PNL-SA--20471

DE92 010150

USE OF THE EDMONDS-REILLY MODEL TO MODEL ENERGY-SECTOR IMPACTS OF GREENHOUSE GAS EMISSIONS CONTROL STRATEGIES

D.W. BARNS
J.A. EDMONDS
J.M. REILLY

January 1992

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Washington, DC 20024

SUMMARY

The 1991 Energy Modeling Forum (EMF-12) was convened to compare the results of several different energy/economic computer models using, insofar as possible, a common set of standardized assumptions along with a set of scenarios involving greenhouse gas emissions control measures. This paper describes the modification of the Edmonds-Reilly Model (ERM) for that purpose and reports the model results for the various cases.

USE OF THE EDMONDS-REILLY MODEL TO MODEL ENERGY SECTOR IMPACTS OF GREENHOUSE GAS EMISSIONS CONTROL STRATEGIES

I. INTRODUCTION

The purpose of this paper is to document the results of our application of the Edmonds-Reilly Model (ERM) using several scenarios provided in connection with the 1991 Energy Modeling Forum (EMF). The purpose of this session of the forum is to compare the efforts of several modeling teams using common assumptions to examine the energy sector impacts of strategies to control greenhouse gas emissions, Because the output of this exercise is data-rich, most of this exposition is in graphical form with the narrative serving mainly as a roadmap for moving from one highlight to the next. The following sections briefly describe the model and some of the special modifications made for this effort. The case-by-case discussion is contained in Section IV, followed by a summary of the potential pitfalls involved in attempting to assess the cost of emissions reduction from the model data.

II. MODEL DESCRIPTION

For this exercise we have used a specially modified version of the ERM. The ERM is a well documented, frequently used, long-term model of global energy and fossil fuel greenhouse gas emissions. The model consists of four modules: supply, demand, energy balance, and greenhouse gas emissions. The first two modules determine the supply of and demand for each of six major primary energy categories in each of nine global regions. The energy balance module ensures model equilibrium in each global fuel market. (Primary electricity is assumed to be untraded; thus supply and demand balance in each region.) The greenhouse gas emissions module is a set of three post-processors which calculate the energy-related emissions of CO_2, CH_4, and N_2O. The original version of the model is documented in Edmonds and Reilly (1985), while major revisions are discussed in Edmonds et al. (1986).

Energy demand for each of the six major fuel types is developed for each of the nine regions. Five major exogenous inputs determine energy demand: population; labor productivity; exogenous energy end-use intensity; energy prices; and energy taxes, subsidies, and tariffs.

The model calculates base gross national product (GNP) directly as a product of labor force and labor productivity. An estimate of base GNP for each region is used both as a proxy for the overall level of economic activity and as an index of income. The base GNP is, in turn, modified within the model to be consistent with energy-economy interactions. The GNP feedback elasticity is regional, allowing the model to distinguish energy supply dominant regions, such as the Mideast, where energy prices and GNP are positively related, from the rest of the world where the relationship is inverse.

The exogenous end-use energy-intensity improvement parameter is a time-dependent index of energy productivity. It measures the annual rate of growth of energy productivity which would continue independent of such other factors as energy prices and real income changes. In the past, technological progress and other non-price factors have had an important influence on energy use in the manufacturing sector of advanced economies. By including an exogenous end-use energy-intensity improvement parameter, scenarios can be developed that incorporate either continued improvements or technological stagnation assumptions as an integral part of scenarios.

The final major energy factor influencing demand is energy prices. Each region has a unique set of energy prices derived from world prices (determined in the energy balance component of the model) and region-specific taxes and tariffs. The model can be modified to accommodate non-trading regions for any fuel or set of fuels. It is assumed that no trade is carried on between regions in solar, nuclear, or hydroelectric power, but all regions trade fossil fuels.

The energy-demand module performs two functions: 1) it establishes the demand of energy and its services, and 2) it maintains a set of energy flow accounts of each region. Oil and gas are transformed into secondary liquids and gases used either directly in end-use sectors or indirectly as electricity. Hydro, nuclear, and solar electric or fusion are accounted for directly as electricity. Non-electric solar energy is included with conservation technologies as a reduction in the demand for marketed fuels. The four secondary fuels are consumed to produce energy services.

The demand for energy services in each region's end-use sector(s) is determined by the cost of providing these services and by the levels of income and population. The mix of secondary fuels used to provide these services is determined by the relative costs of providing these services using each alternative fuel. The demand of fuels to provide electric power is then determined by the relative costs of production, as is the share of oil and gas transformed from coal and biomass.

Energy supply is disaggregated into two categories, renewable and non-renewable. Energy supply from all fossil fuels is related directly to the resource base by grade, to the cost of production (both technical and environmental), and to the historical production capacity. The introduction of a graded resource base for fossil fuel (and nuclear) supply allows the model to explicitly test the importance of fossil fuel resource constraints as well as to represent fuels such as shale oil, in which only small amounts are likely available at low cost, but for which large amounts are potentially available at high cost.

Note here that nuclear is treated in the same category as fossil fuels. Nuclear power is constrained by a resource base as long as light water reactors are the dominant producers of power. Breeder reactors, by producing more fuel than they consume, are modeled as an essentially unlimited source of fuel that is available at higher cost.

A rate of technological change is also introduced on the supply side. This rate varies by fuel and is expected to be both higher and less certain for emerging technologies.

The supply and demand modules each generate energy supply and demand estimates based on exogenous input assumptions and energy prices. If energy supply and demand match when summed across all trading regions in each group for each fuel, then the global energy system balances. Such a result is unlikely at an arbitrary set of energy prices. The energy balance component of the model is a set of rules for choosing energy prices which, on successive attempts, bring supply and demand nearer a system-wide balance. Successive energy price vectors are chosen until energy markets balance within a prespecified bound.

Given the solution of the energy balance component of the model, greenhouse gas emissions for CO_2, CH_4 and N_2O are calculated by applying emissions coefficients. Emissions coefficients for CO_2 (given in carbon weight emissions) are as follows:

· liquids	19.9 TgC/EJ
· gases	13.7 TgC/EJ
· solids	24.1 TgC/EJ
· carbonate rock mining	27.9 TgC/EJ

Modern biomass is treated as if its carbon absorption occurred in the year of release. This approximation can either under- or over-estimate actual net annual fluxes depending upon whether the underlying stock of biomass is either expanding or contracting.

III. MODEL MODIFICATIONS

To promote a common approach, certain standardized input assumptions were provided for the EMF which required some significant modifications to the model. The first of these had to do with time periods for reporting results. It was desired that reporting commence in 1990, with results given every 5 years through 2010, and then every 10 years through 2100. The standard version of ERM starts in 1975 and uses 25-year intervals through 2100. As a compromise approach, it was decided to change the ERM periodicity to 15 years, commencing in 1975, and to modify parameters as necessary to conform to the specified energy consumption data for 1990. These data were based on Organization for Economic Cooperation and Development (OECD) energy balances. In the recalibration, the number of end-use consumption sectors for developing countries was expanded from one to three. Primary energy prices to clear 1990 markets were production-weighted averages of prices for the previous 15 years.[a]

Geographical regions for reporting purposes were to be 1) the U.S., 2) Other OECD, 3) USSR, 4) China, and 5) the rest of the world (ROW). The ERM provides results for nine regions which were telescoped to five for EMF purposes, except that it should be noted that the ERM groups USSR with Eastern Europe nations and China with other Asian centrally-planned economies. The result is that totals reported to the EMF are inflated by roughly half for the USSR, with a corresponding reduction to the ROW totals; whereas, the effect on China totals is virtually insignificant.

Economic growth was specified in terms of 1990 regional gross domestic product (GDP) totals along with growth rates to be applied. For this effort, GDP was used interchangeably with GNP. Population projections specified had previously been incorporated in the model and no change was required. Oil and natural gas resource base assumptions were incorporated, resulting in somewhat less oil and somewhat more gas than had previously been provided in the ERM.

The goal of the modifications was to have the model's 1990 projections coincide as nearly as possible with energy data derived from OECD Energy balances. The specific target was secondary energy, both by source and by consuming sector. The result is shown below:

[a] The use of average prices for the 15 years prior to 1990 is necessary to reflect the fact that energy demands in the year 1990 reflect both 1990 prices and the much higher prices that existed prior to that date. In fact, throughout the prior 15 years energy prices were higher than in 1990, with the peak in world oil prices occurring in 1981.

Variable	EMF-12 Target	ERM Result
Primary Energy		
Oil	134.18	136.66
Gas	72.89	71.56
Coal	96.43	94.36
Biomass	0.00	4.02
Hydro	22.20	23.90
Other	18.86	21.73
Total	344.56	352.23
Secondary Energy		
Liquids	112.23	113.83
Solids	42.28	42.77
Gases	43.98	42.07
Electric	36.04	44.21
Heat	7.97	0.00
Total	242.50	242.88
Final Consumption		
Industry	102.78	124.77
Transport	61.61	59.88
Residential/Commercial	58.42	58.24
Other	15.05	0.00
Total	237.86	242.89
Carbon Emissions	6003	5767

Note that the ERM has no provision for handling "Heat", so that quantity was combined with electricity. Also, the final consumption category listed as "Other" was reassigned, mainly to the industrial sector.

IV. DISCUSSION OF RESULTS

As a vehicle to explore greenhouse emissions control strategies, some fourteen scenarios were to be modeled, along with a few variations within the scenarios. These are discussed in the following sections in the order given, starting with the reference case.

Case 0-Unconstrained Emissions. This is simply the baseline run with no control measures applied. Figure 1 shows the resulting primary energy consumption by source. It will be seen that oil consumption is essentially level through the first third of the next century, then diminishes gradually, approaching depletion near the end of the century. Natural gas use nearly triples, then falls off sharply approaching depletion by the end of the century. Coal progressively dominates the economy accounting for 63% of the total in the final period. Some growth in nuclear and renewable sources is seen approaching a third of the total. What is not apparent in the figure is that an increasing share of solids is converted to synthetic fuels, approaching 60% of the total by 2095, corresponding to 313 Ej of SynOil and 58 Ej of SynGas at that point. Figure 2 shows this same primary energy total by consuming region. Here the developed regions show only modest growth while the developing regions exhibit dramatic growth, their share increasing from 24% in 1990 to 63% in 2095.

Figure 3 displays the consumption of secondary energy by source, showing a nearly five-fold growth in electricity, reflecting not only market preference but also the increase in nuclear, solar, and hydro sources. Solids and liquids both grow significantly, while gases drop off as the period closes. One must recall that the majority of liquids and gases are from synthetic origin by this time. Figure 4 shows secondary consumption by sector, each one growing by a factor of about 2-1/2 to 3 times.

Carbon emissions from the combustion of fossil fuel are given in Figure 5 which closely parallels regional primary consumption as shown in Figure 2, expanding almost 4 times in the period of interest.

Case I-20% Reduction. In this scenario the intention is to apply carbon taxes as necessary to force developed regions to reduce carbon emissions from 1990 levels by 20% by the year 2010, while limiting developing regions to no more than 50% growth, as shown in Figure 6. The net result is that global totals are effectively stabilized at 1990 levels. The impact on primary energy consumption is shown in Figure 7, with coal substantially constricted, growing only as it becomes a source for synfuels with 80% converted by 2095. Gas use is similarly diminished, thereby forestalling depletion within the time under consideration. Oil use is less affected because of the relatively inflexible demand for transportation. Nuclear and renewable consumption increases to a nearly three-quarters share of the total.

Tax rates imposed to effect this reduction are given in Figure 8. Here, the developing regions although held to a less stringent limitation, are at a disadvantage because of the tremendous growth in demands which requires larger taxes to suppress. For a variety of reasons, the U.S. also is more difficult to control. These include the relatively high demand share of energy for transportation and proportion of coal initially used in the overall total.

Case II-20% Reduction, followed by a 50% Reduction. This is a follow-on to Case I with a further reduction by 50% from 1990 levels by 2050 in the developed countries. Developing countries remain limited to 50% growth. Figure 9 shows this result, with a net effect of an overall reduction to 77% of 1990 levels. Figure 10 portrays the primary energy consumption, with demand suppressed very slightly from Case I (Figure 7), but with nuclear and renewables assuming a 79% share of the total. Tax rates required are as shown in Figure 11, where it is seen that the U.S. has an even more difficult time attaining the goals as indicated by tax rates more than double any other region.

Case III-Stabilization of Emissions. Here the requirement for the developed regions is to limit emissions to 1990 levels by the year 2000; developing regions, as before. As seen in Figure 12, the net effect is to allow total emissions to grow to about 115% of 1990. Primary energy shares are similar to those previously shown, except that nuclear and renewables ultimately assume only 62% of the total (see Figure 13). Carbon tax rates are as shown in Figure 14. The implication here is that it is relatively much easier for the U.S. to stabilize than to reduce emissions.

Case IV-Accelerated Technology. This is a 20% reduction case similar to Case I, except that a non-carbon backstop fuel becomes available at a price equivalent to $50/bbl, along with an electric backstop at a price of 50 mills/kWh. Using the ERM, this scenario was simulated by providing an unlimited resource of traditional biomass to each region at the given equivalent price, and assigning the electric backstop price to the solar source. Unfortunately for this case, the ERM combines biomass with coal before it gets to the secondary fuel level, thereby limiting the flexibility in handling the biomass as a backstop, and imposing some artificialities on the solution. Nonetheless, this non-electric source, as seen in Figure 15, takes over nearly 15% of the market by 2095. Of more significance is the response to the electric backstop source which captures 46% of the market by the final period with taxes imposed. Also, note that total *demand is suppressed very little from the unconstrained case, even though emissions are* reduced. Tax rates are as shown in Figure 16, where it is seen that the burden of reducing emissions is significantly lighter for all regions. (Carbon emissions in this and all following 20% reduction/50% growth scenarios are as shown in Figure 6.)

Case V-Emissions Trading. This scenario calls for reducing carbon emissions by 20% through some scheme of trading emissions permits. For the approach taken in this case, we imposed a global goal of 20% reduction in emissions which makes this more stringent than the limitations in Case I. First, in order to establish the price of emissions permits, a uniform global tax was imposed to achieve the aggregate reduction of 20%. These rates are as shown in Figure 17. Next, to establish the marginal cost of reduction in each region another run was made imposing discrete rates on each region to force that region to reduce emissions by 20%. The result is shown in Figure 18 with the previously determined permit price overlaid. Presumably, those regions whose marginal cost of emissions reduction is less than the permit price could reduce emissions by other unspecified, but lower cost means. They could then sell emissions permits at the trading price to regions whose marginal cost is higher than the trading price. Resulting emissions would tend to approach those shown in Figure 19 in the limit.

Case VI-Phased-in Worldwide Carbon Tax. For this case a specified uniform tax was imposed on all regions starting at $15/tonne carbon in 1990, peaking at $1000/tonne, as shown in Figure 20. Since these are the most severe taxes applied so far, the resulting reduction in emissions is the greatest as shown in Figure 21 where the 2080 total is 40% of 1990 levels; then, because the tax has leveled out, begins to grow again. This reduction is achieved by the largest demand suppression so far (see Figure 22), coupled with nuclear and renewable sources capturing 86% of the market. Nearly all coal is converted to synfuels in 2080.

Case VII-GHG Reduction 1. Rather than simply controlling carbon emissions from fossil fuel combustion, here the control is aimed at the total warming effect of all process emissions. This poses some special problems, since it is difficult to establish tax rates that fairly relate consumption to any sort of global warming potential (GWP) measure. Whereas, it can reasonably be assumed that nearly all contained carbon will be emitted during consumption, only a very small amount of the methane in natural gas will be emitted from its use, including the steps leading up to consumption. Moreover, this fraction is a function of the technology level involved and is presently poorly estimated. Similar pitfalls attend the estimation of other energy-related GWP calculations. Notwithstanding these problems, simple carbon taxes were applied in order to control selected GWP totals. The ERM calculates emissions of CH_4 (including natural gas leakage, coal mine emissions, landfill losses, etc.), as well as N_2O emissions from combustion processes, although the emissions coefficient for the latter are presently little better than place holders. To these emissions totals the specified 100-yr GWP factors were applied giving the profile shown in Figure 23. Taxes as depicted in Figure 24 were imposed to effect a 20% reduction in developed regions while limiting developing regions to 50% growth.

Case VIII-GHG Reduction 2. For comparison, the taxes from Case I were applied to see the resulting GWP reduction. As shown in Figure 25, the difference from Case VII is almost imperceptible. The reasons for this are: (1) carbon dioxide dominates the total, (2) methane emissions are very roughly proportional to CO_2 emissions, and (3) N_2O emissions are an insignificant portion of the total. Interestingly, the taxes for Case VII are somewhat more favorable to the U.S., and slightly less favorable to the USSR than Case VIII (see Figure 26). This is likely due in part to the greater use of coal and natural gas as a percent of the total in the USSR.

Primary energy consumption profiles for both cases are virtually identical to Case I.

Case IX-2% Per Year Growth Reduction. This was interpreted to require the calculation for each region from the unconstrained emissions case an average annual growth rate for each 15-year period. From the average annual rate, two percentage points was subtracted, resulting in many cases in negative growth. These revised growth rates were then recompounded for each region and each 15-year period to derive the allowable emissions as shown in Figure 27. The effect on individual regions, because it hinges on the unconstrained trajectory, is obviously different among the regions. Global totals are reduced to 50% of 1990 levels, but the U.S. must reduce to 25%, while China is permitted to grow to 166%. Required tax rates are shown in Figure 28. The U.S., resistant in any case to tax-initiated reductions, is particularly penalized under this scheme.

Case X-Quadrupled Gas Resource. In this scenario, it is intended to examine the effect of greatly increasing the resource base for natural gas on the difficulty of controlling carbon emissions. Presumably, there should be a greater shift to gas with its lower emissions coefficient. As implemented for the ERM, each region was augmented in proportion to its existing resource of lower-grade gas. This has the effect of slightly reducing the slope of the right side of the supply curve so that the effective price reduction is relatively smaller and does not come into play until higher grades are exhausted. From Figure 29 it can be seen that, in the unconstrained case, there no effect from this increase of lower-grade gas until after 2020, and after that point, gas use increases only gradually until after 2065, where depletion would start to be felt in the reference case. Taxing to reduce emissions, as set forth in Case I, serves to attenuate this effect further, because the reduction in energy demand delays the time when the lower-grade gas starts to be produced and moves depletion out of the picture as is also seen in Figure 29. The taxes required to effect the reduction (see Figure 30) are very similar to Case I, but tend to favor ROW (which includes the Middle East), slightly penalizing the U.S. and China, while remaining neutral to the other two regions.

Case XI-Low U.S. Economic Growth. This case is focused on the U.S. only, imposing significantly reduced rates of growth on the national economy, as shown in Figure 31. To see the effect on energy demand, let us look first at the U.S. share from Case 0 (unconstrained, high growth) as shown in Figure 32. Like the world picture, it is dominated by coal in the later years while oil and gas fall away. With stunted economic growth alone, energy demand is reduced overtime through gains in end-use efficiency as shown in Figure 33. Because of the lack of demand there is little or no growth in nuclear and renewables. Carbon emissions are actually reduced because of the reduced demand, in spite of the upward pressure from increased coal use (see Figure 34). However, in order to effect a 20% reduction as early as 2010, it is necessary to impose some level of taxation, which is compared in Figure 35 with taxes from the high growth case. Figure 36 shows the resulting energy profile with constricted coal supply which never fully recovers, even after taxes are removed.

Case XII-Level U.S. Oil Price. This case calling for maintaining a level oil price in the U.S., was to be run for the U.S. only. However, since the ERM is a partial equilibrium world model, the run could only be made by overriding the equilibrium process for U.S. oil demand. The result is that the rest of the world subsidizes U.S. oil consumption, which is a significant artificiality. Nonetheless, the result is shown in Figure 37, with substantially greater oil consumption over the reference case. The only downward force is from improved end-use efficiency over time. Note also that the increased affluence from the quasi-subsidy stimulates greater overall energy demand. Resulting carbon emissions are shown in Figure 34.

Case XIIIA-Least Cost Combination. Demonstration of least cost, as required by the scenario, is problematic. Rather, this set of runs represents a combination of emissions reduction techniques, which is at least arguably feasible. It consists of imposing improved transportation end-use efficiency improvement roughly equivalent to 55 mpg by 2020, and 80 mpg by 2060 worldwide, along with a step increase in coal-fired electrical generation efficiency to 45% in 2020. To achieve the remaining emissions reduction to the Case I scenario, a uniform carbon tax is applied. Thirty years should be adequate for transportation stocks to turn over and the new technology incorporated as it becomes available; however, attainment of the generation efficiency within that time would likely require some extraordinary investment which is not addressed here. The most nearly comparable case is seen in the uniform tax applied in Case V; Figure 38 compares these tax levels for the two cases.

Case XIIIB-Revenue Recycling. Not attempted.

Case XIIIC-Within U.S. Emissions Trading. Not attempted.

Case XIIID-Sensitivity to Selected Parameters. The purpose of this set of runs was to examine the effect on emissions of variations in autonomous end-use efficiency improvement (AEEI) and elasticity of substitution parameters.

AEEI. In the ERM, energy-use efficiency improvement is taken up in one variable, TKL, which is annual rate of improvement. Previous sensitivity studies with the model have shown this to be one of the most powerful of the parameters affecting demand. It is compounded over the time interval of iteration and serves to reduce the demand for secondary energy. It is normally set at 1% in the ERM. For this study, the value was varied from 0% to 2%. Figure 39 and Figure 40 show the resulting effect on primary energy demand from these two extreme values. No improvement nearly triples demand by 2095, resulting in the exhaustion of conventional oil and gas resources. The 2% rate, on the other hand, keeps demand level at about the 1990 total. Figure 41 gives the results of a third run where TKL is set at 0.5%, which it is understood is the value of AEEI used in the Global 2100 model. Note that demand is increased over the reference case by about 60% by the end of the period. Figure 42 shows the resulting emissions, which are similar to the fossil fuel envelope of the demand curves, but which are increasing at a greater rate because of the progressively increasing share of coal.

