2
G3
G4
G5

horizon. The effects of the global constraints on emissions are shown in another way in Chart 2. That chart summarizes the results from all of the five solutions. It indicates the percentage reductions in total carbon emissions, summed over the period from 1987 to 2002, versus the reduction in average annual growth rate over that period. The picture may be a little misleading, since, as Chart 1 indicates, the effects are not uniformly distributed over the model's time horizon.

It will be noticed that, overall, there is an indication of an increase in the relative sacrifice in growth required to achieve increases in relative emissions reductions. This, again, is not a surprising result for economists. The difference between the G3 and G4 solution shows the effects of the impact of required relative reductions in emissions in the years beyond 2002. This is shown in Table 3, which also presents elasticities of the changes in growth rates with respect to changes in carbon emissions. It is clear that the elasticities become relatively high and, in particular, are substantially larger in the G2 solution than in the G1 solution, although the carbon emission restrictions in the former are only 5 and 10 per cent higher, in specific years.

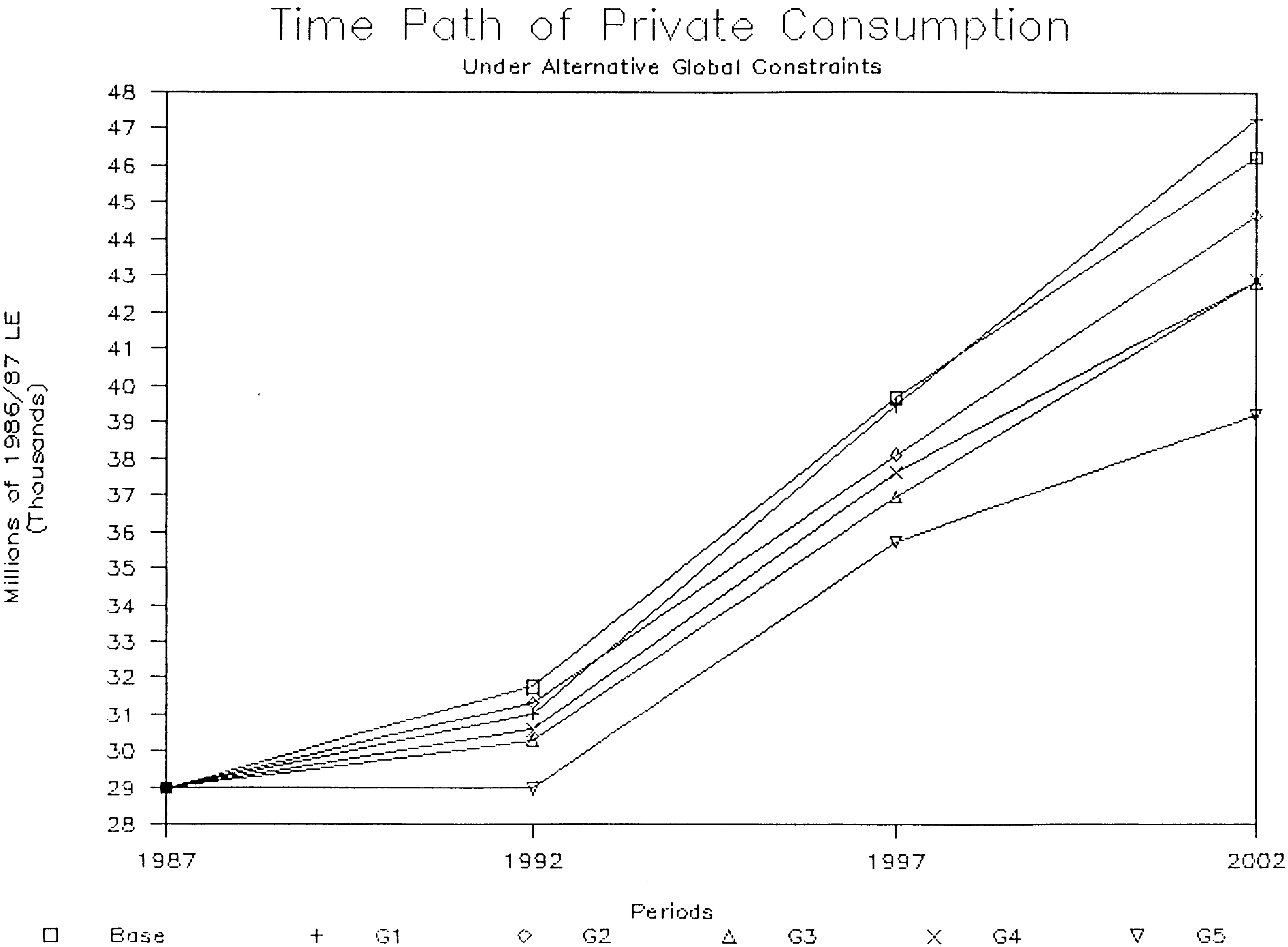
Chart 3 shows the growth paths of total private consumption that are associated with the alternative sets of global emissions constraints. It may be somewhat puzzling that the time path associated with the G1 set of constraints leads to a higher level

CHART 2



Carbon Emissions and GDP Growth
Under Alternative Global Constraints
45.00%
40.00%
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
% Reduction
G1
G2
G3
G4
G5
Scenarios
Carbon Emissions
GDP Growth

CHART 3



Time Path of Private Consumption
Under Alternative Global Constraints
Millions of 1986/87 LE
(Thousands)
48
47
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
31
30
29
28
1987
1992
1997
2002
Periods
Base
G1
G2
G3
G4
G5

of consumption in 2002 than if there were no emissions constraints at all, as represented by the base case. The 1992 levels of consumption in the G1 case, however, are significantly

Table 3

Carbon Emissions versus GDP Growth
Under Global Carbon Constraints
(millions of tons)