Elasticity of Substitution. End-use elasticity in the ERM is controlled by the variable RPJ which is normally set at -3.0. For this study, the value was varied between -1.0 and -7.0, with the effects on primary energy consumption shown in Figure 43 and Figure 44. With the higher (more negative) value, the bias towards least cost is increased, resulting in greater direct use of fuels rather than conversion to synfuels and electricity. In this case for the final period, 1210 Ej of primary energy is consumed as 905 Ej of secondary energy (of which 82 Ej is electrical), with the balance of 305 being lost in conversion to electricity and synfuels. For the lower value of elasticity, 1384 Ej of primary energy provides 642 Ej of secondary energy (of which 219 Ej is electrical) with the balance of 742 Ej being lost in conversion. Carbon emissions for both cases, as shown in Figure 42, are nearly equal, although the high elasticity case is slightly higher for most of the time. This is because the total amount of fossil fuel is nearly the same in both cases, and the difference in total emissions is determined by the relative shares of the three fuels.

Elasticity of substitution for electric utilities is controlled by the variable RUI which is normally set at -3.0. Runs were made setting this variable to -1.0 and -6.0, giving primary energy profiles as shown in Figures 45 and 46. In both cases, secondary energy is nearly equal. For the higher elasticity case, utilities have a greater preference for lower cost and consistently use more coal. Because electricity costs less, it constitutes a somewhat larger share of secondary energy, so primary energy use increases because of the greater conversion losses as seen in Figure 46 where consumption slightly exceeds the reference case. In Figure 45, primary consumption is less than the reference. Although not clear from Figure 42, emissions for the high elasticity case consistently exceed the low case by about 5% to 10%.

V. COST OF EMISSIONS REDUCTION

The discussion of the total cost of emissions reduction has not heretofore been addressed in this paper. The EMF reporting instructions call for GNP reductions resulting from the various control measures, and these have been provided separately. However, we feel that where major restrictions are imposed, the ERM-calculated GNP reduction is probably not a true measure of the economic scarcity costs involved. In Edmonds and Barns (1990), which was also based on ERM modeling results, we concluded that simply examining the change in GNP was unlikely to provide a useful measure of the total cost of emissions reductions. The reason for this is that the change in GNP is determined by the change in the cost of energy services and a single elasticity parameter. This value of the GNP feedback elasticity is, in general, small. It is, therefore, not a matter of great concern in determining the total rate of carbon emissions or energy production and consumption. As a measure of cost, a more sensitive measure is needed. In Edmonds and Barns (1990) we measured cost as the integral of the marginal cost schedule derived by systematically varying the tax rate. The integral over marginal cost approach to estimating the total cost of emissions reductions can be shown to be equal to the loss in GNP under appropriate conditions. The integral over marginal cost measure reflects more accurately information in the model relevant to the production and use of energy. The quantitative differences between using the integral over marginal cost approach and the GNP feedback approach are sufficient. Economic losses based on a GNP elasticity are as much as a factor of 4 greater than costs derived as an integral over marginal cost.

Using the ERM as presently configured, running with increasing tax rates applied to all regions yields the marginal cost curves in Figure 47. Integration using a simple trapezoidal rule method gives total costs shown in Figure 48. Shown in terms of percent reduction, the total costs become closely grouped and nearly linear as seen in Figure 49. By contrast, the GNP reduction calculated by the ERM for this same set of runs looks like Figure 50. It is seen that for the year 2005 the GNP loss and the total costs are about the same, but in later periods, the GNP loss grows, compared to the total costs, until in the last period it is larger by four-fold. As an experiment, the same set of runs was repeated with the value of the GNP feedback elasticity cut by a factor of 4 which yielded GNP losses as shown in Figure 51. Here, the latest year line is close to the total cost, but the earliest is low by a factor of 4. It would be tempting but not intellectually satisfying to pick some middle value of feedback elasticity which would minimize the apparent distortions. A much better approach, we feel, would be to compute total costs for each scenario; however, this requires several iterations per scenario which is beyond the scope of this effort. For the present, we can only say that for extreme conditions, the GNP reduction figures reported by the model likely overstate the cost of emissions reduction by a significant amount.

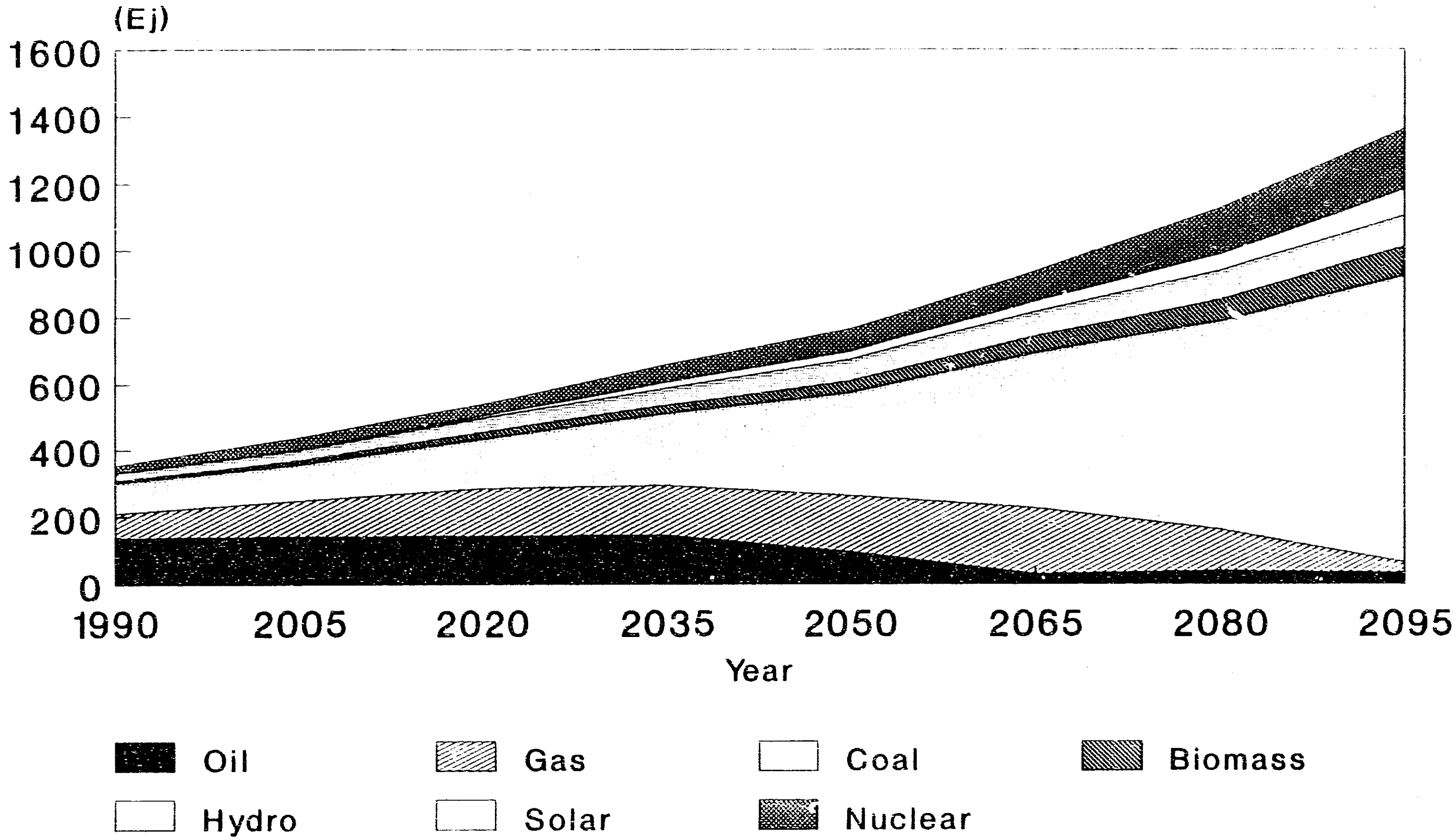
VI. REFERENCES

Edmonds, J.A. and D.W. Barns. 1990. ***Estimating the Marginal Cost of Reducing Global Fossil Fuel CO_2 Emissions***. PNL-SA-18361, Pacific Northwest Laboratory, Washington, D.C.

Edmonds, J.A. and J.M. Reilly. 1985. ***Global Energy: Assessing the Future***. Oxford University Press, New York.

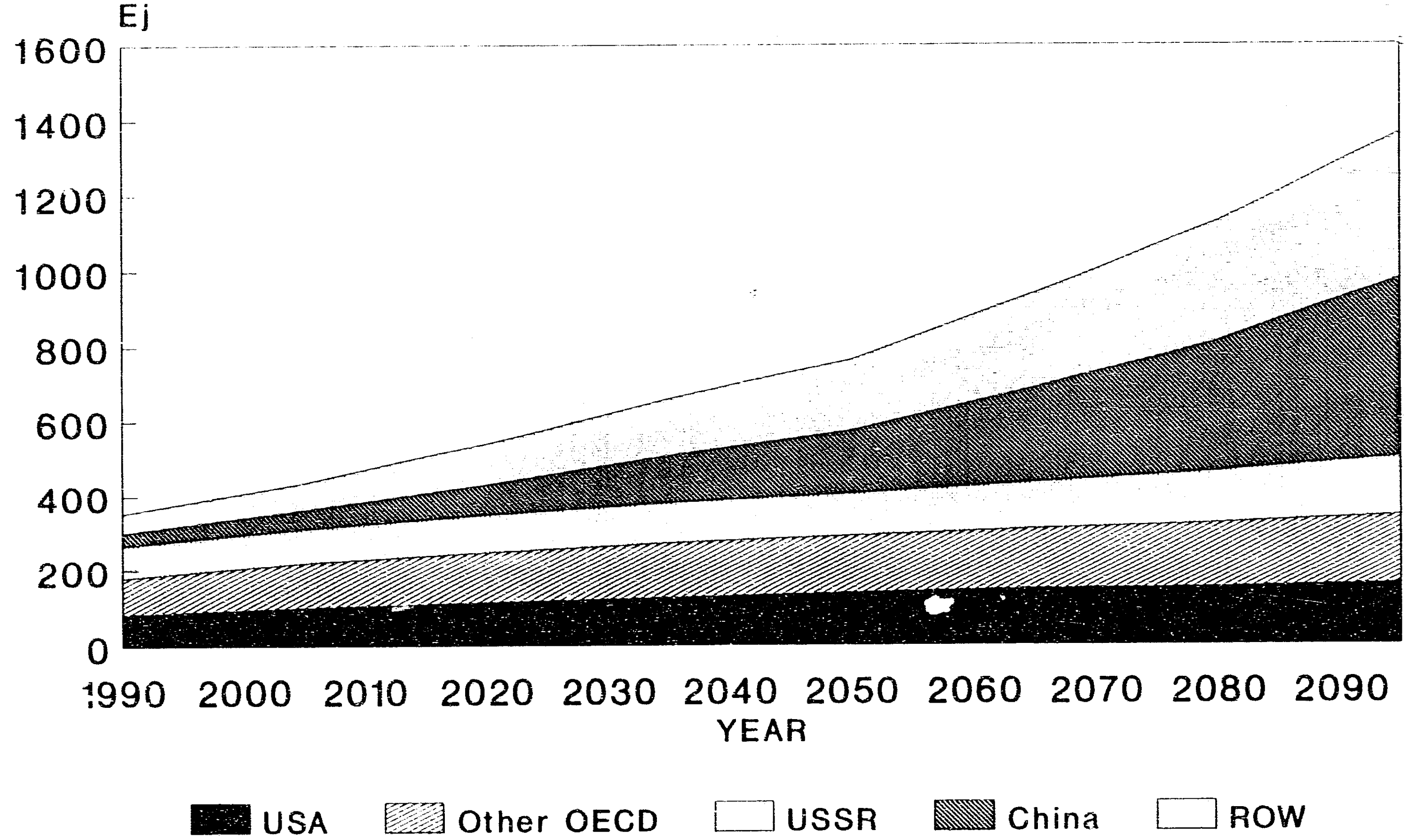
Edmonds, J.A., J.M. Reilly, R.H. Gardner, and A. Brenkert. 1986. ***Uncertainty in Future Global Energy Use and Fossil Fuel CO_2 Emissions 1975 to 2075***. TR036, DO3/NBB-0081 Dist. Category UC-11, National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia.

Figure 1. Case 0-Unconstrained Primary Energy Consumption by Source



EMF-12

Figure 2. Case 0-Unconstrained
Primary Energy Demand
by Region



EMF-12

Figure 3. Case 0-Unconstrained Secondary Energy Demand Fuel Shares

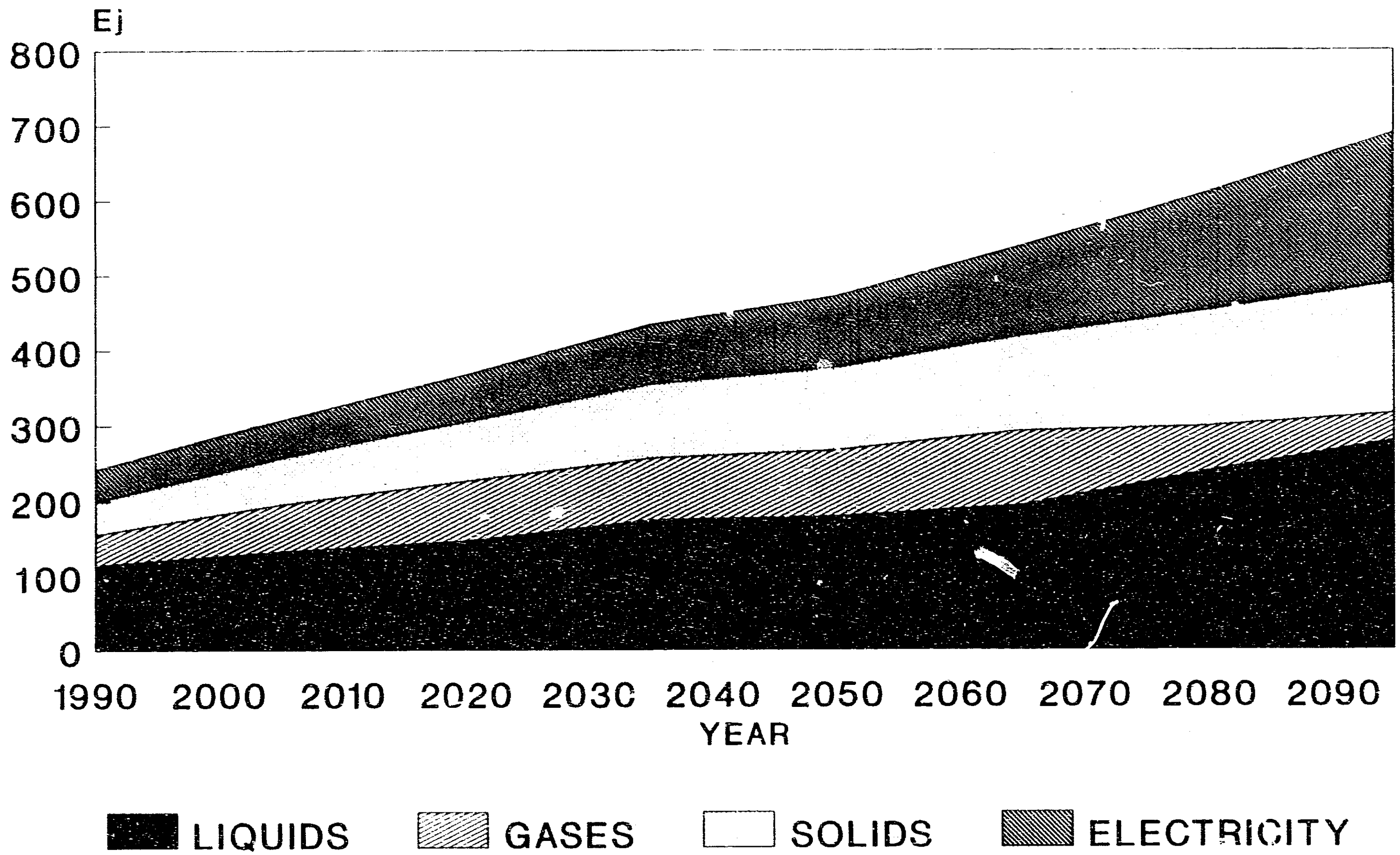


Figure 4. Case 0-Unconstrained
Secondary Energy Demand
Economic Sectors

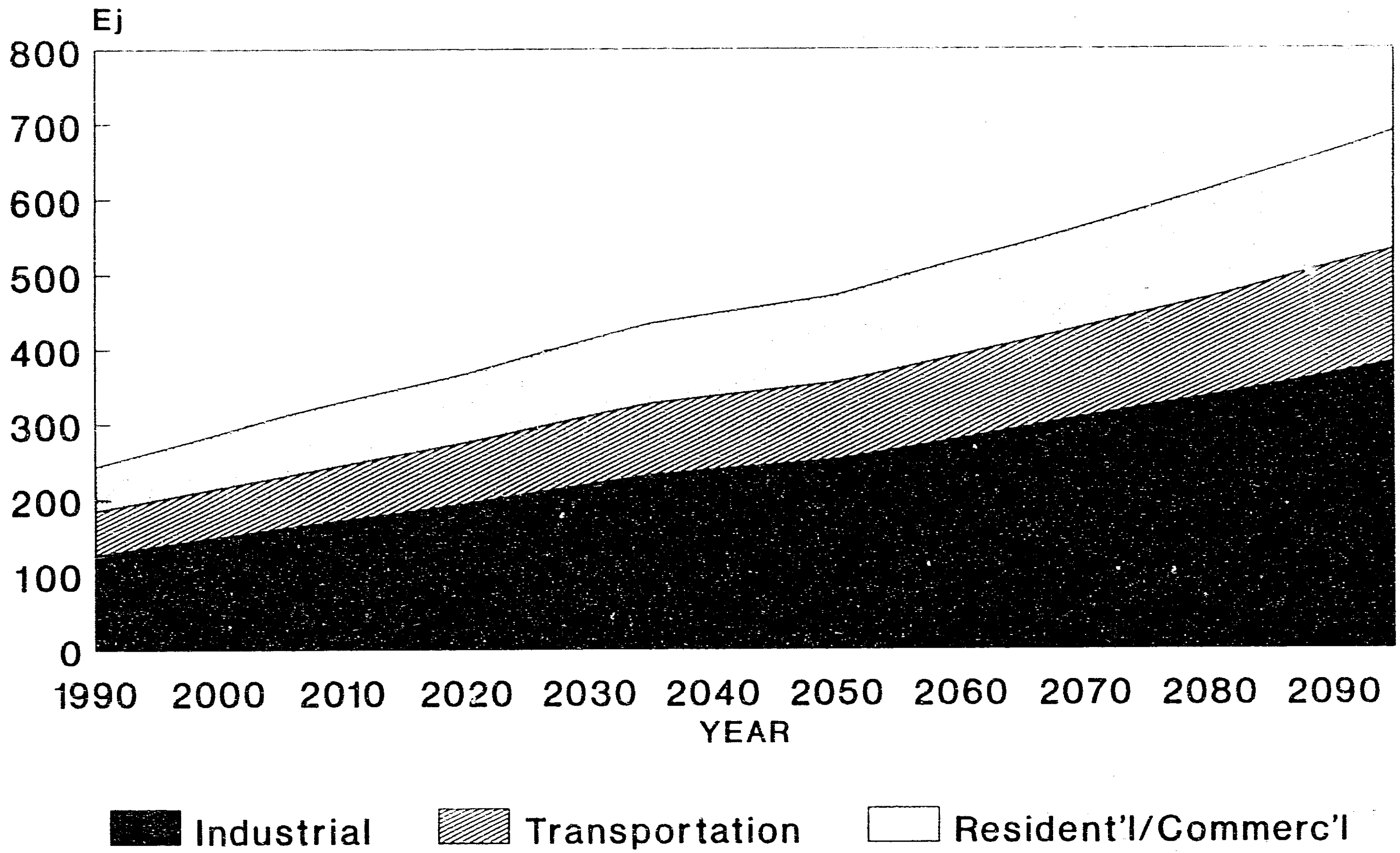


Figure 5. Case 0-Unconstrained Case Carbon Emissions

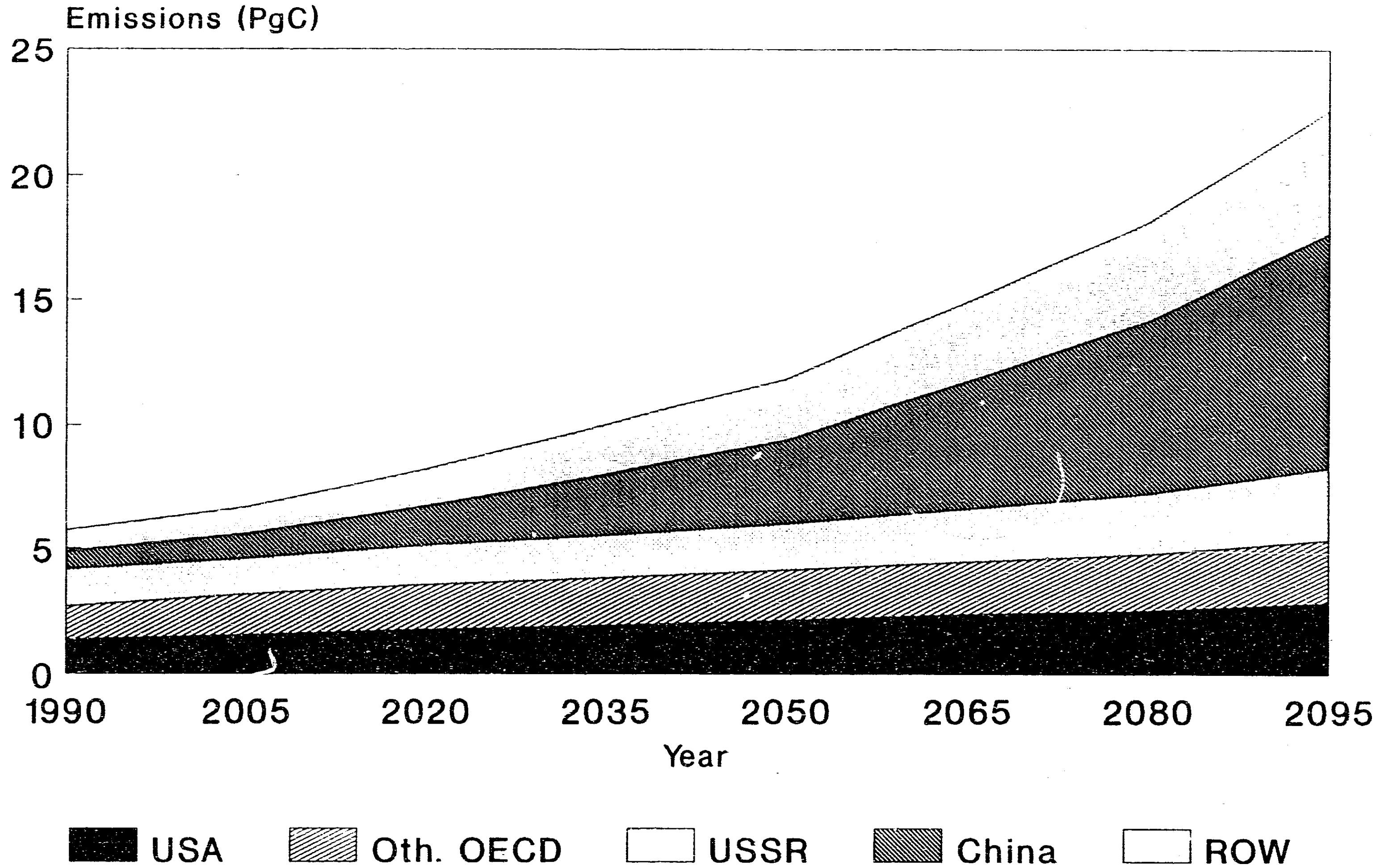


Figure 6. Case I-20% Reduction by 2010
Carbon Emissions
Developing Regions Limited to 50% Growth