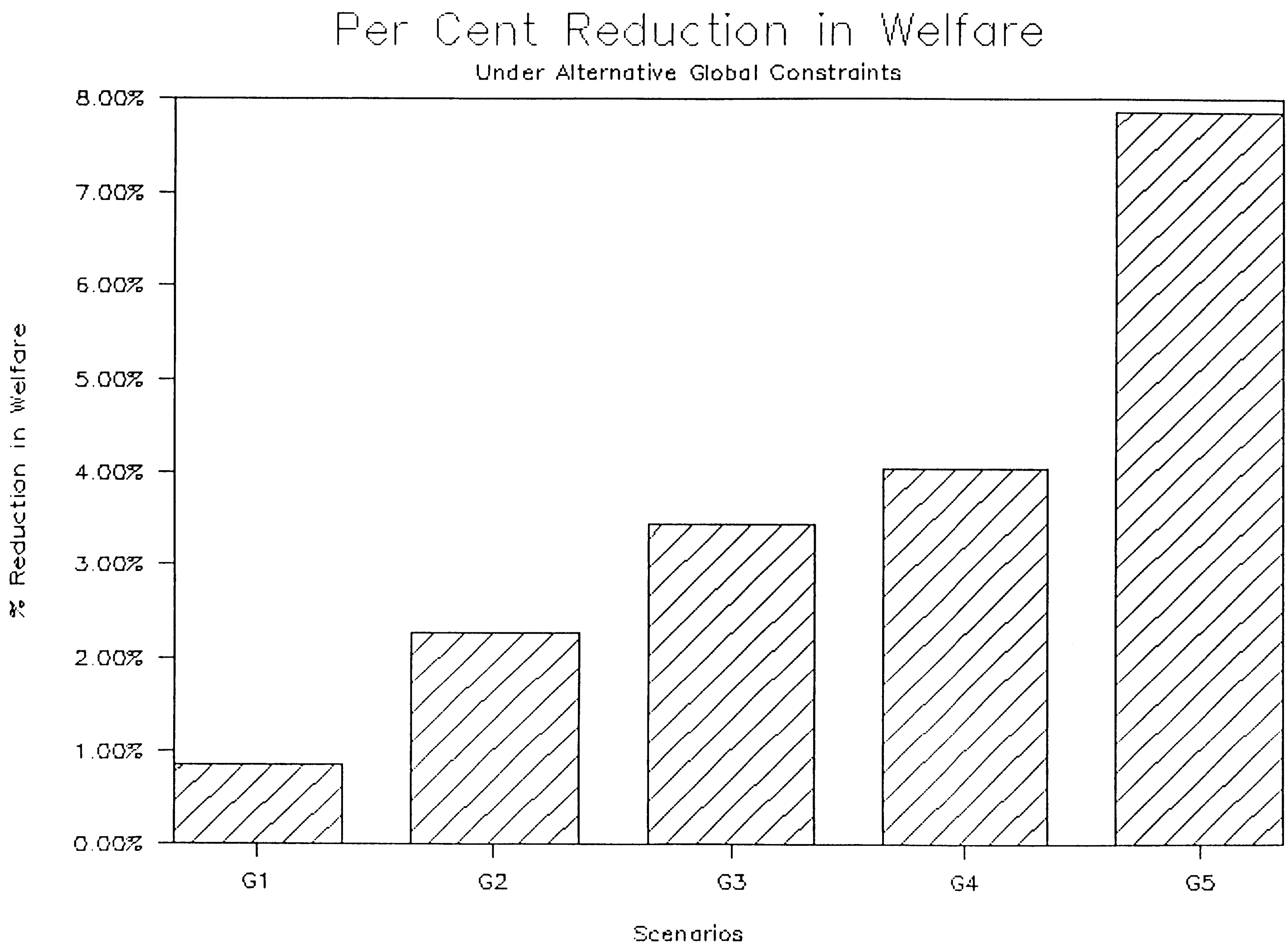
	Base Case	G1	G2	G3	G4	G5
Total Carbon Emissions	75518	70779	67483	64607	64087	61259*
Per cent Change in Carbon		-6.28	-10.64	-14.45	-15.14	-18.88
Agregate GDP Growth	3.51	3.40	2.79	2.48	2.37	2.05
Per cent Change in GDP Growth		-3.15	-20.62	-29.32	-32.44	-41.72
Elasticity		0.502	1.938	2.029	2.143	2.209

* This is a total for the years 1987, 1992, 2002 and, therefore, should only be regarded as an index for all the years in this period of time.

lower than for the base case. In effect, in the G1 case the optimization process found it desirable to depress consumption, relatively, in the near term and increase in later years. The discounted value of the associated utility is, of course, higher in the base case.

Chart 4 displays the relative welfare losses associated with each of the solutions as compared to the base solution without emissions constraints. Welfare is measured in terms of the objective function being maximized. It demonstrates differently the differential economic response to different degrees of restrictiveness. But even the most modest change tested creates almost a 1 per cent loss in welfare, which is not modest in a

CHART 4


Per Cent Reduction in Welfare
Under Alternative Global Constraints
8.00%
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
% Reduction in Welfare
G1
G2
G3
G4
G5
Scenarios

poor country. Unfortunately we cannot know directly the welfare gain from the reduction in emissions.

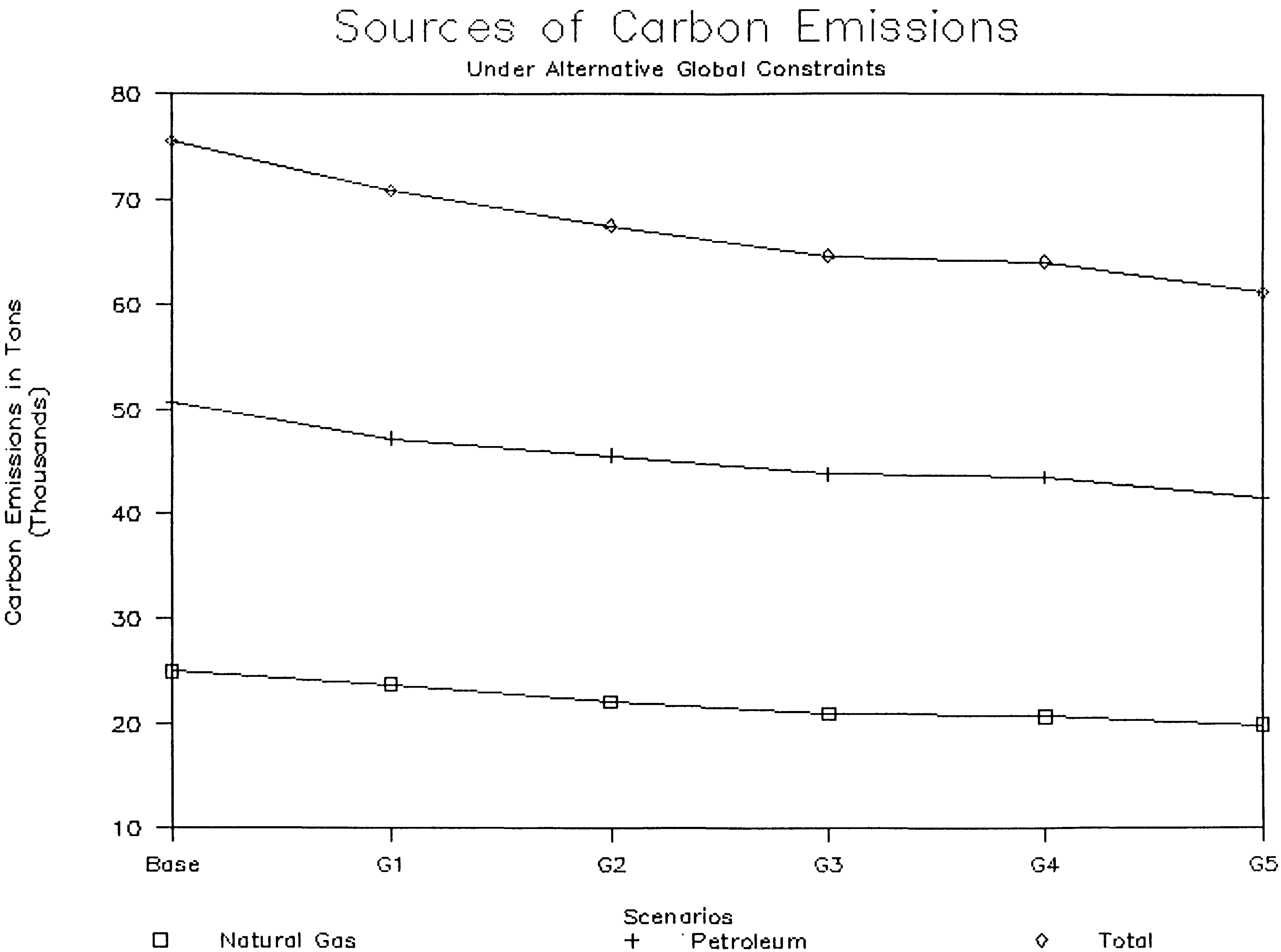
The impact of the emissions restrictions differs substantially across sectors. The optimization process, which simulates profit maximizing behavior by firms, is, of course, quite clever. There is a complete elimination of petroleum refining because that, itself, generates emissions. However, there is an increase in the production and export of crude petroleum, the proceeds of which are used to pay for the import of petroleum products. This provides a way for the economy to "export" its carbon emissions.

In general, there is a substitution of natural gas for petroleum products in both production and consumption. This is reflected in Chart 5, which shows the changes in the relative importance of petroleum products and natural gas as a source of carbon emissions. The changes are modest, however, because of the rather severe limits imposed on substitution in most sectors.

There is also a movement toward the use of more capital intensive processes in all sectors where that is possible. That is one of the sources of the growth slowdown, since the capital intensity of production has to increase.