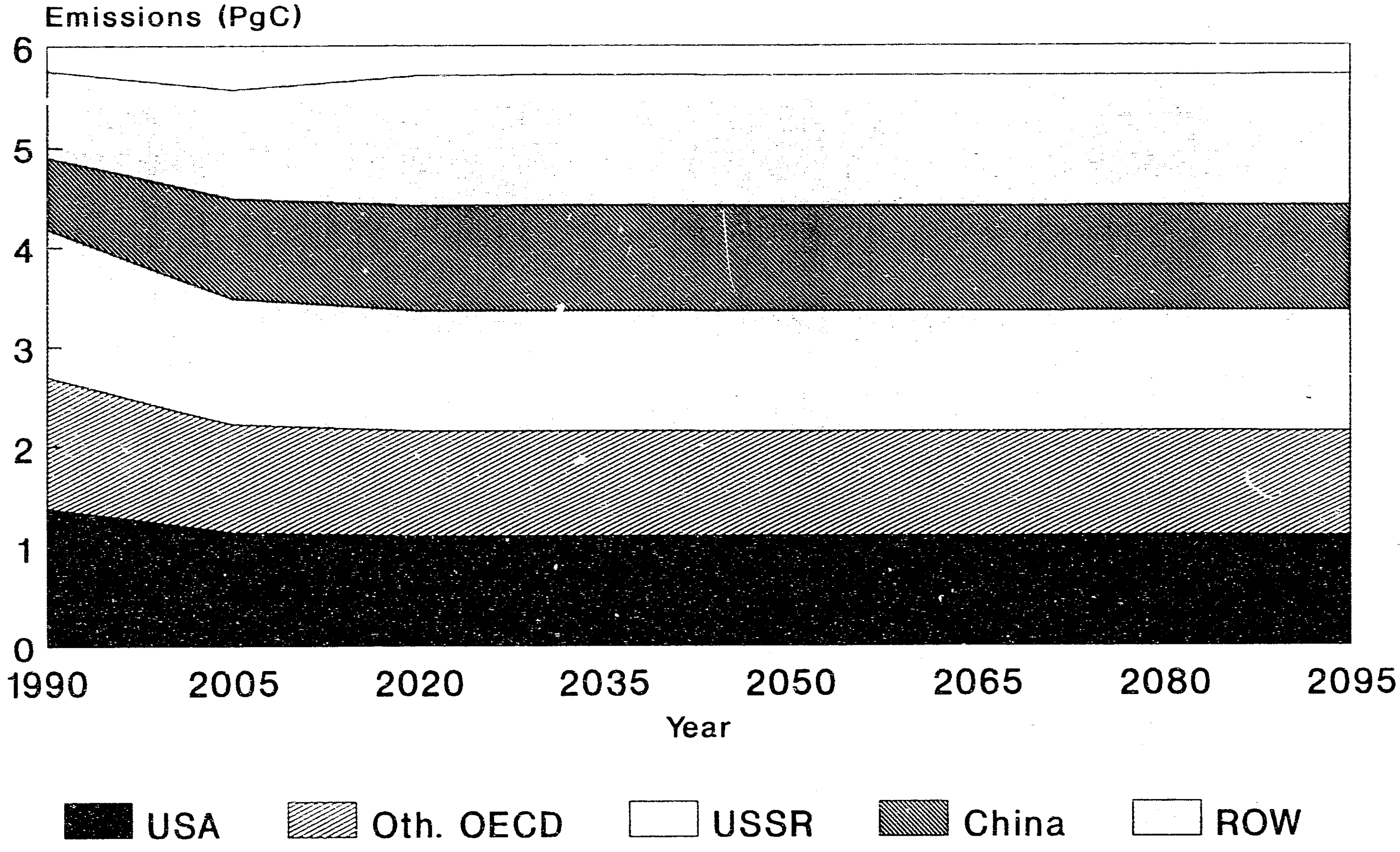


Figure 7. Case I-20% Reduction
Primary Energy Consumption

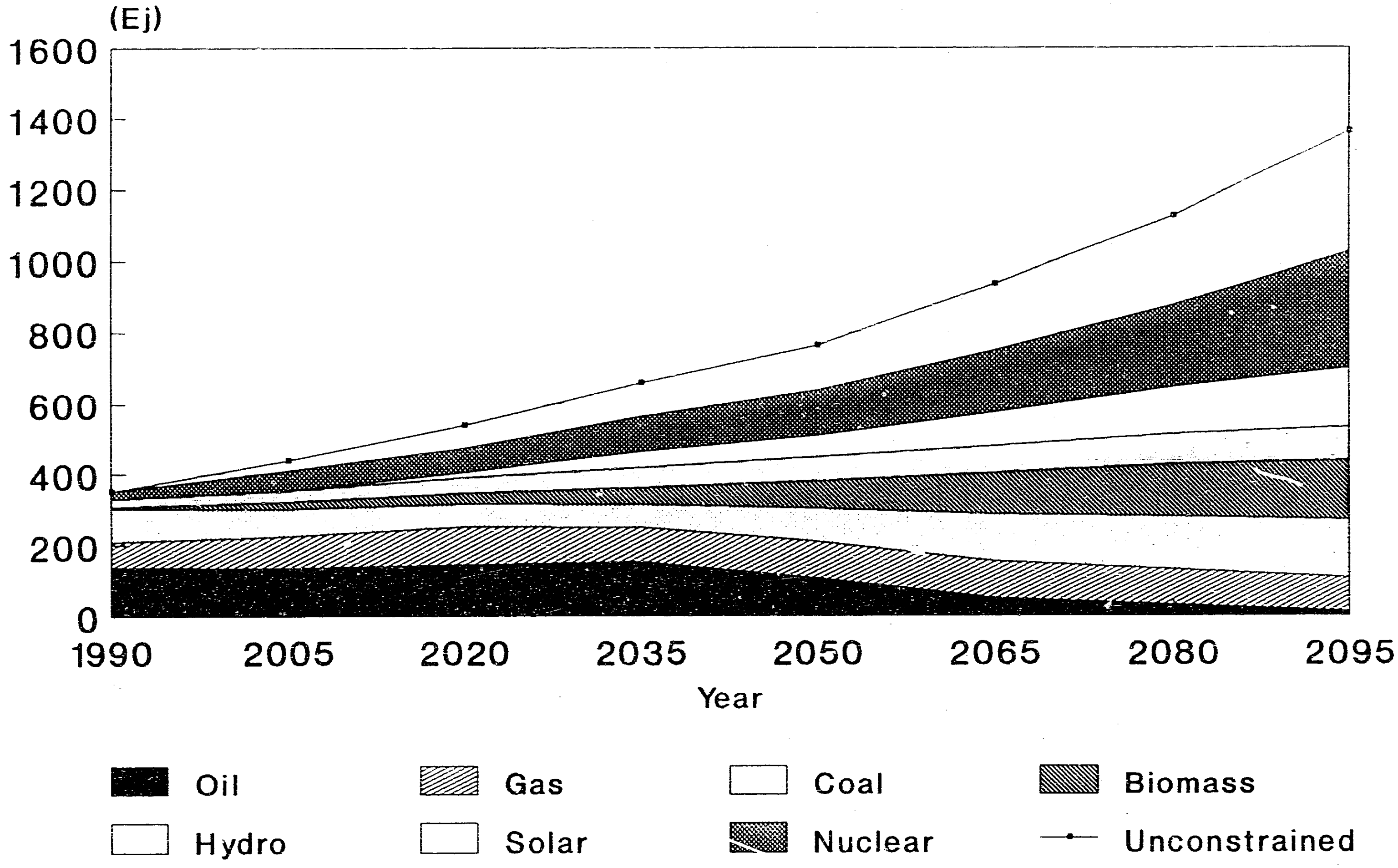


Figure 8. Case I-20% Reduction by 2010
Carbon Taxes

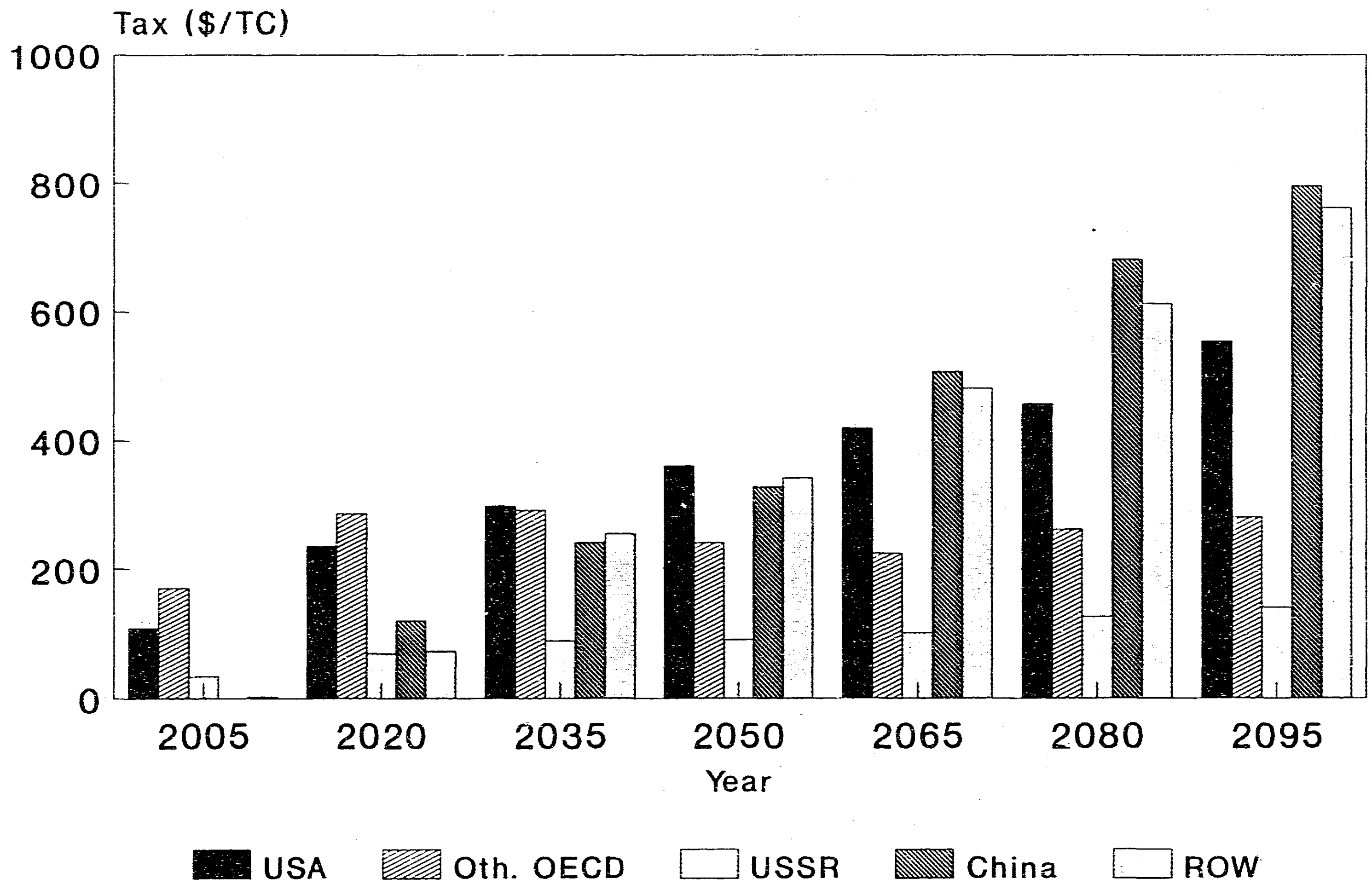


Figure 9. Case II-20% by 2010; 50%, 2050
Carbon Emissions
Developing Regions Limited to 50% Growth

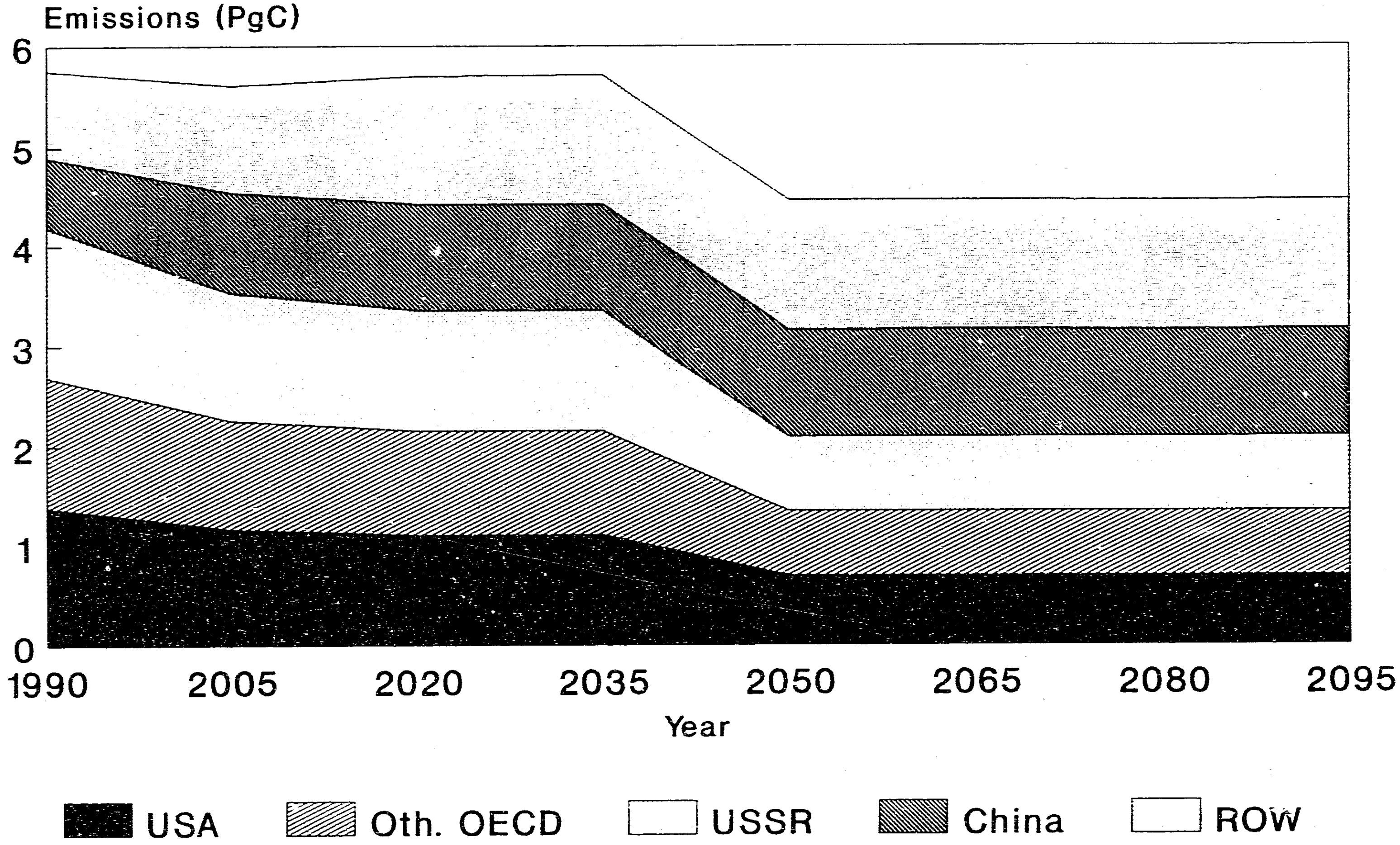


Figure 10. Case II-20%/50% Reduction
Primary Energy Consumption

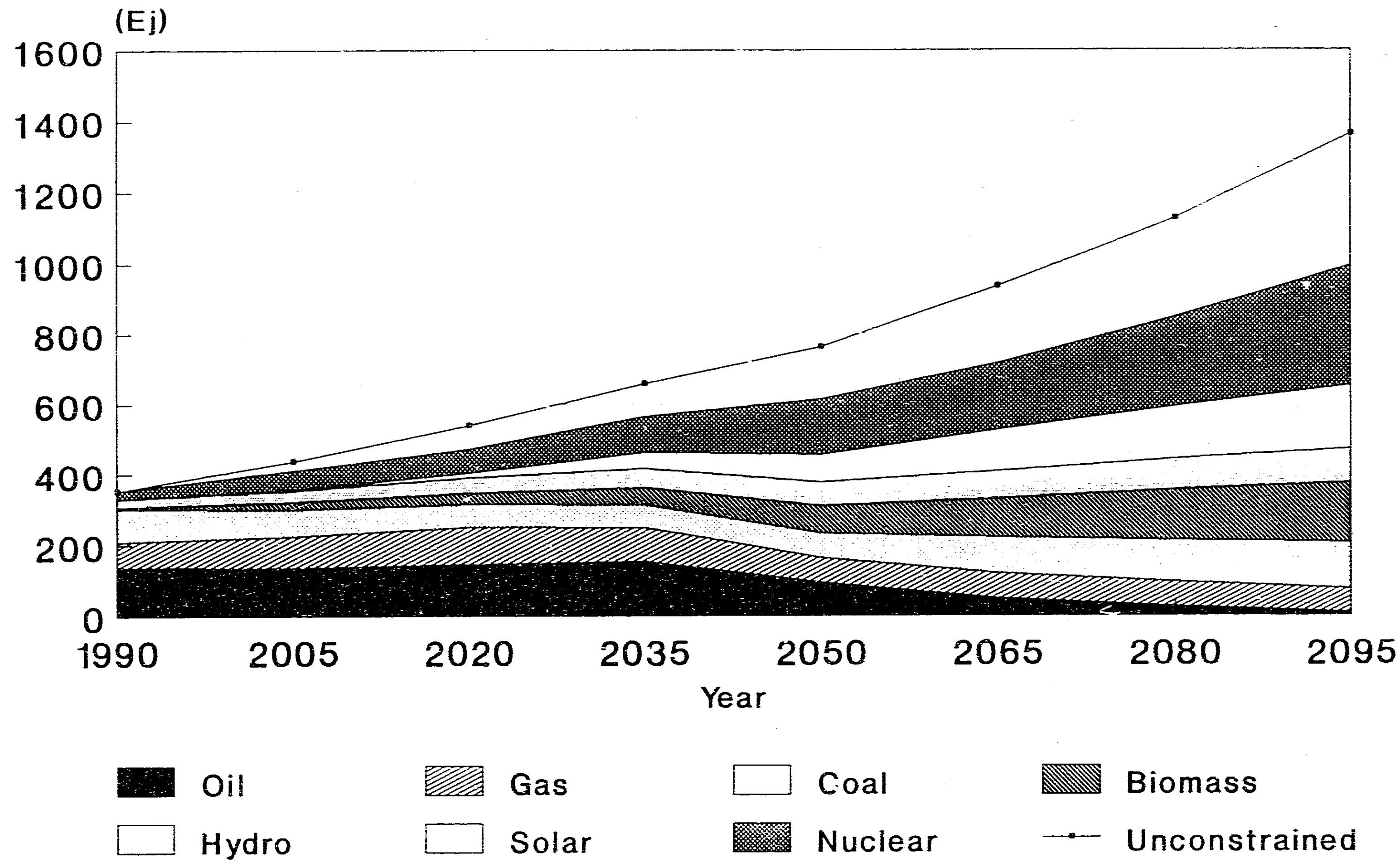


Figure 11.Case II-20% by 2010; 50%, 2050 Carbon Taxes

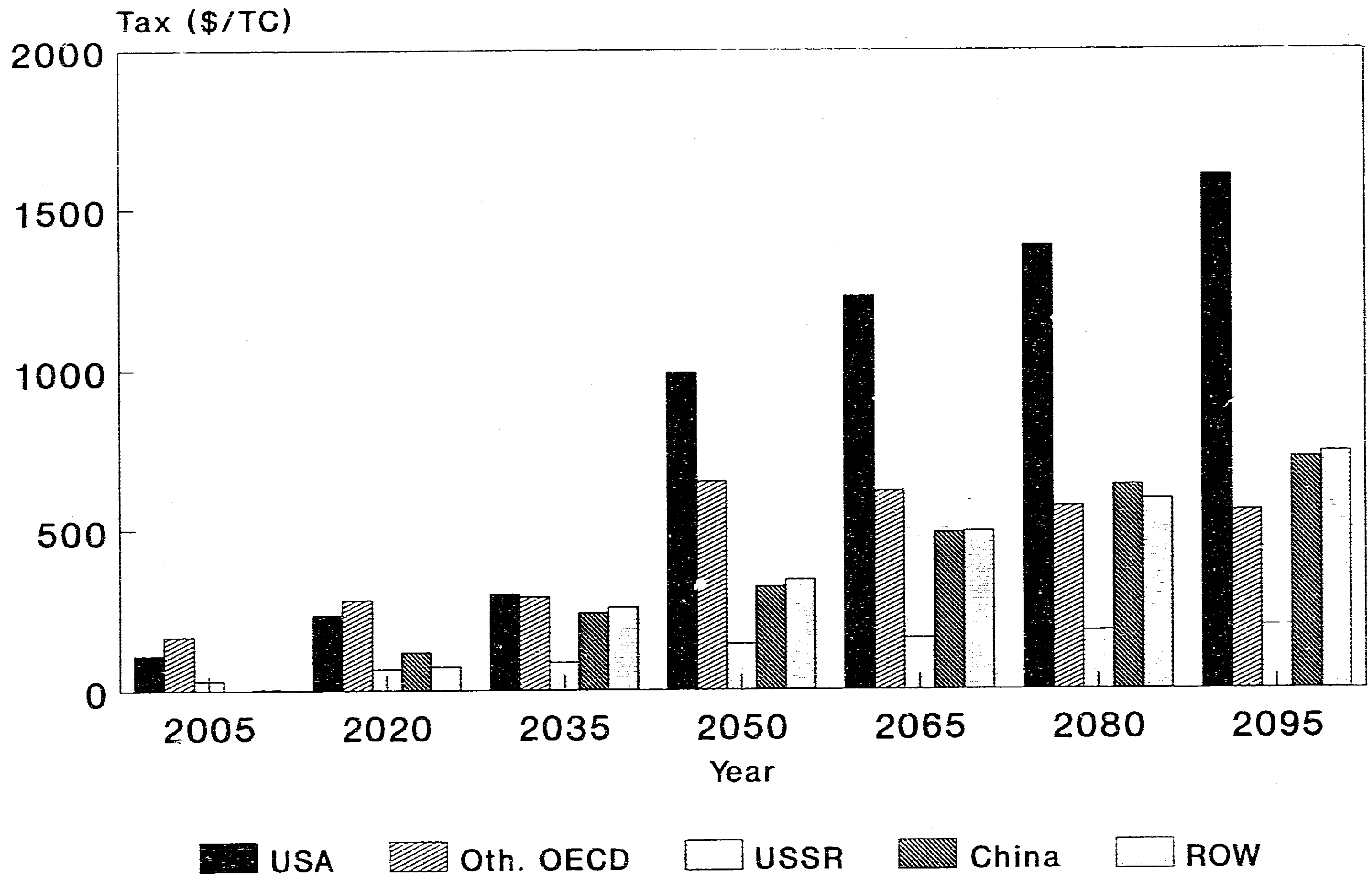


Figure 12. Case III-Stabilize by 2000
Carbon Emissions
Developing Regions Limited to 50% Growth