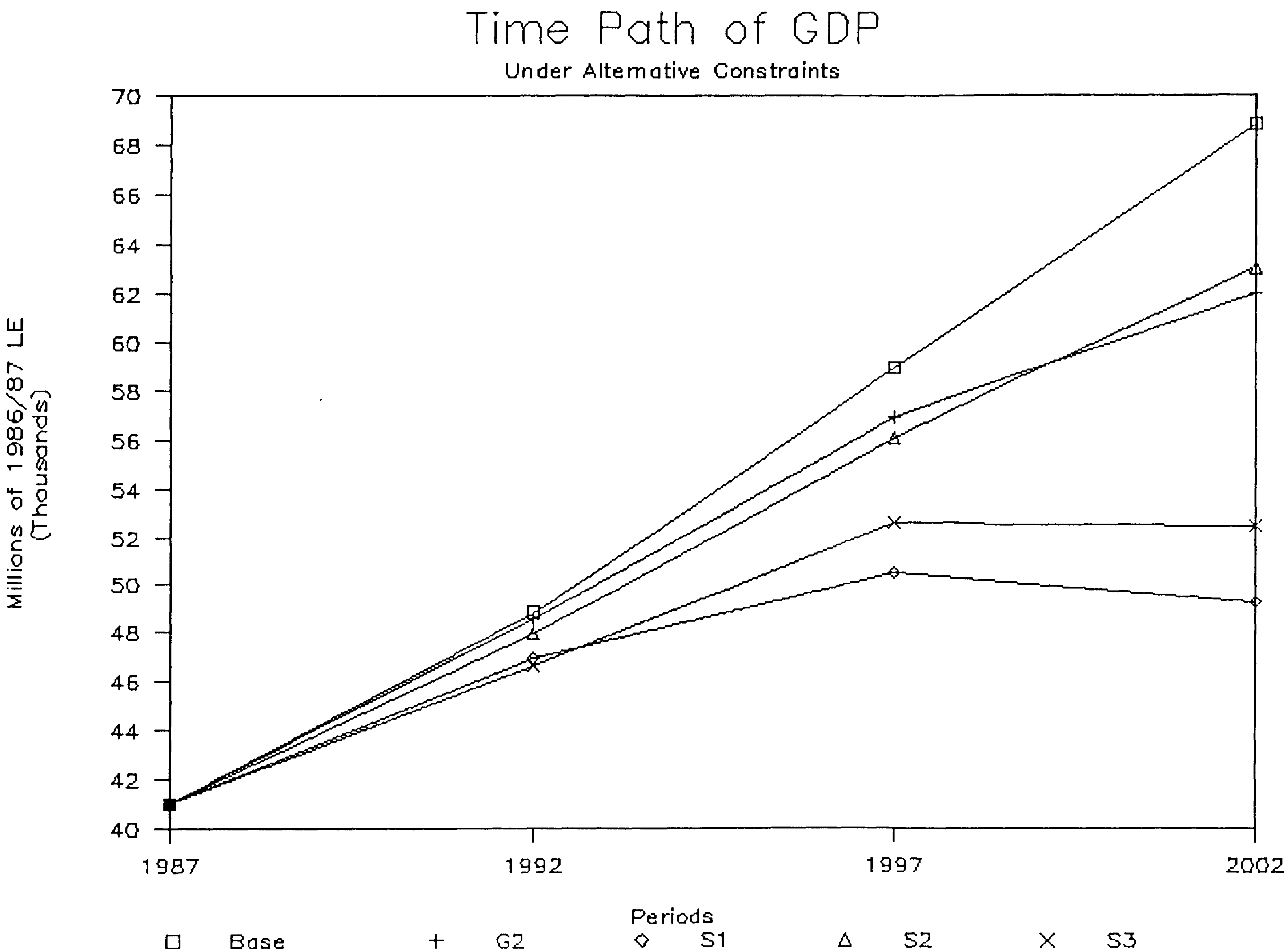
Turning to the analysis of the effects of emissions constraints when they are applied on a sectoral basis, Chart 6 presents the time paths of GDP generated by the solutions to the base case, without emissions constraints, and the solutions with the constraints S1, S2 and S3 as stipulated in Table 2. It is clear that the overall performance is more and more limited as

CHART 5



Sources of Carbon Emissions
Under Alternative Global Constraints
Carbon Emissions in Tons (Thousands)
80
70
60
50
40
30
20
10
Base
G1
G2
G3
G4
G5
Scenarios
Natural Gas
Petroleum
Total

CHART 6


Time Path of GDP
Under Alternative Constraints
Millions of 1986/87 LE
(Thousands)
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
1987
1992
1997
2002
Periods
Base
G2
S1
S2
S3

the constraints become more restrictive. That is the case even though, in the cases of the S2 and S3 constraints, the service sector is not constrained.

Chart 6 also includes the time path of GDP for the solution with the global constraint, G2, with overall percentage reductions exactly the same as the percentage reductions that are applied sector-by-sector in the S1 case. It is clear that application of global constraints, which is sometimes called "bubble regulation", provides the system with more flexibility. That is exploited to generate a significantly better overall level of performance.

The overall results in reducing carbon emissions for the three sets of sectoral constraints are shown in Chart 7. The percent reductions in GDP growth that result from satisfying the required reductions in carbon emissions in the S2 and S3 cases are clearly quite substantial.

Chart 8 shows the time paths of private consumption under the alternative sectoral constraints and Chart 9 shows the welfare losses, again in terms of the specific maximand. The changes in sources of carbon emissions in this set of solutions are shown in Chart 10.

VII. Conclusions

The primary purpose of this paper is methodological: to demonstrate the usefulness of a particular approach to analyzing a central issue of environmental quality, the trade-offs between improving that quality and economic growth. While there may be

CHART 7

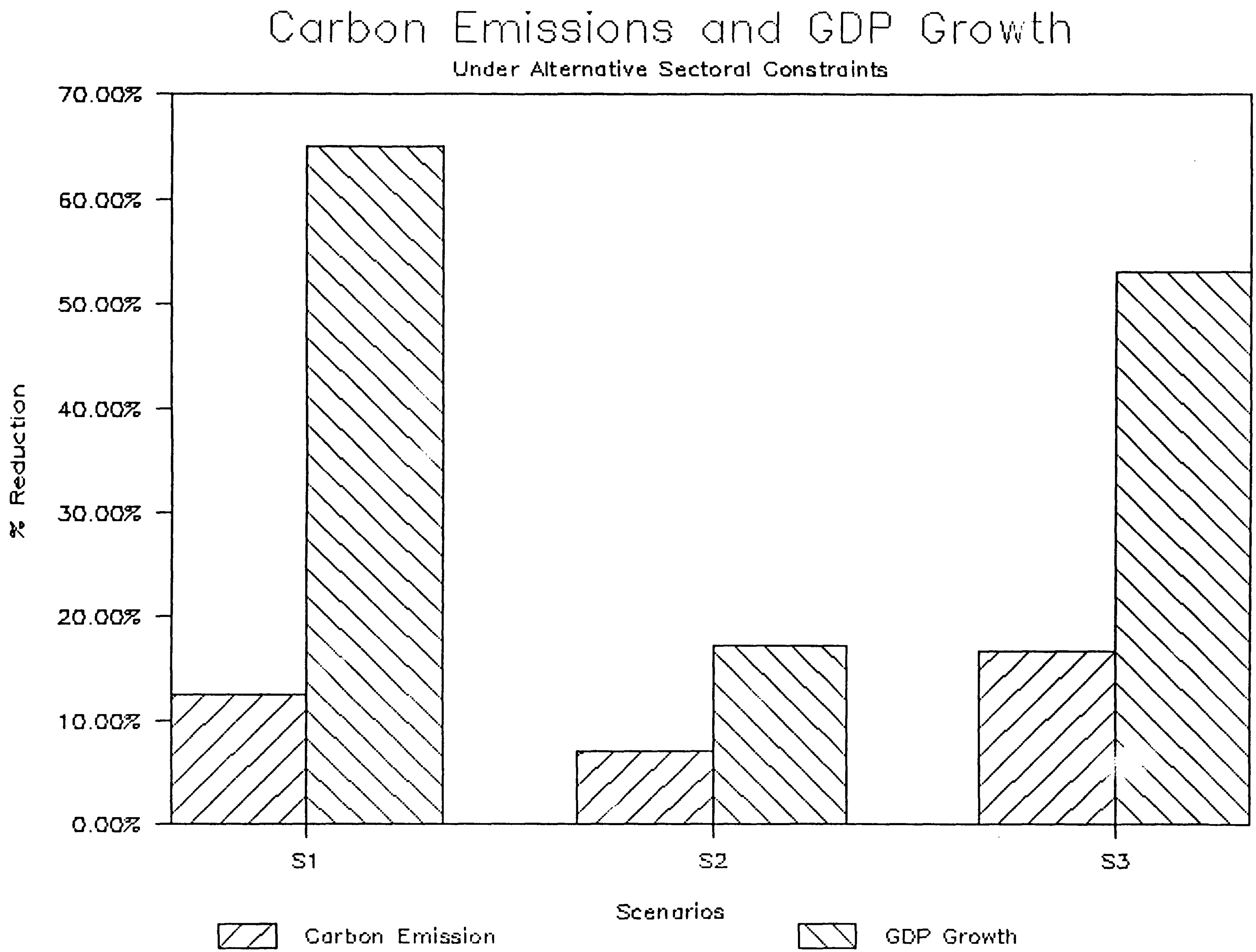