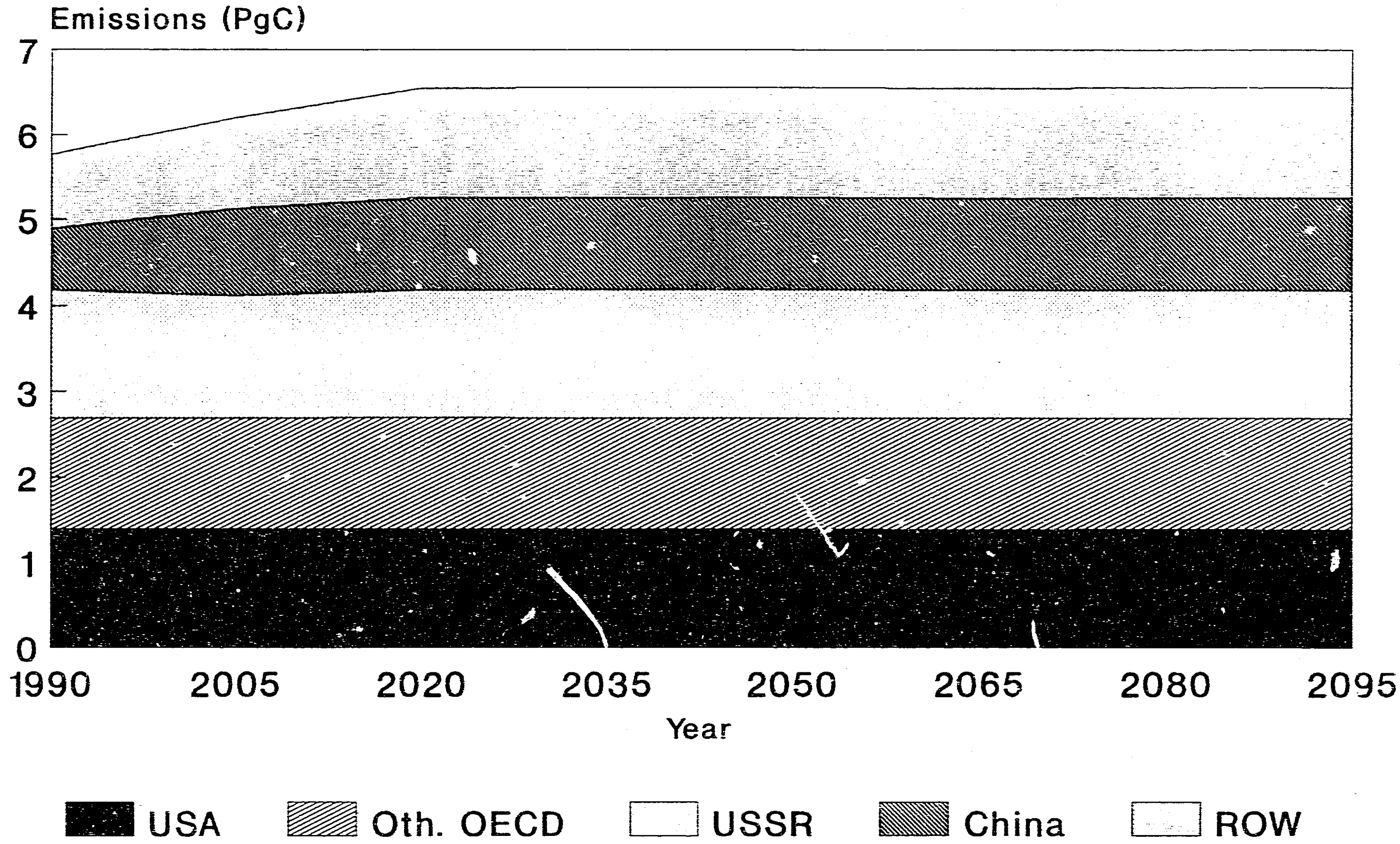


Figure 13. Case III-Stabilize Primary Energy Consumption

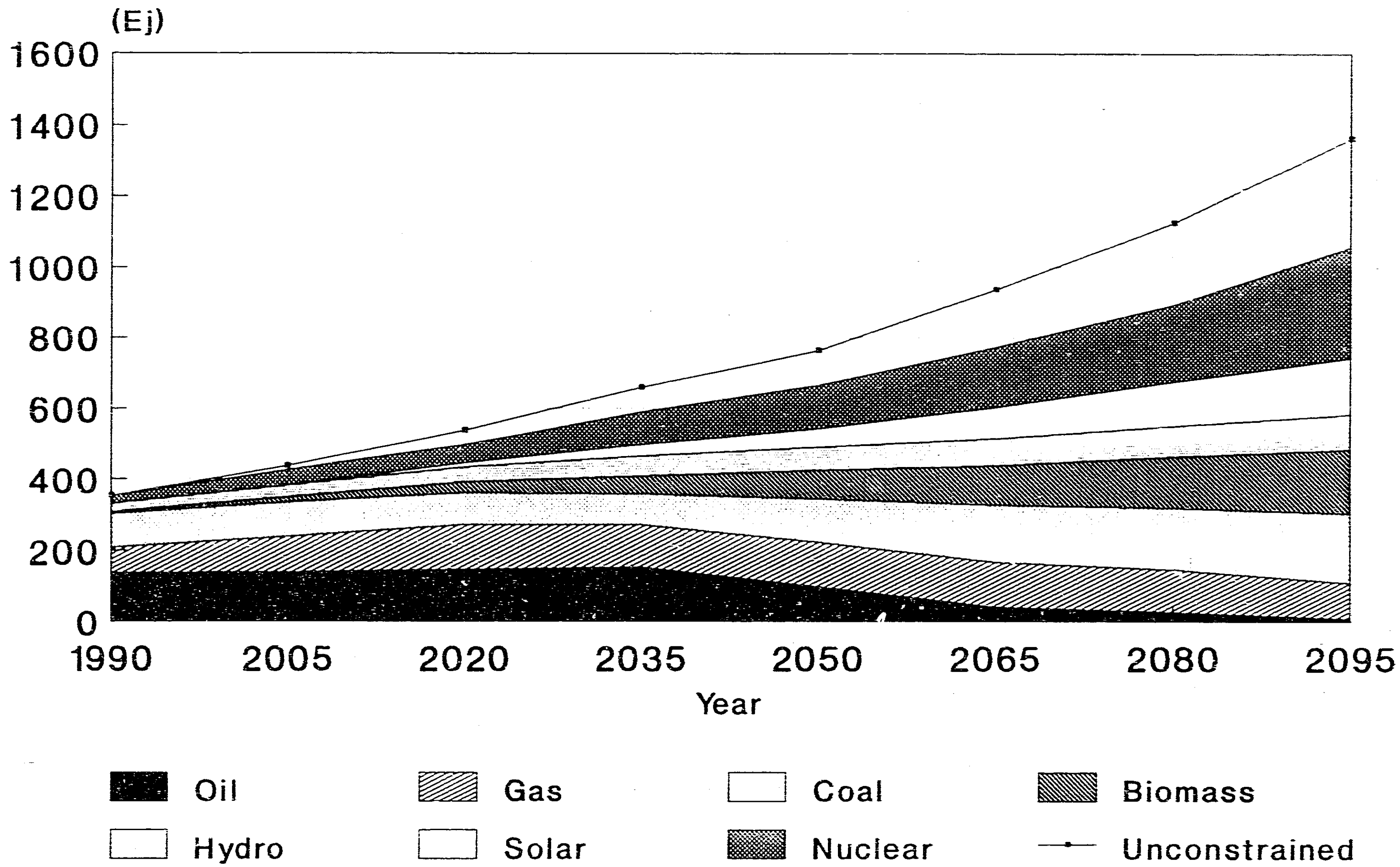


Figure 14. Case III-Stabilize by 2000
Carbon Taxes

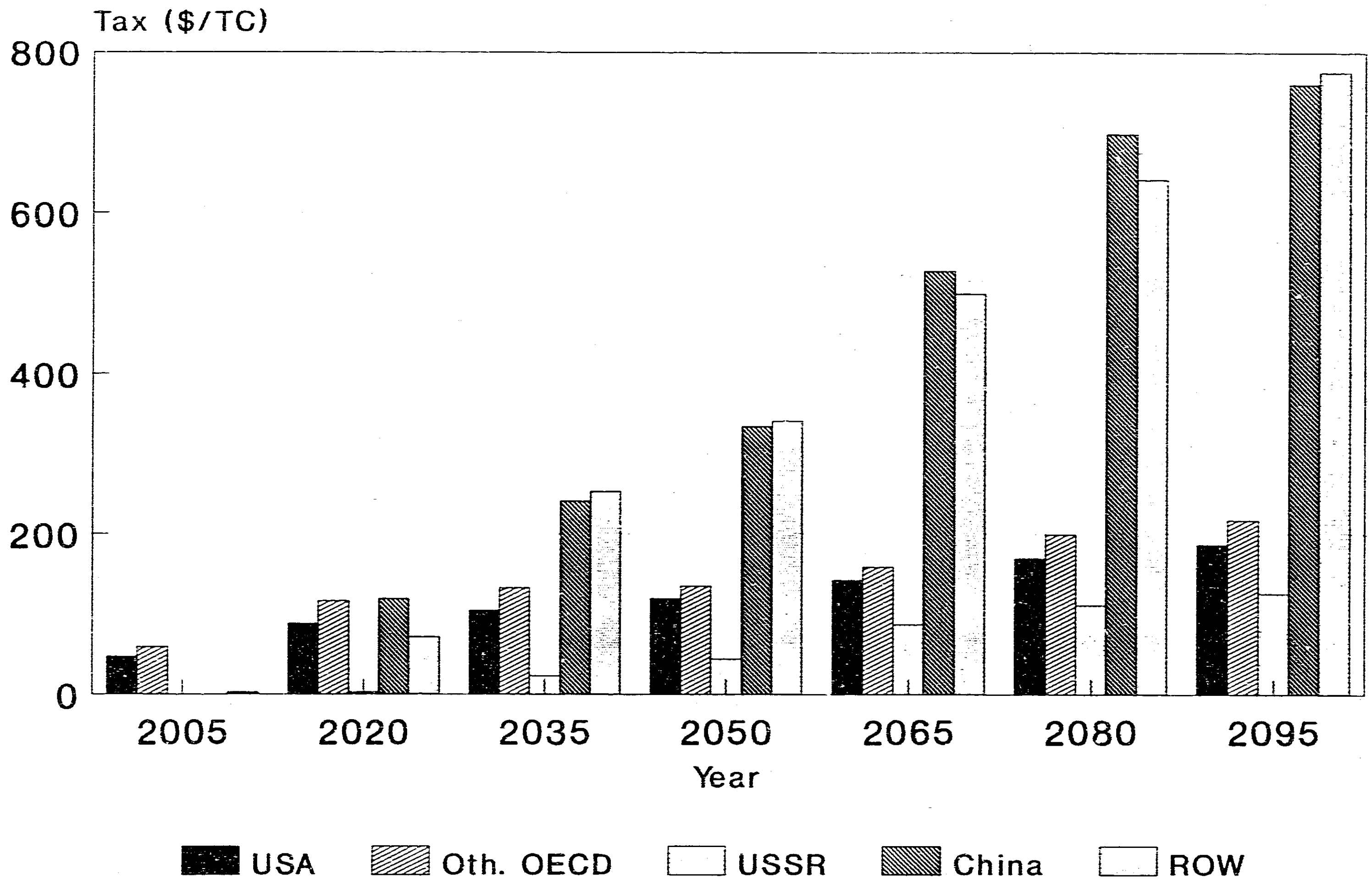


Figure 15.Case IV-Accelerated Technology Primary Energy Consumption

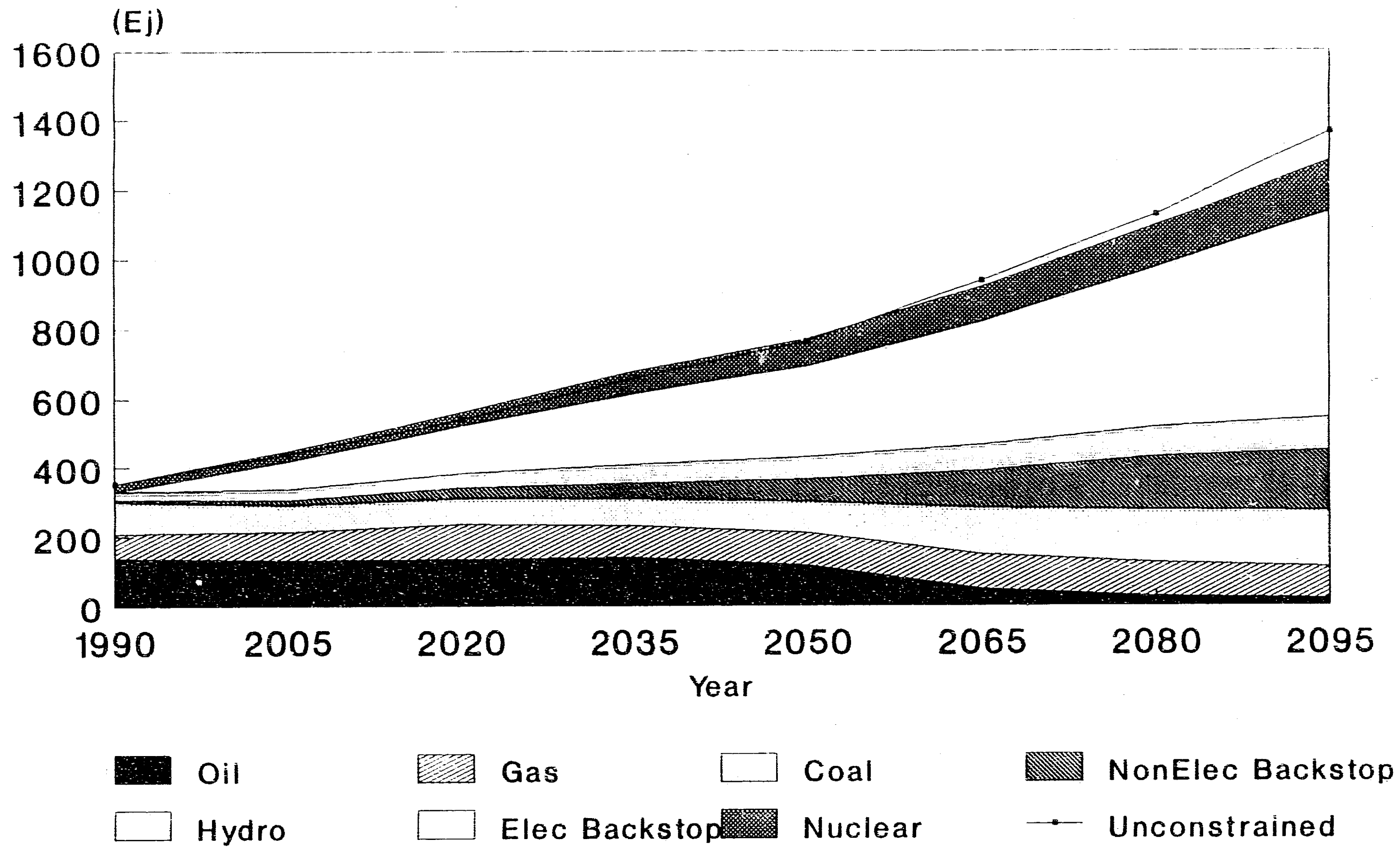
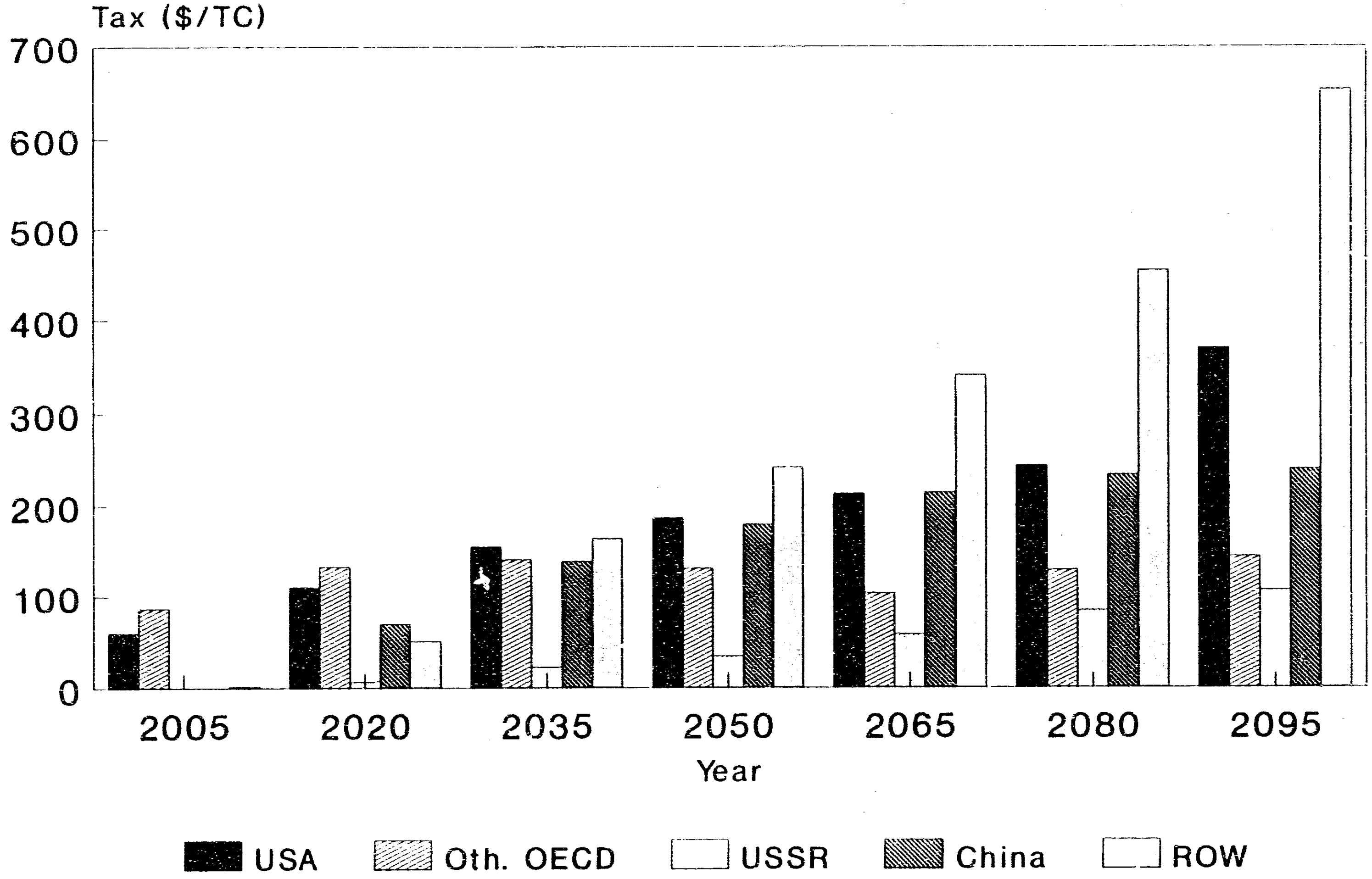