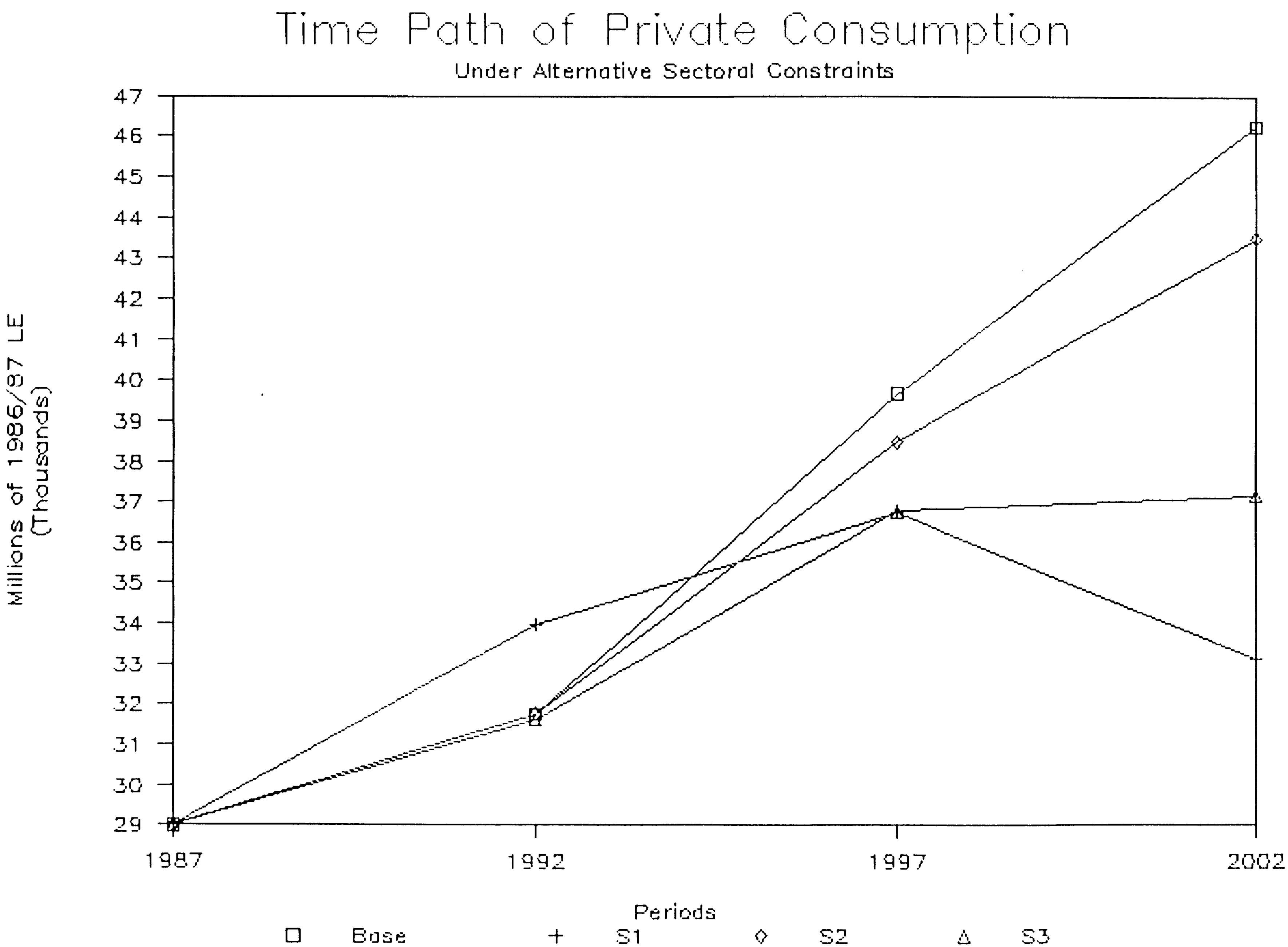
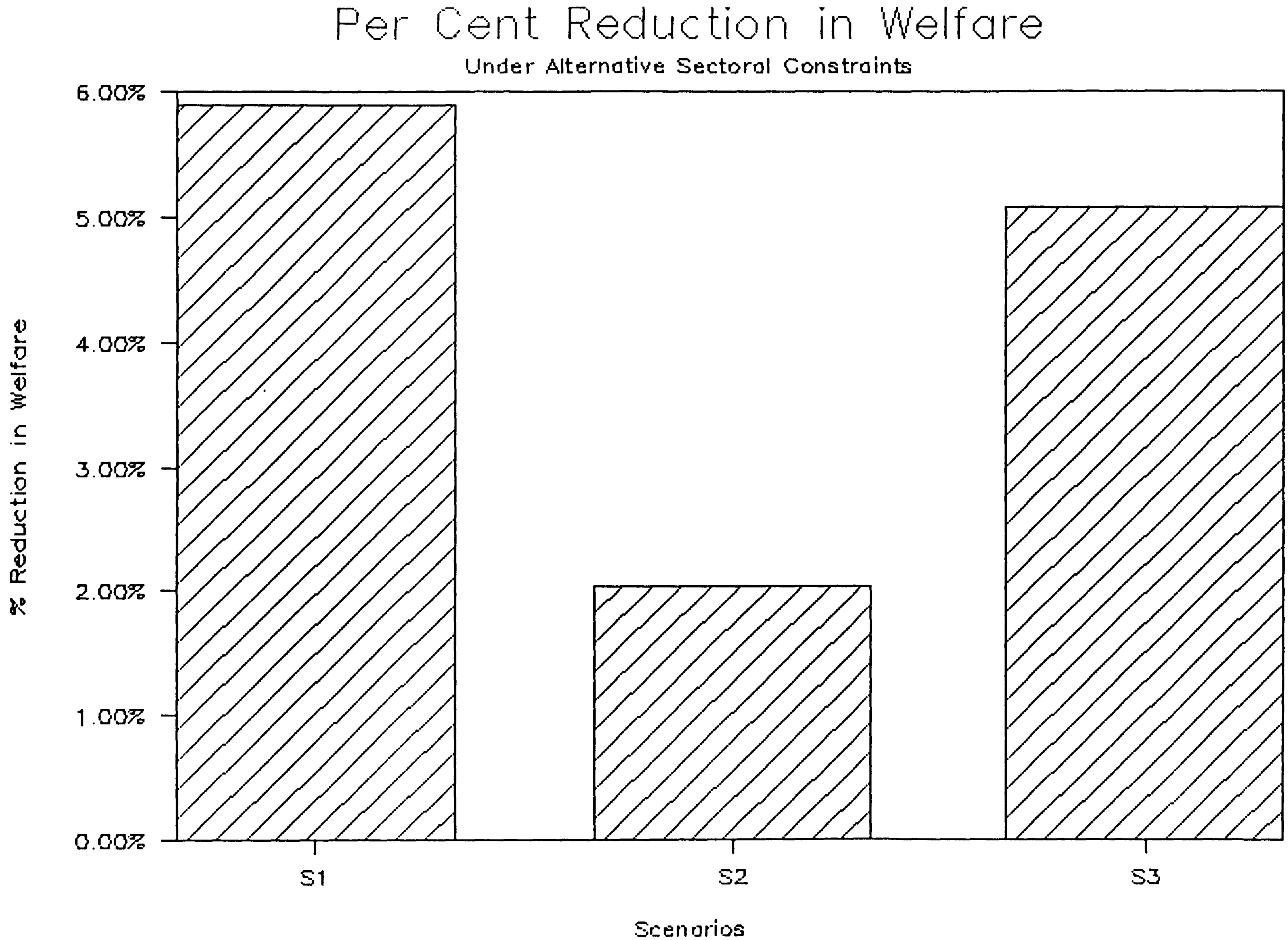

Carbon Emissions and GDP Growth
Under Alternative Sectoral Constraints
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
% Reduction
S1
S2
S3
Scenarios
Carbon Emission
GDP Growth

CHART 8



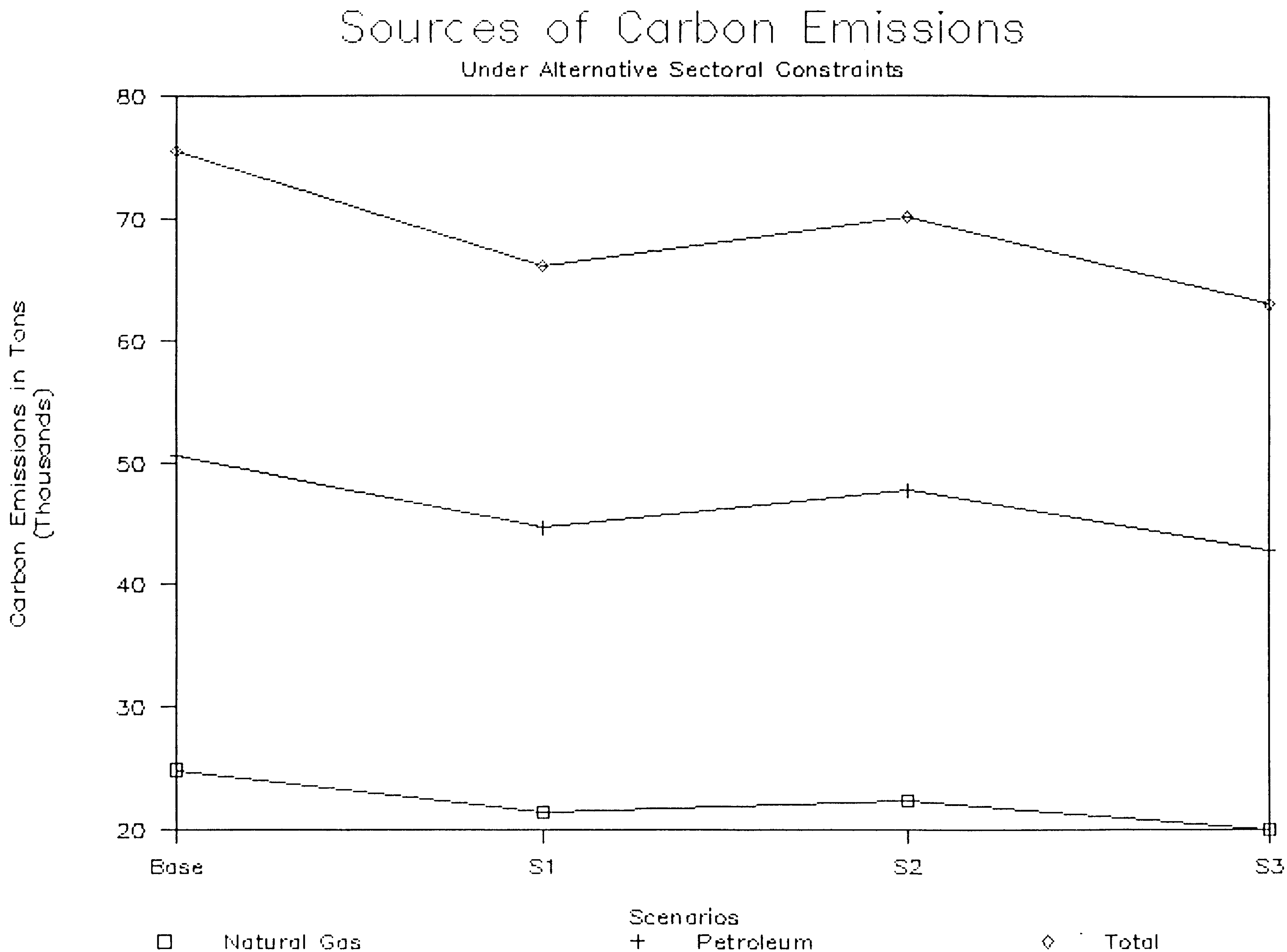
Time Path of Private Consumption
Under Alternative Sectoral Constraints
Millions of 1986/87 LE (Thousands)
47
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
31
30
29
1987
1992
1997
2002
Periods
Base
S1
S2
S3

CHAPT 9



Per Cent Reduction in Welfare
Under Alternative Sectoral Constraints
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
% Reduction in Welfare
S1
S2
S3
Scenarios

CHART 10


Sources of Carbon Emissions
Under Alternative Sectoral Constraints
Carbon Emissions in Tons (Thousands)
80
70
60
50
40
30
20
Base
S1
S2
S3
Scenarios
Natural Gas
Petroleum
Total

objections to the particular substantive results, those do not detract from the methodological point.

The substantive results are, in a general sense, not surprising: When additional binding constraints are added to a maximization problem, the value of the objective function is reduced. However, two specific aspects of these results are so striking that they clearly deserve more substantive research. The first of these is the nonlinearity in the trade-off between reduction in carbon emissions and economic growth. The second is the striking difference in the economic burden imposed by global and sectoral constraints on carbon emissions, with the latter being much more onerous.

APPENDIX

Table 4
Parameters and Exogenous Variables

a_i	Maximum annual rate of depletion of hydrocarbon resource i (oil or natural gas)
$a_{i,j,k}$	Input of good i per unit of production of good j using technology k
$a_{fuel,j,k}$	Input fuel per unit of production of good j using technology k
$a_{gas,j,k}$	Input of natural gas per unit of production of good j using technology k
$a_{pet,j,k}$	Input of petroleum products per unit of production of good j using technology k
$b_{i,j,k}$	Proportion of capital good i in the capital required to produce good i using technology k
$d_{i,k}$	Five-year rate of depreciation of capital for production of good i using technology k
e_i	Maximum rate of increase of exports of good i between two periods
i_t	interest rate of foreign debt in year t
g_i	Minimal post-terminal growth rate for sector i
$f_{i,k}$	capacity conversion factor for capitol producing good i using technology k
$ICOR_{i,k}$	Incremental capital-output ratio for production of good i using technology k
$l_{i,k}$	Demand for labor per unit of production of good i using technology k
$l_{agr,k}$	Demand for labor per unit of agricultural production using technology k
m_i	Maximum rate of fall of imports of good i between two periods
q_i	Conversion factor for hydrocarbon resource i (oil or natural gas)
$s_{j,k}$	Maximum share of natural gas in meeting fuel demand of producing good j using technology k
β_i	Elasticity parameter for consumption good i
γ_i	Intercept parameter for consumption good i
ρ	Utility discount rate between periods
$\overline{B}_t$	Maximum net foreign borrowing in year t
$\overline{G}_{i,t}$	Public consumption of good i in year t
I_{1987}	Aggregate imported in 1987
$\overline{L}_t$	Total supply of labor in year t
$\overline{L}_{agr,t}$	Supply of agricultural labor in year t
$\overline{N}_t$	Population in year t
$\overline{\Delta R}_{i,t+1}$	Discoveries of resource i (oil or natural gas) between year t and year t+1
$\overline{T}_t$	Other foreign exchange transfers in year t
$\overline{FP}_t$	Foreign firms' profit remittances in year t
$\overline{W}_t$	Workers' remittances in year t
$p^e_{i,t}$	world price of exports at good i in year t
$p^m_{i,t}$	world price of imports at good i in year t

$\bar{V}_t$ — Maximum amount of carbon that may be generated in period, t

$\bar{V}_{it}$ — Maximum amount of carbon that may be generated, by sector j, in period, t