Figure 16.Case IV-Accelerated Technology Carbon Taxes



EMF 12

Figure 17. Case V-Emissions Trading Carbon Taxes

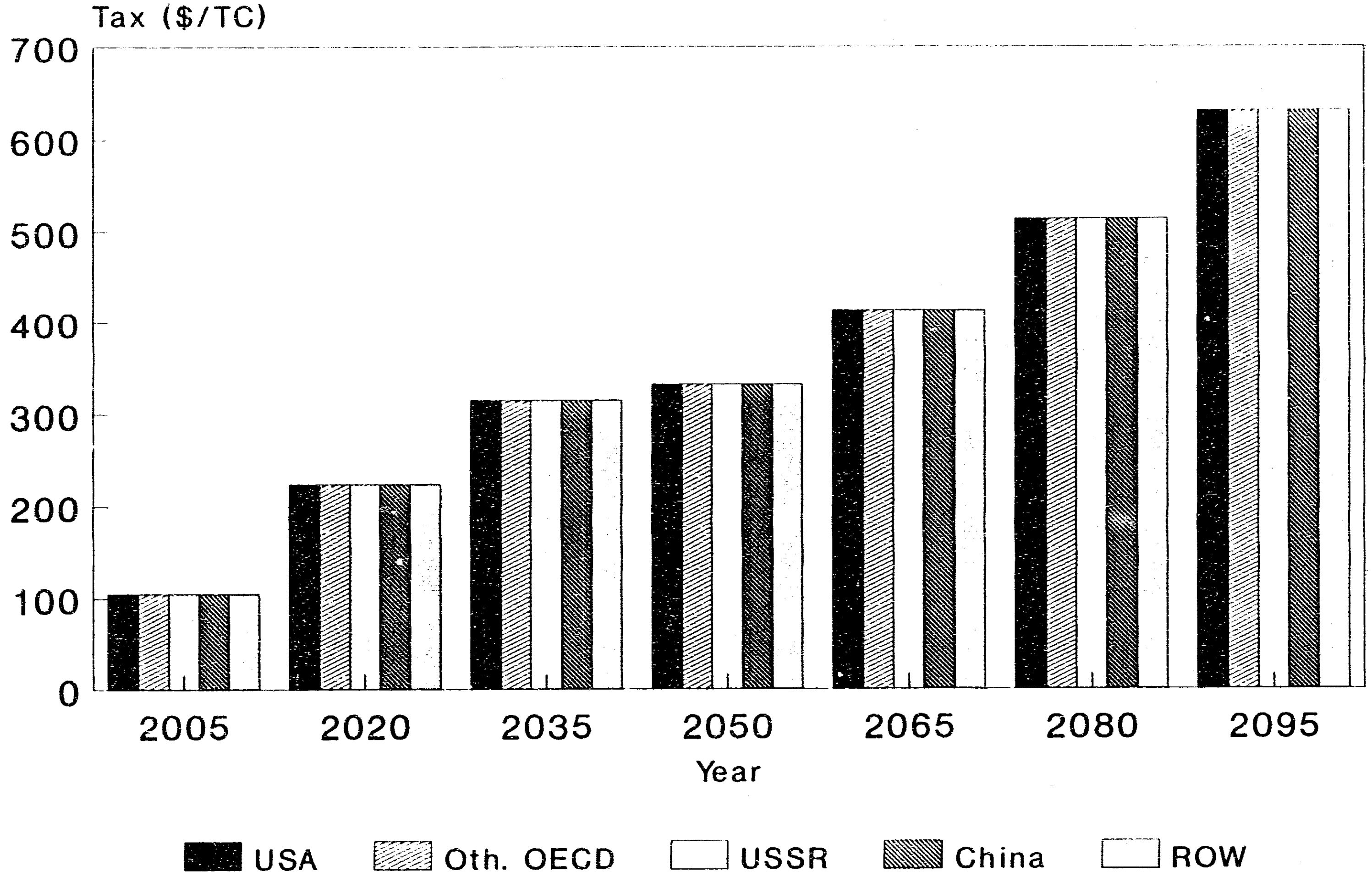


Figure 18. Case V-Emissions Trading Regional Taxes to Attain 20% Reduction Compared with Permit Prices

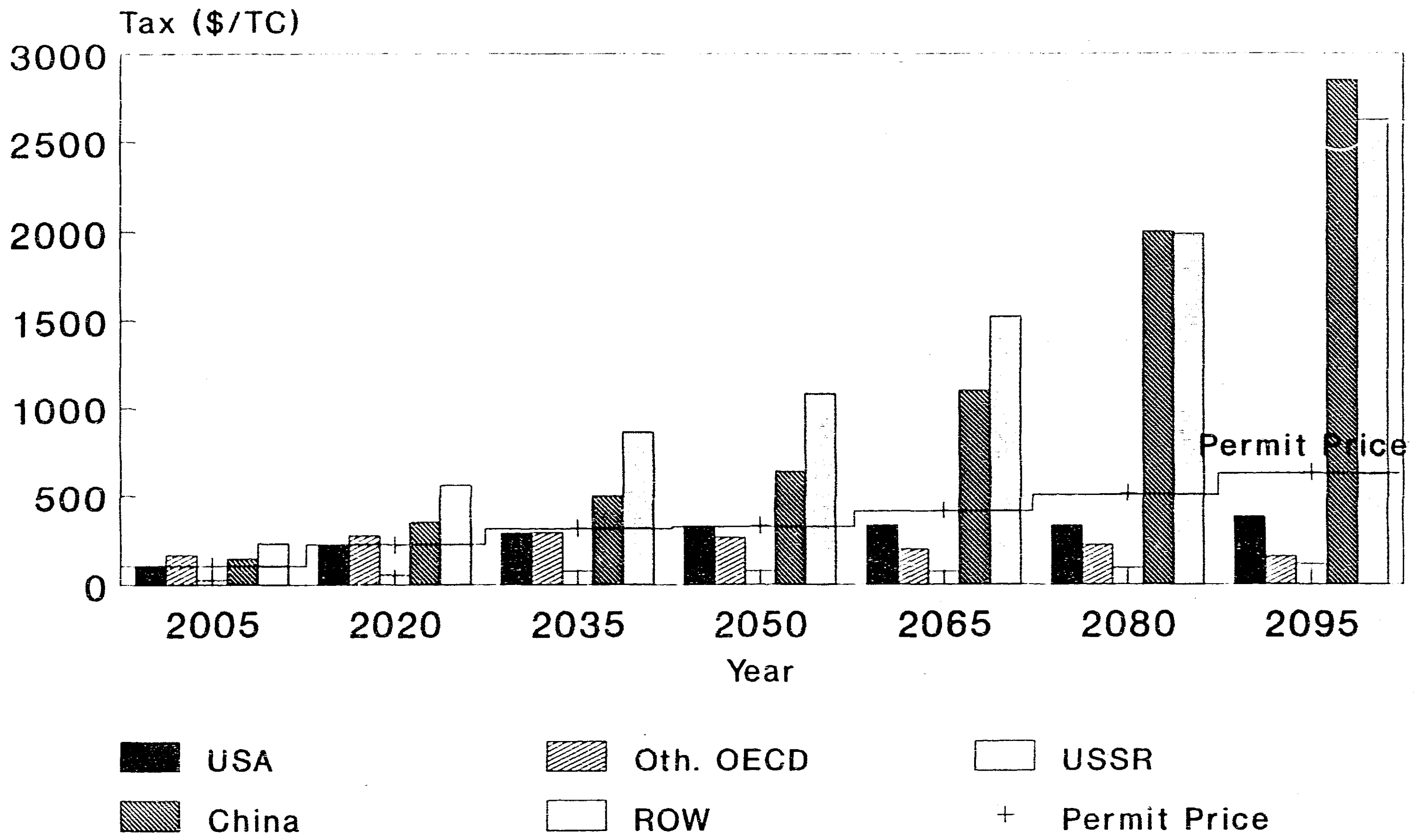
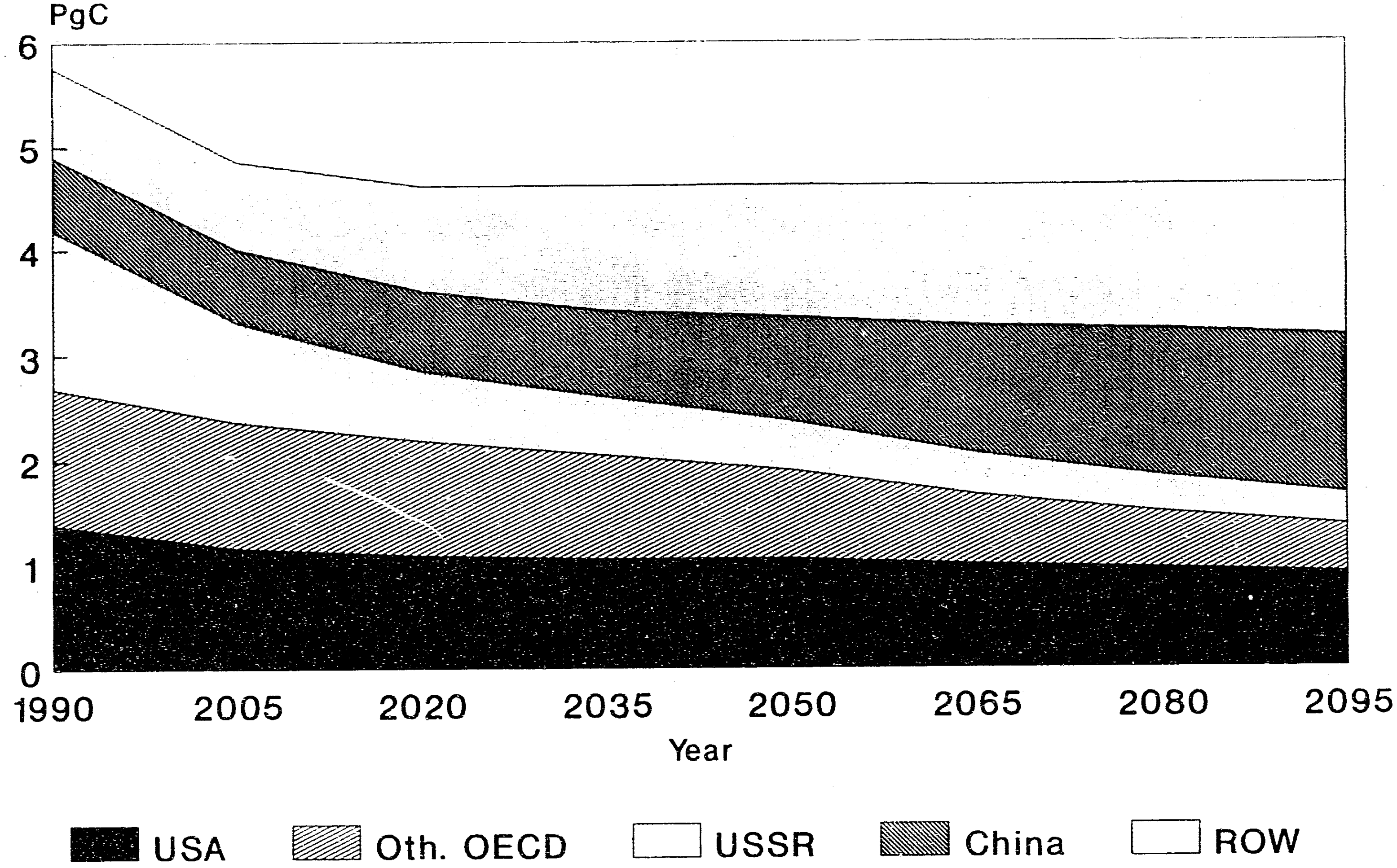


Figure 19. Case V-Emissions Trading Carbon Emissions



EMF-12

Figure 20. Case VI-Phased-in Carbon Tax
Carbon Taxes

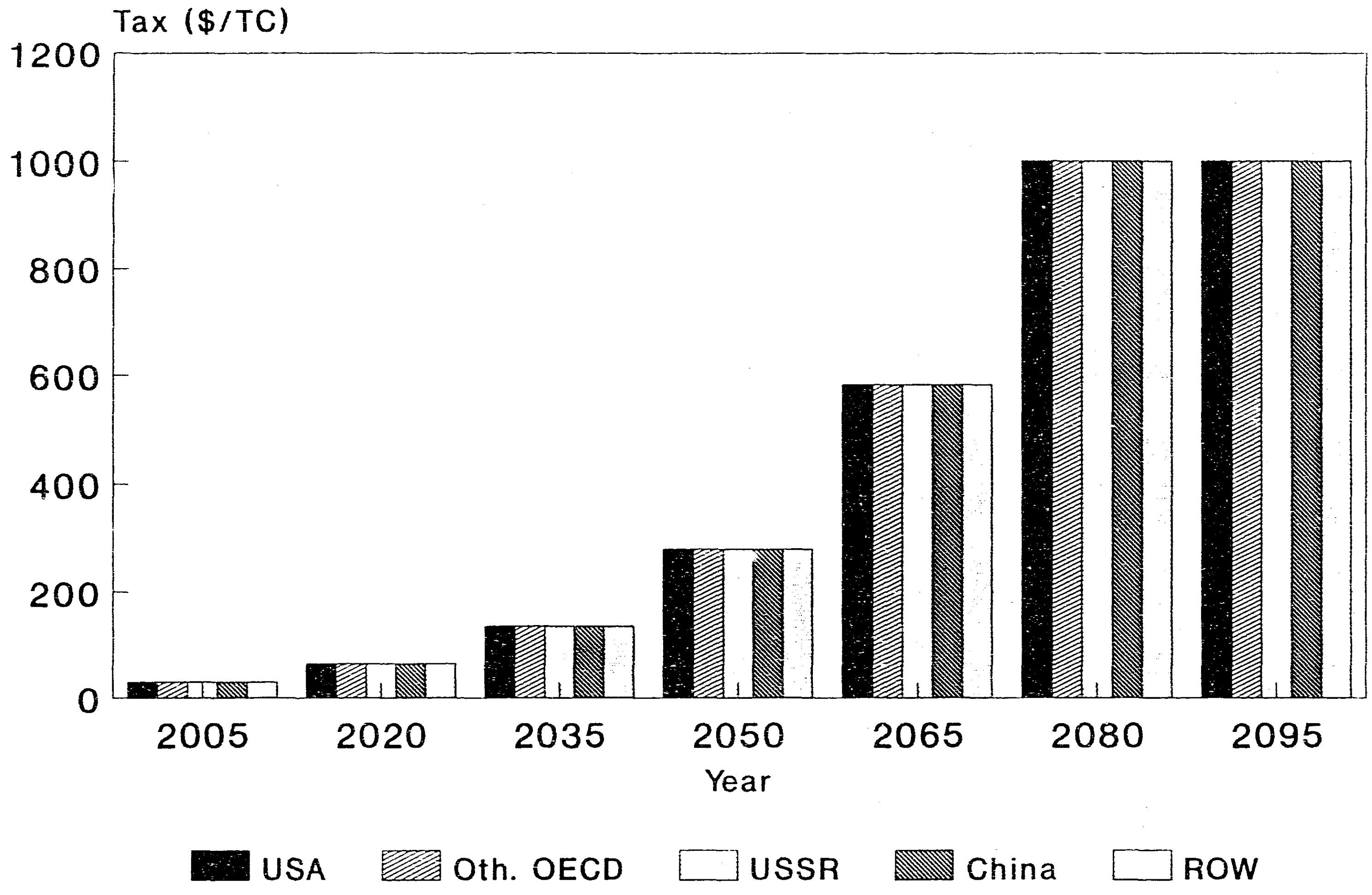


Figure 21. Case VI-Phased-in Tax Carbon Emissions

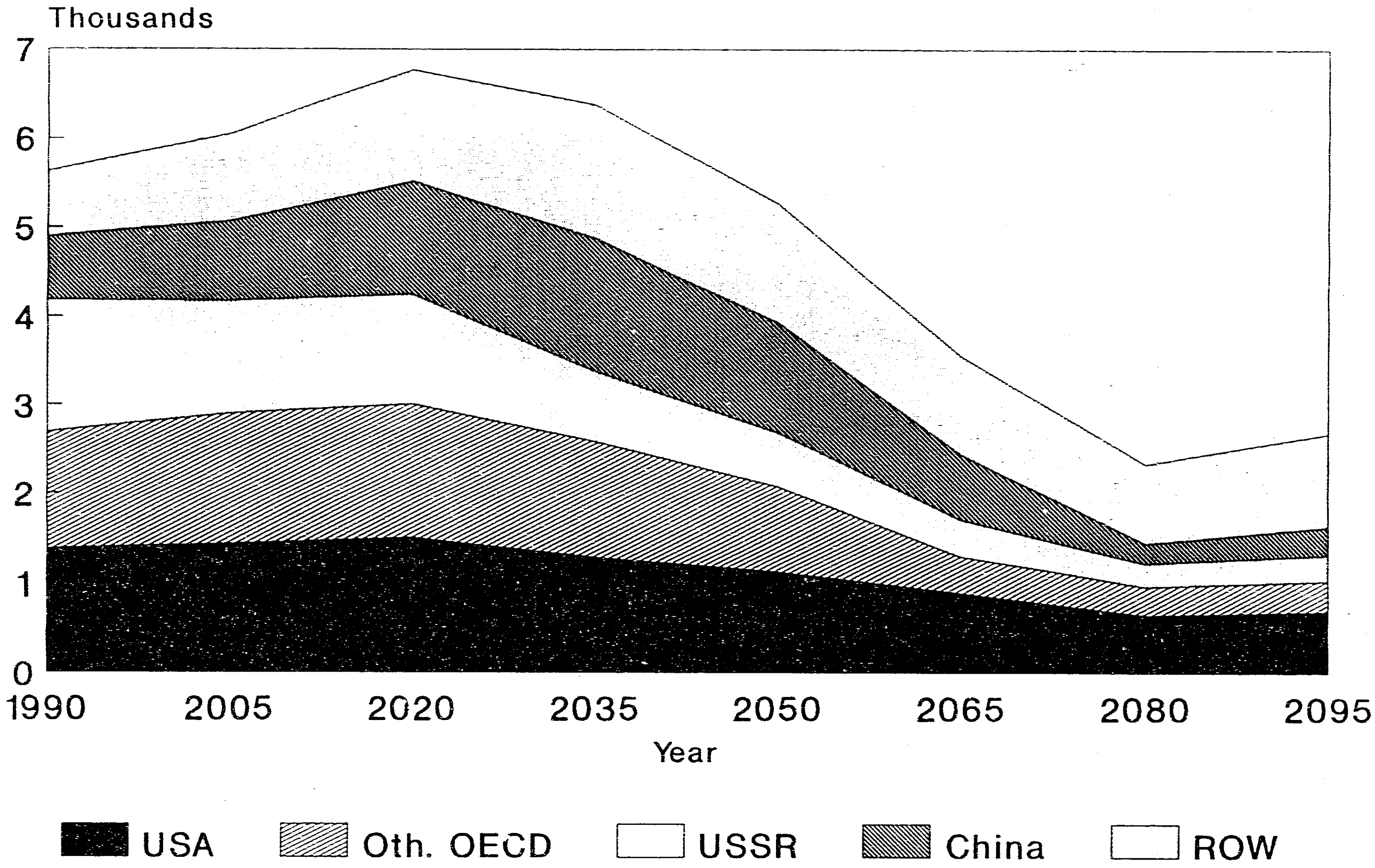


Figure 22. Case VI-Phased-in Tax
Primary Energy Consumption

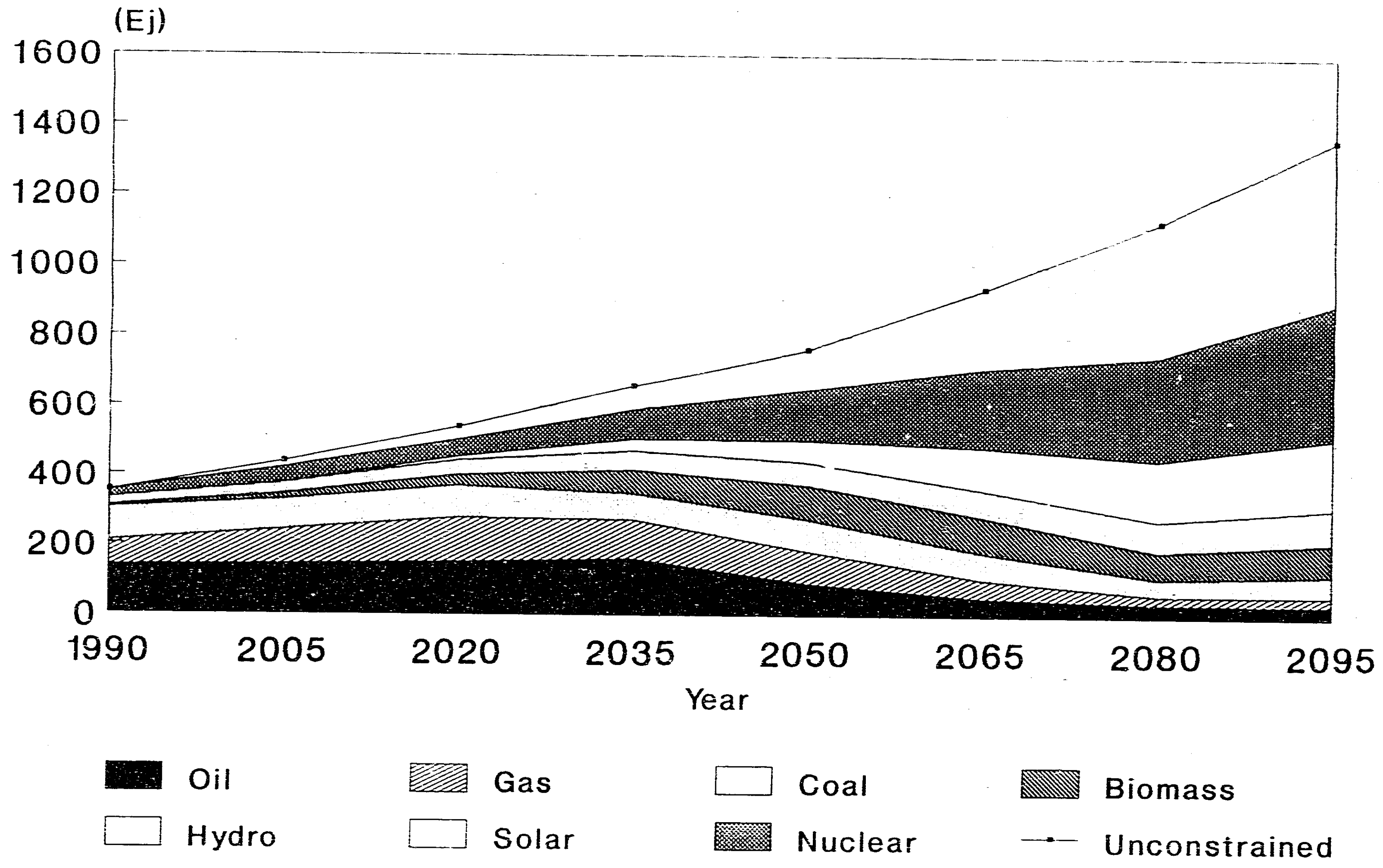


Figure 23. Case VII-GHG Reduction 1
Greenhouse Warming Potentials
Unconstrained Emissions