$\bar{V}_{ikjt}$ — Maximum amount of carbon that may be generated, by the use of a particular fuel i, using technology k, in sector j, in period, t

Table 5

Endogenous Variables

B_t	Net foreign borrowing in year t
$C_{i,t}$	Private consumption of good i in year t
D_t	Foreign debt in year t
$E_{i,t}$	Exports of good i in year t
$I_{i,t}$	Investment demand for good i in year t
$I_{i,j,k,t}$	Demand for investment good i by sector j, technology k, in year t
$K_{i,k,t}$	Installed capacity in year t to produce good i using technology k
$\Delta K_{i,k,t}$	New capacity to produce good i using technology k,first available in year t
$M_{i,t}$	Imports of good i in year t
$P_{i,t}$	Shadow price of good i in year t
$R_{i,t}$	Reserves of hydrocarbon i (oil or natural gas) in year t
$U(C_t)$	Utility of per capita consumption in year t
W	Total discounted utility; the maximand
$X_{i,t}$	Gross domestic output of good i in year t
$X_{i,k,t}$	Gross output of good i, produced using technology k,in year t
$Z_{i,t}$	Intermediate deliveries of good i in year t
V_{it}	Total amount of carbon generated by the use of a particular fuel, i, in period, t
V_{ijt}	Total amount of carbon generated by the use of a particular fuel, i, in sector j, in period, t
V_{ikjt}	Amount of carbon generated by the use of a fuel, i, using technology k, in sector j, in period, t
V_{ict}	Amount of carbon generated by the use of a particular fuel, i, in consumption in period, t
v_{ikjt}	Quantity of carbon emission <u>per unit</u> use of particular fuel, i, using technology k, in sector j, in period, t
v_{ict}	Quantity of carbon emission per unit use of a fuel, i, in consumption in period, t

MODEL

Accounting Identities

$$X_{i,t} + M_{i,t} = Z_{i,t} + C_{i,t} + \overline{G}_{i,t} + I_{i,t} + E_{i,t} \tag{1}$$

$$X_{i,t} = \sum_{k} X_{i,k,t} \tag{2}$$

$$Z_{i,t} = \sum_{j} \sum_{k} a_{i,j,k} X_{j,k,t} \tag{3}$$

$$\sum_{i} P^{e}_{i,t} E_{i,t} + \overline{W}_t + \overline{T}_t + B_t = \sum_{i} P^{m}_{i,t} M_{i,t} + i_t D_t + \overline{FP}_t \tag{4}$$

Technology and Production Constraints

$$a_{gas,j,k} + a_{pet,j,k} = a_{fuel,j,k} \tag{5}$$

$$a_{gas,j,k} \leq s_{j,k}\, a_{fuel,j,k} \tag{6}$$

$$\sum_{i} \sum_{k} l_{i,k} X_{i,k,t} \leq \overline{L}_t \tag{7}$$

$$\sum_{k} l_{agr,k} X_{agr,k,t} \leq \overline{L}_{agr,t} \tag{8}$$

$$X_{i,k,t} \leq K_{i,k,t} \tag{9}$$

$$q_i X_{i,t} \leq a_i R_{i,t} \tag{10}$$

Balance of Payments and Trade Constraints

$$B_t \leq \overline{B}_t \tag{11}$$

$$M_{i,t} \geq (1-m_i) M_{i,t-1} \tag{12}$$

$$E_{i,t} \leq (1+e_i) E_{i,t-1} \tag{13}$$

Dynamic Linkages

$$K_{i,k,t+1} = K_{i,k,t}(1-d_{i,k}) + f_{i,k}\,\Delta K_{i,k,t} \tag{14}$$

$$R_{i,t+1} = R_{i,t} + \overline{\Delta R}_{i,t+1} - 2.5(X_{i,t+1} + X_{i,t})q_i \tag{15}$$

$$D_{t+1} = D_t + 2.5(B_{t+1} + B_t) \tag{16}$$

Investment Demand

$$I_{i,t} = \sum_j \sum_k I_{i,j,k,t} \tag{17}$$

$$I_{i,j,k,t} = b_{i,j,k}\, ICOR_{j,k}\, \Delta K_{j,k,t+1} \tag{18}$$

$$\sum_i I_{i,1987} \leq \bar{I}_{1987} \tag{19}$$

$$\sum_k K_{i,k,2017} \geq (1+\bar{g}_i) \sum_k K_{i,k,2012} \tag{20}$$

Carbon Emissions

$$V_{ijt} = \sum_k V_{ikjt} \tag{21}$$

$$V_{it} = \sum_j V_{ijt} \tag{22}$$

$$V_{ict} = v_{ict} C_{it} \tag{23}$$

$$V_{kijt} = v_{kijt} X_{kjt} \tag{24}$$

$$V_{ijkt} \leq \bar{V}_{ijkt} \tag{25}$$

$$V_{it} \leq \bar{V}_{it} \tag{26}$$

$$\sum_i (V_{it} + V_{ict}) \leq \bar{V}_t \tag{27}$$

<u>Objective Function</u>

$$W = \sum_t \left(\frac{1}{1+\rho}\right)^t N_t \, U(C_t) \quad (28)$$

$$U(C_t) = \sum_i \beta_i l_n \left(\frac{C_{i,t}}{\bar{N}_t} - \gamma_i\right) \quad (29)$$

1 For a description of the original model see Blitzer, et al, (1989)
2 See, for example, Romer (1986).
3 For a survey of some policy issues see Lave (1988).
4 A. Manne and R.G. Richels (1989)
5 It should be recalled that the purpose in presenting the model is primarily methodological. The omission of coal as a primary energy source would, of course, be quite wrong for most countries, although correct in the case of Egypt.
6 See Blitzer, et al, (1989).
7Central Agency for Public Mobilization and Statistics (CAPMAS).

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