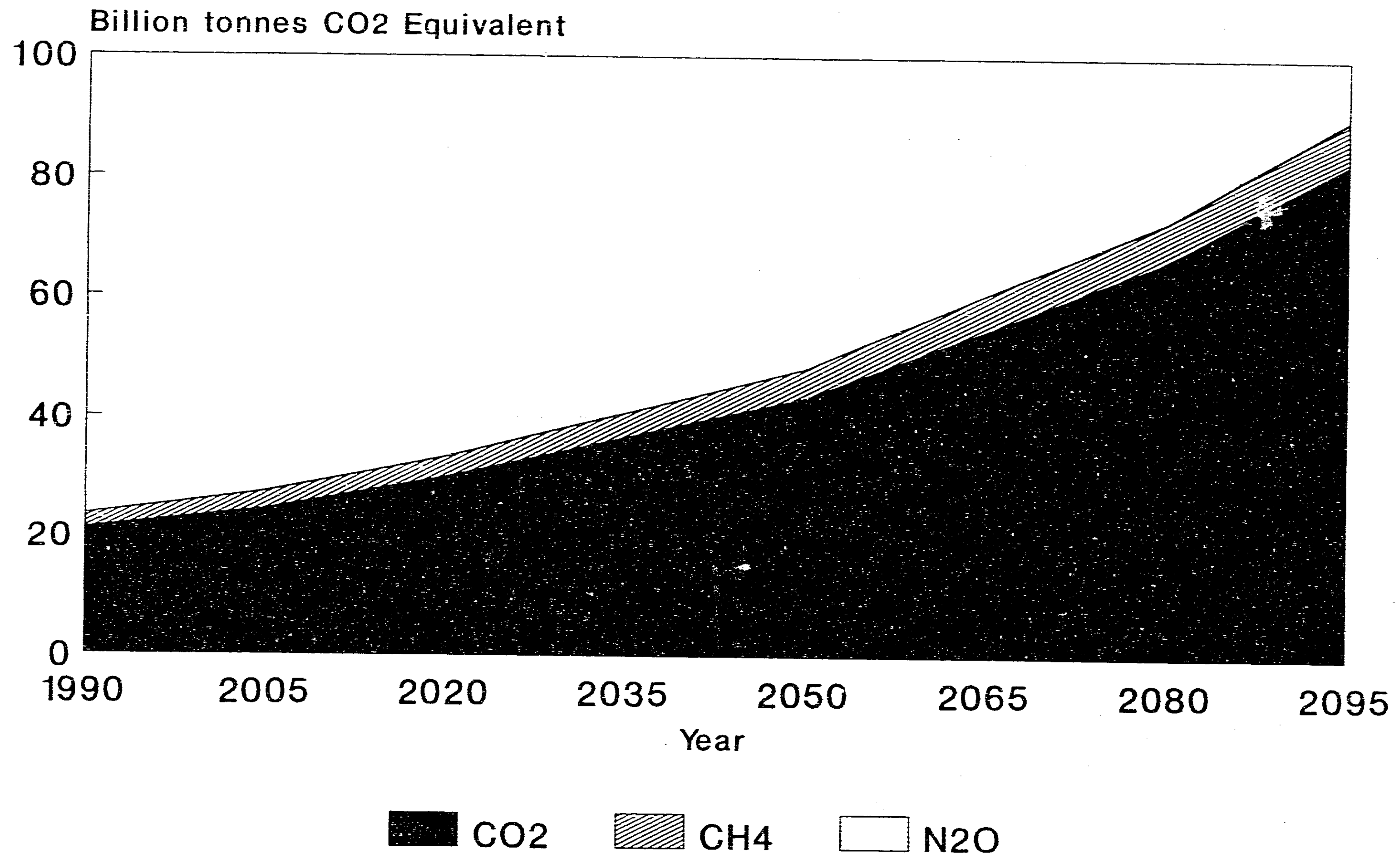


Figure 24. Case VII-GHG Reduction #1
Carbon Taxes to Reduce GWP

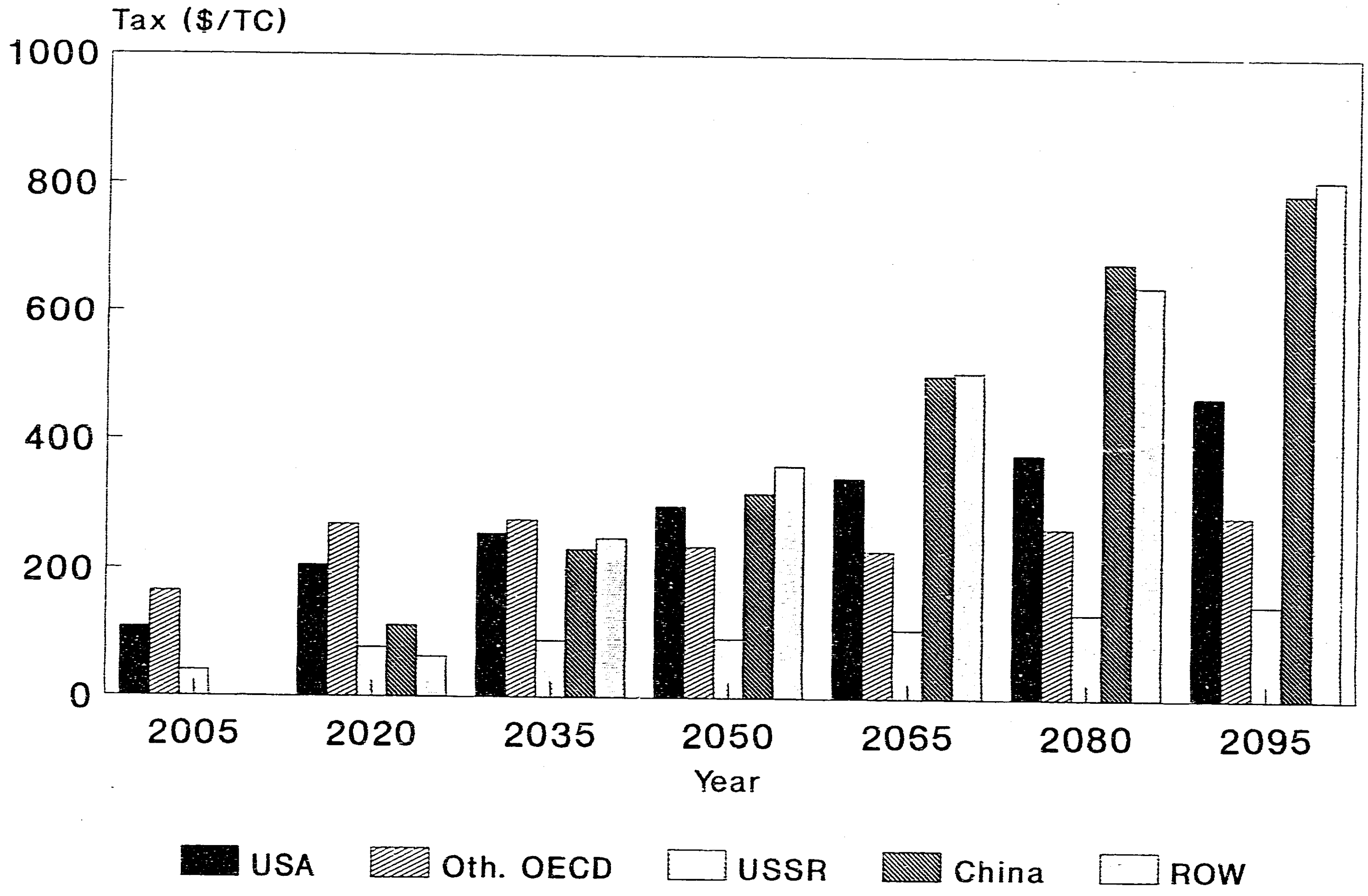


Figure 25. Cases VII and VIII Greenhouse Warming Potentials

Tax Cases Compared with Unconstrained

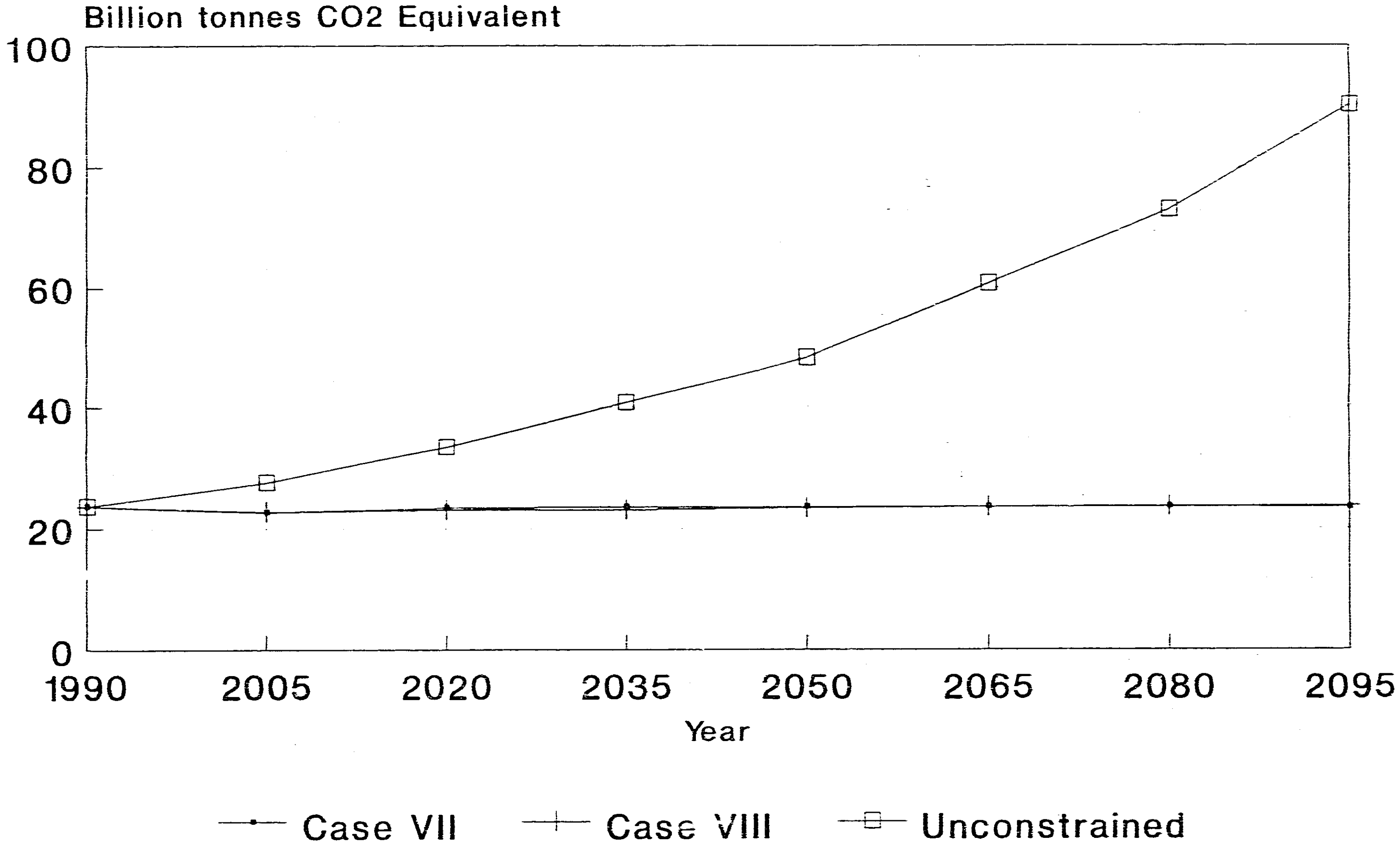


Figure 26. Case VIII-GHG Reduction #2
Carbon Taxes to Reduce GWP

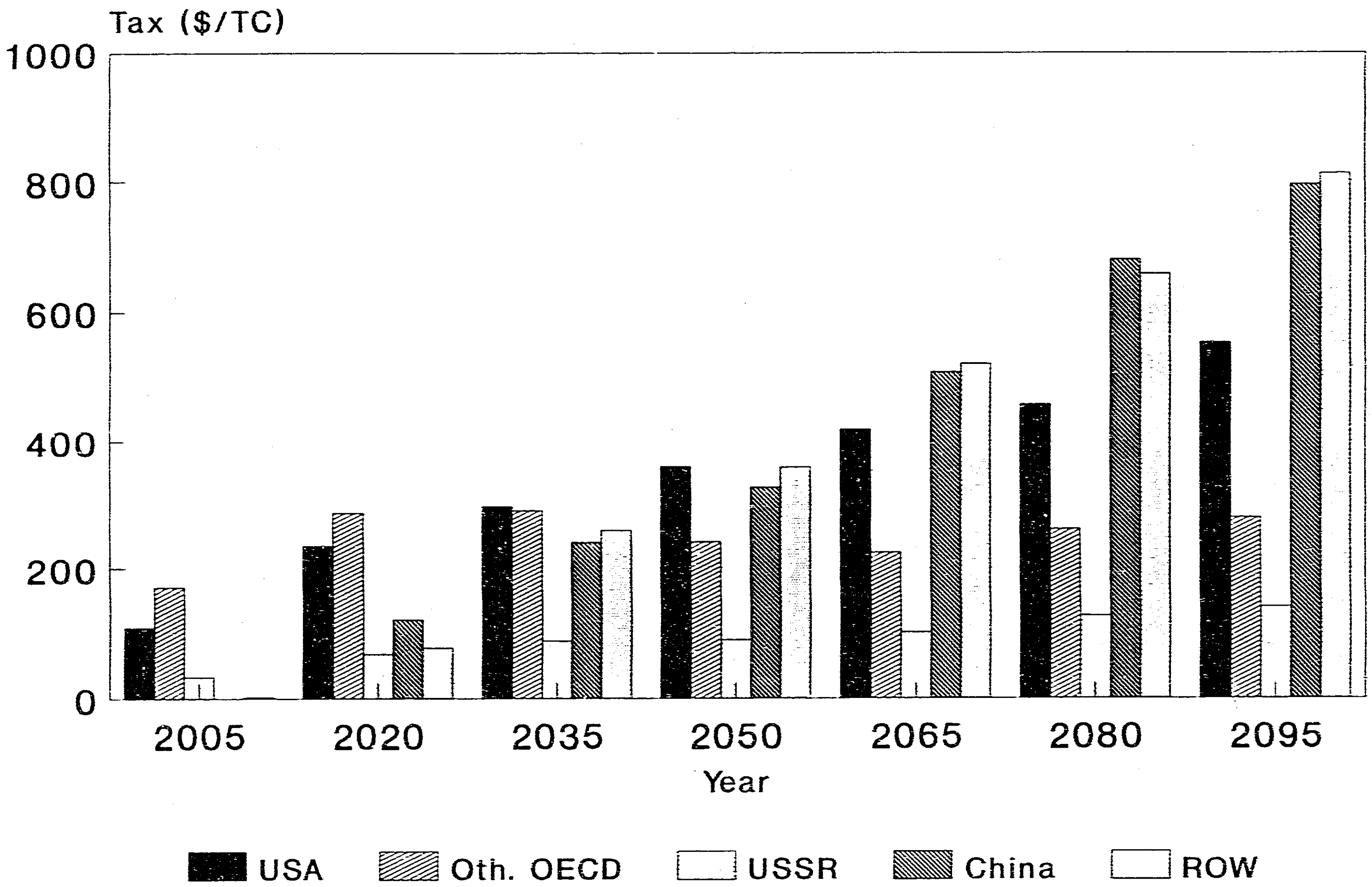
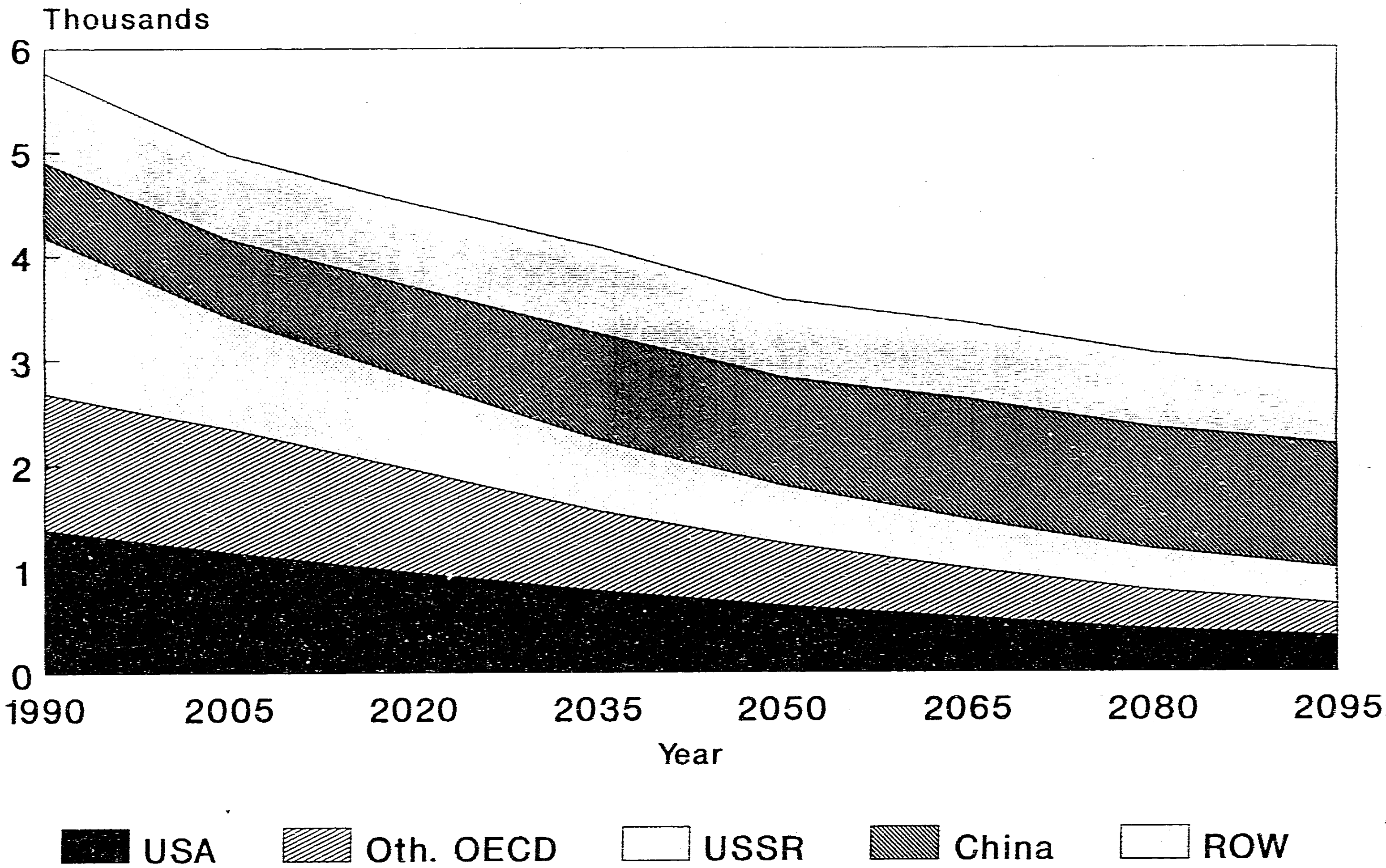


Figure 27. Case IX-2% Growth Reduction
Carbon Emissions



EMF-12

Figure 28. Case IX-2% Reduction per Year Carbon Taxes

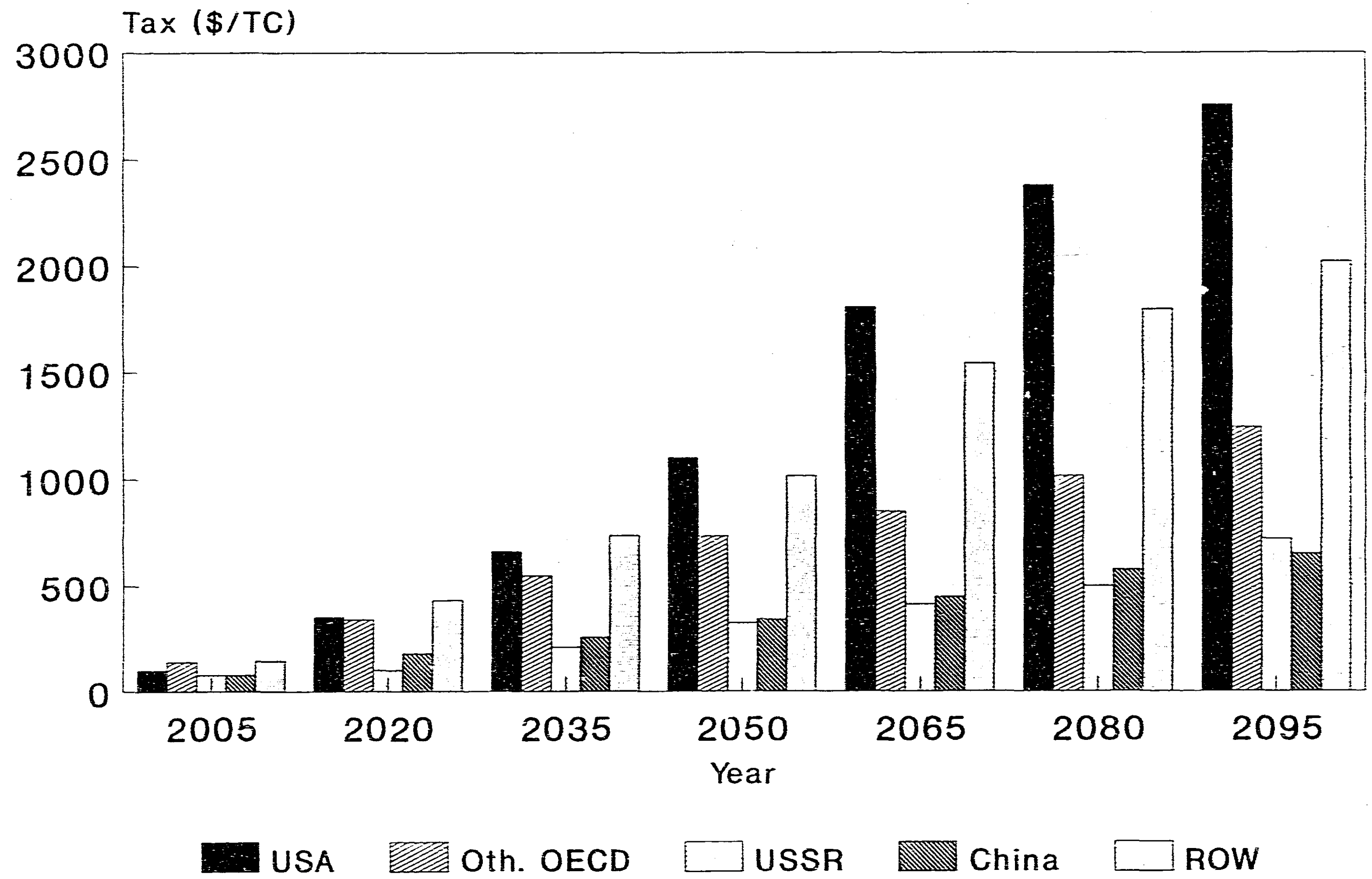
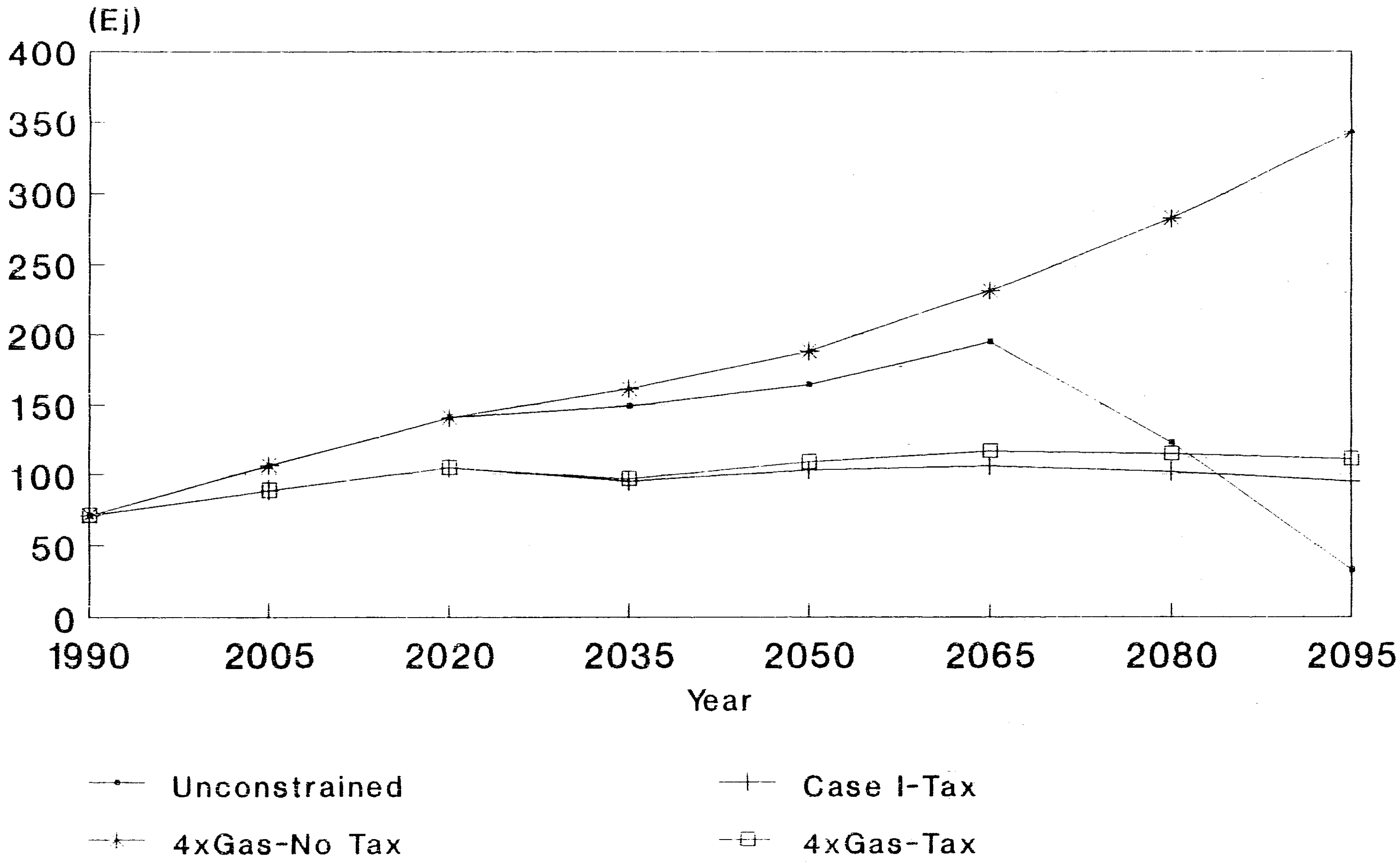
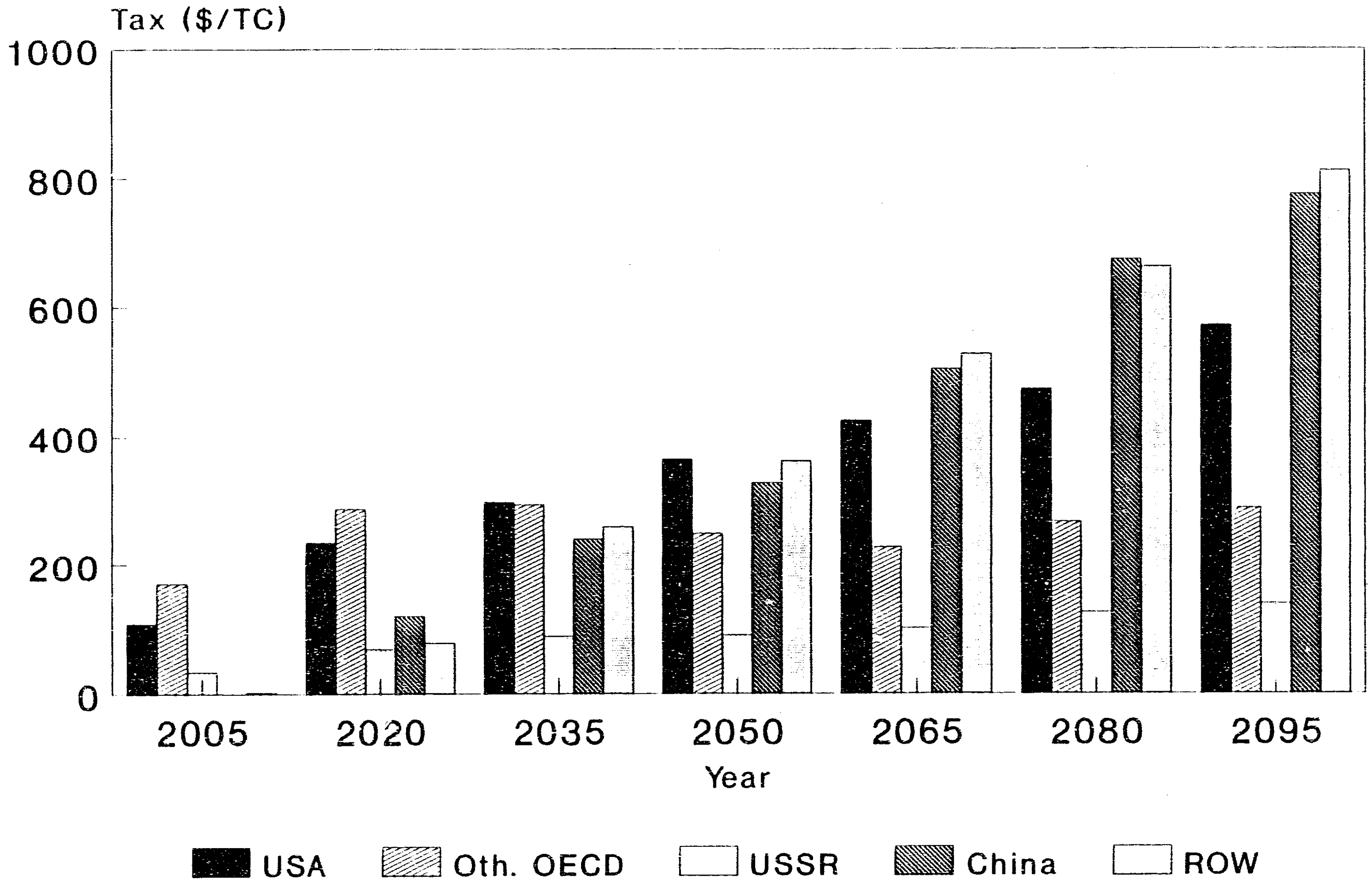


Figure 29. Case X-Quadruple Gas Resource
Primary Gas Consumption



EMF-12

Figure 30. Case X-Quadruple World Gas Carbon Taxes



EMF-12

Figure 31. Case XI-Low U.S. Growth
U.S. GNP

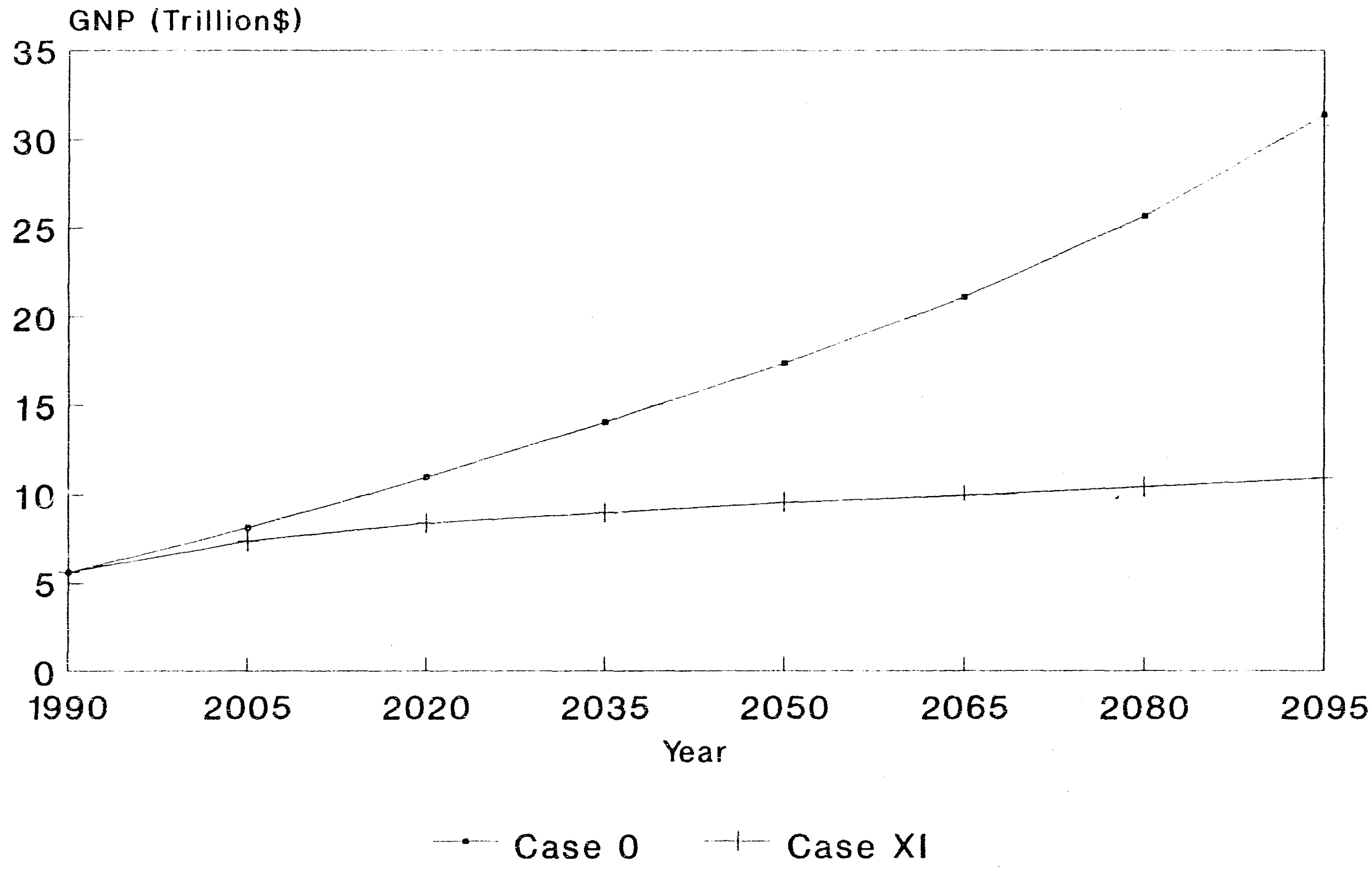


Figure 32. Case XI-Low U.S. Growth
U.S. Primary Energy Consumption
Case 0-Unconstrained; High Growth

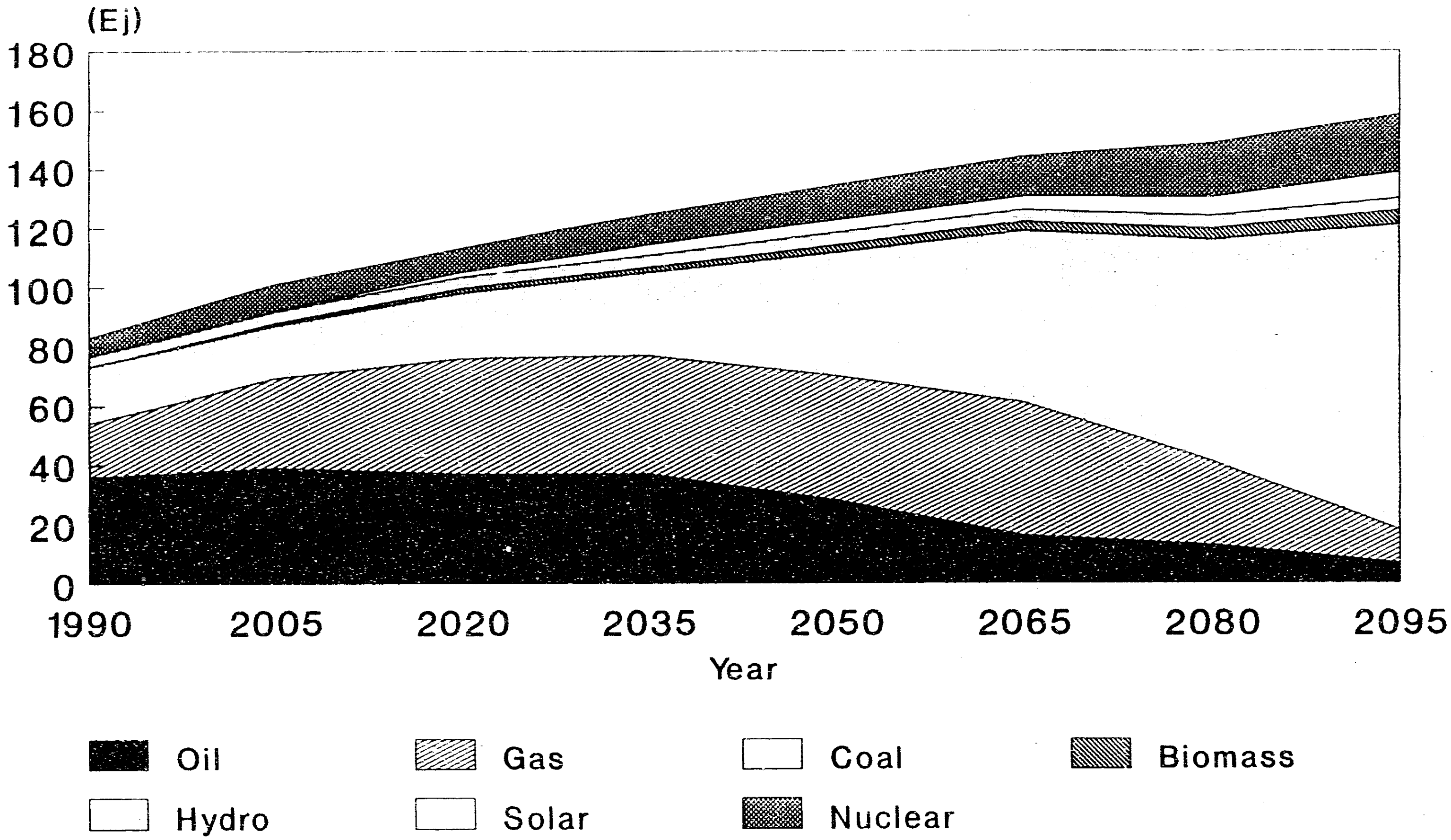
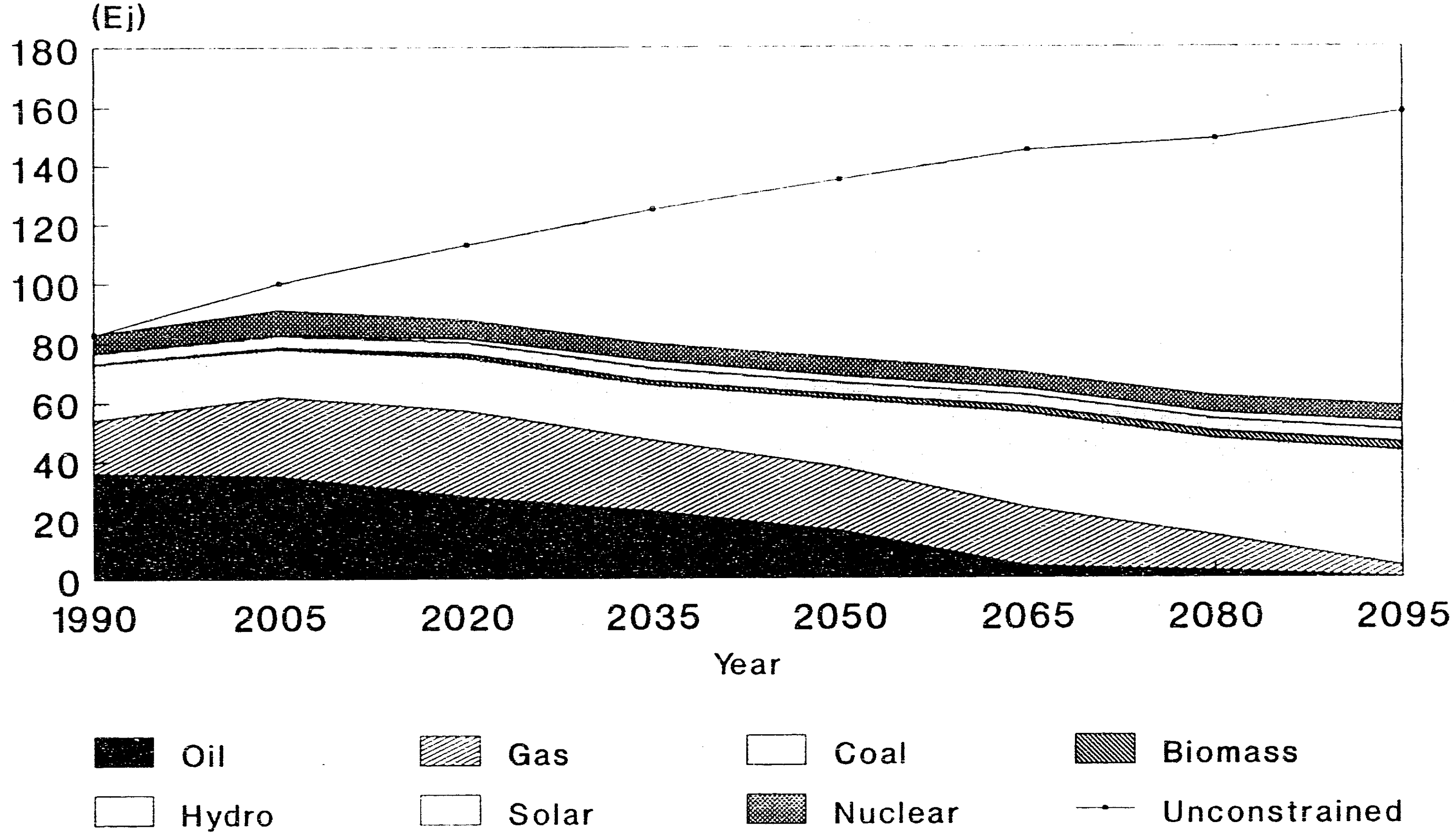
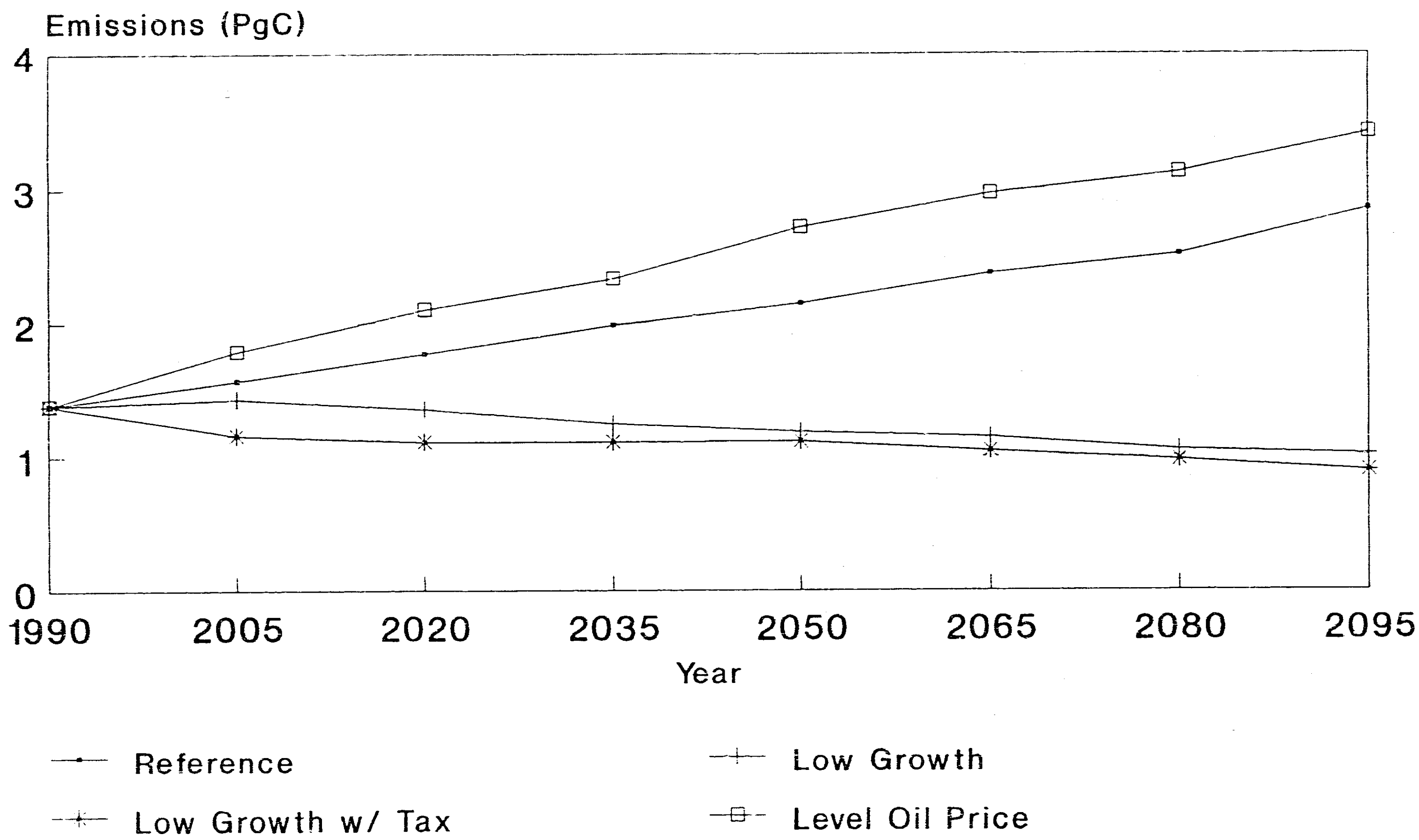


Figure 33. Case Xi-Low U.S. Growth
U.S. Primary Energy Consumption
With Low Economic Growth-No Tax



EMF-12

Figure 34. Cases XI and XII
U.S. Carbon Emissions
Low Economic Growth and Level Oil Price



EMF-12

Figure 35. Case XI-Low Economic Growth
U.S. Carbon Taxes

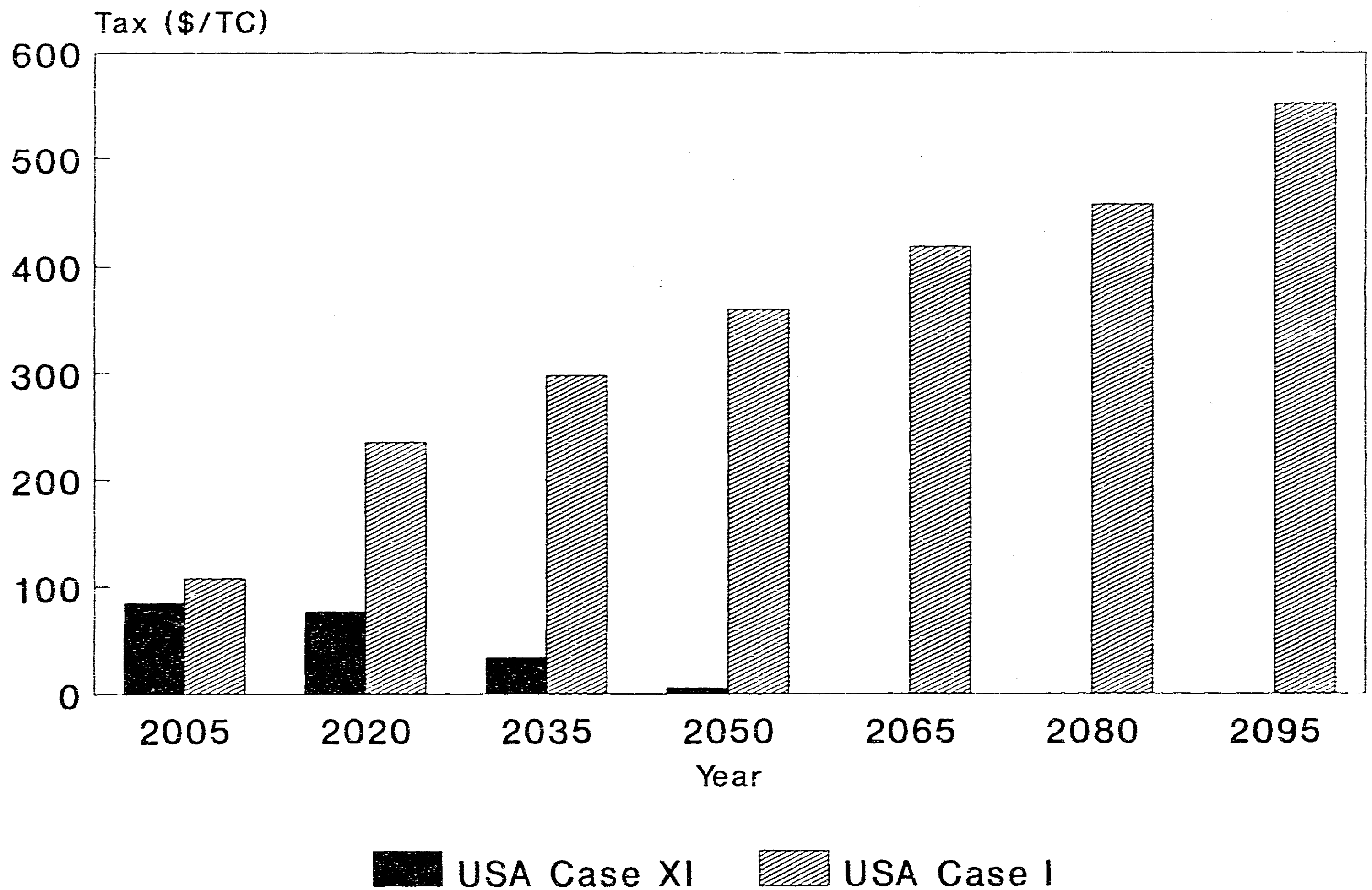


Figure 36. Case XI-Low U.S. Growth U.S. Primary Energy Consumption Low Economic Growth-Taxes Applied

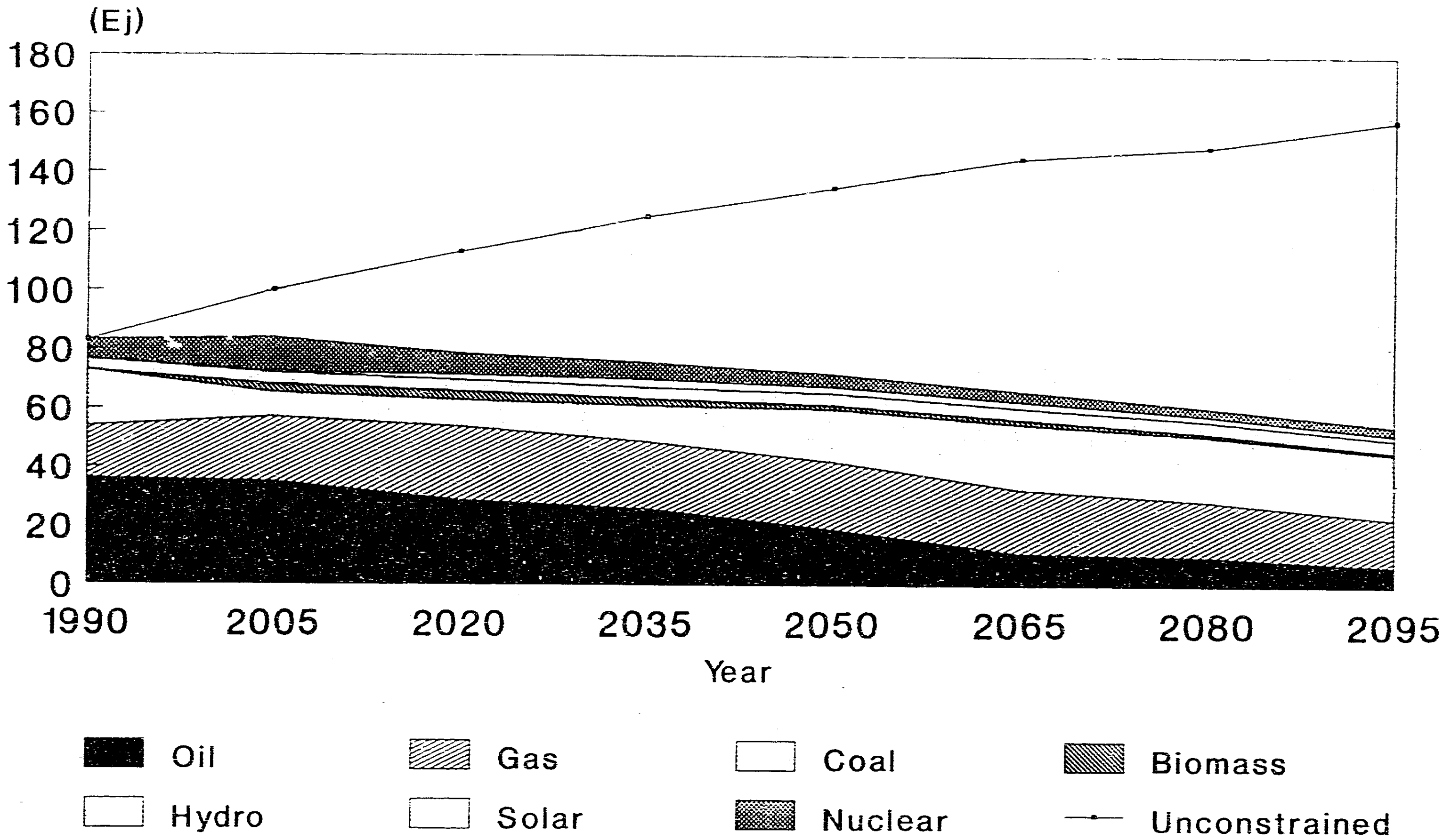


Figure 37. Case XII-Level U.S. Oil Price
U.S. Primary Energy Consumption

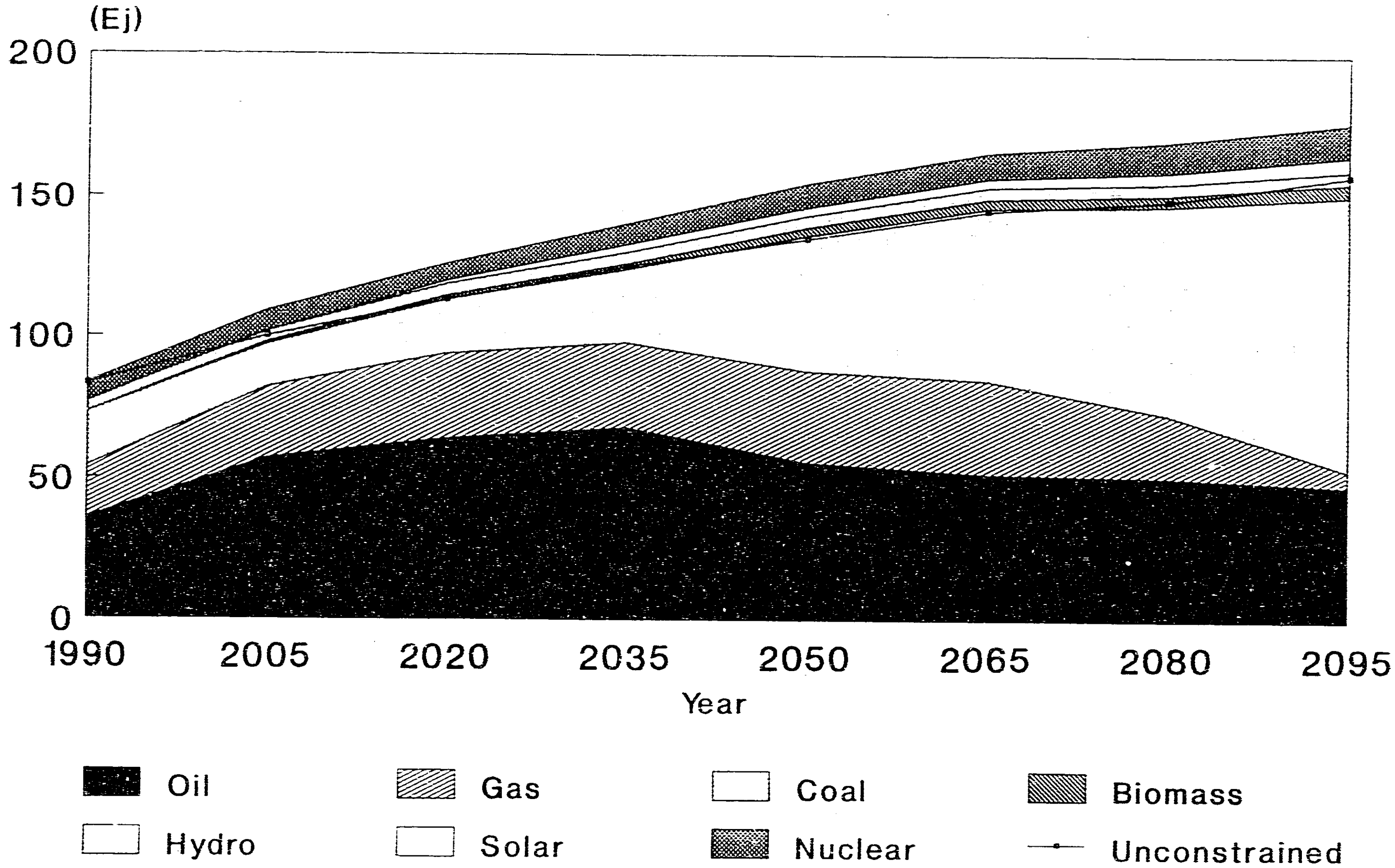


Figure 38. Case XIIIA-Combination
Uniform Carbon Taxes
Case V Compared with Case XIIIA

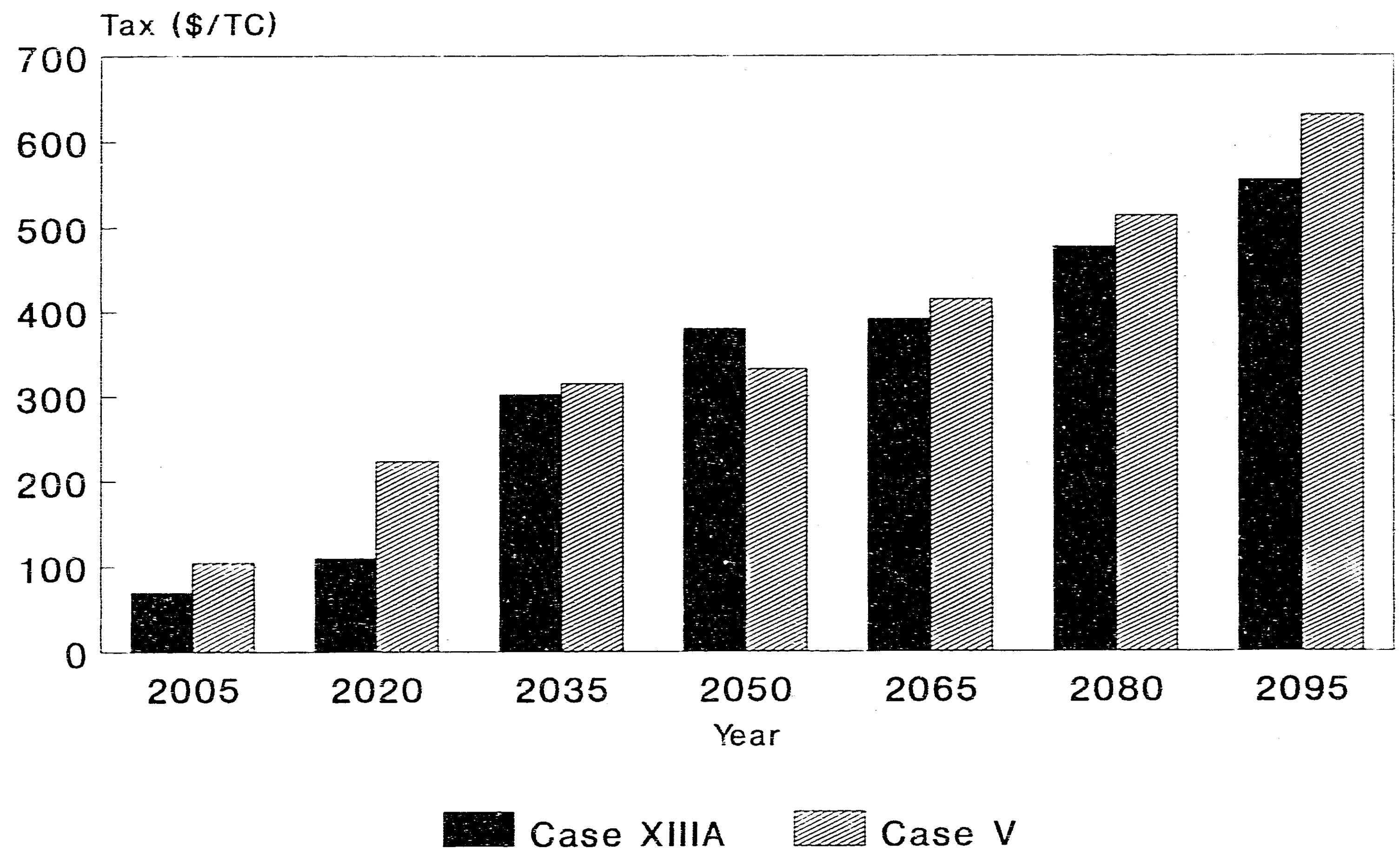


Figure 39. Case XIIID1-Sensitivity Run Primary Energy Consumption Zero Rate of Technical Improvement

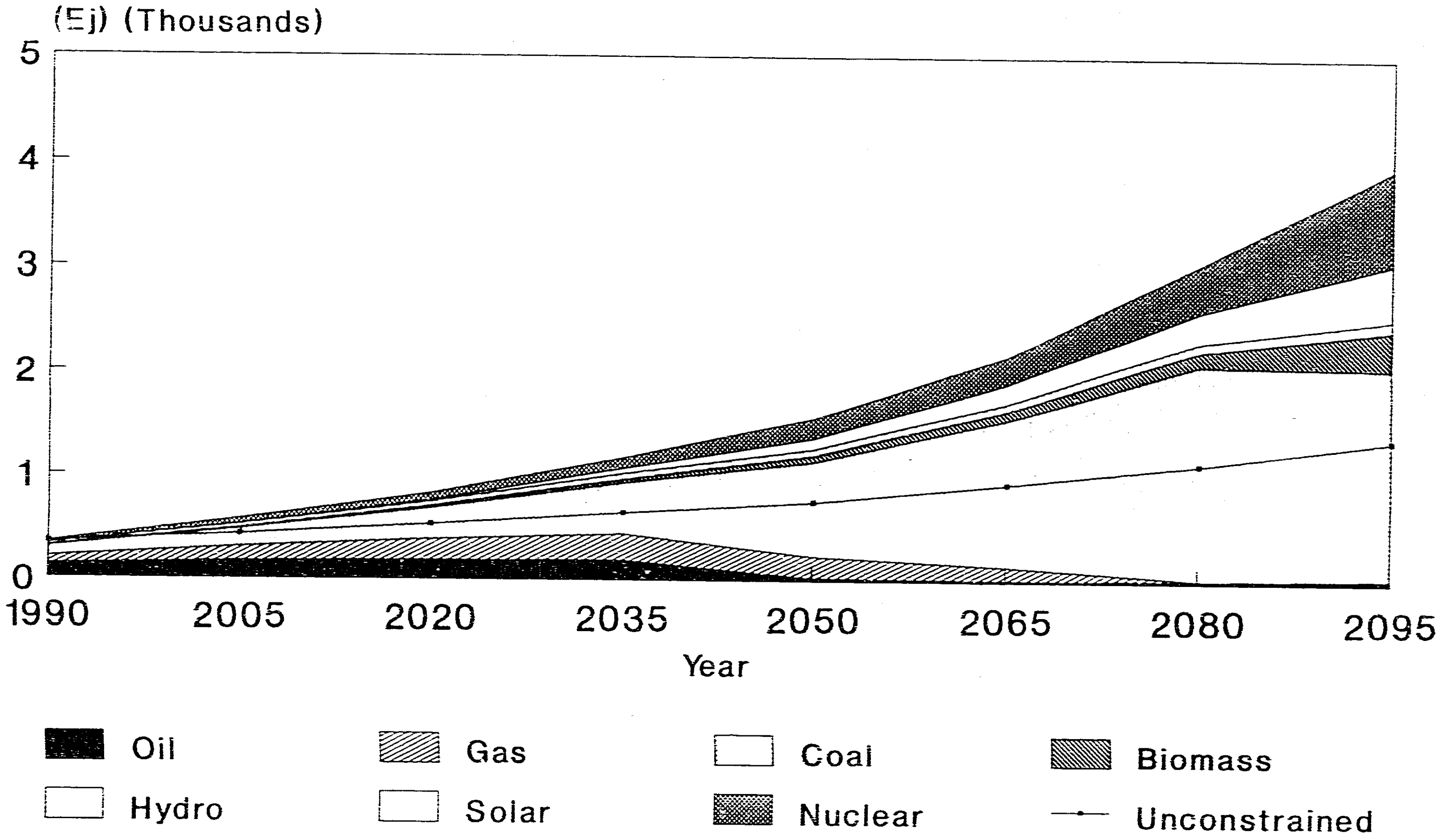


Figure 40. Case XIIID2-Sensitivity Run
Primary Energy Consumption
High Rate of Technical Improvement (2%)

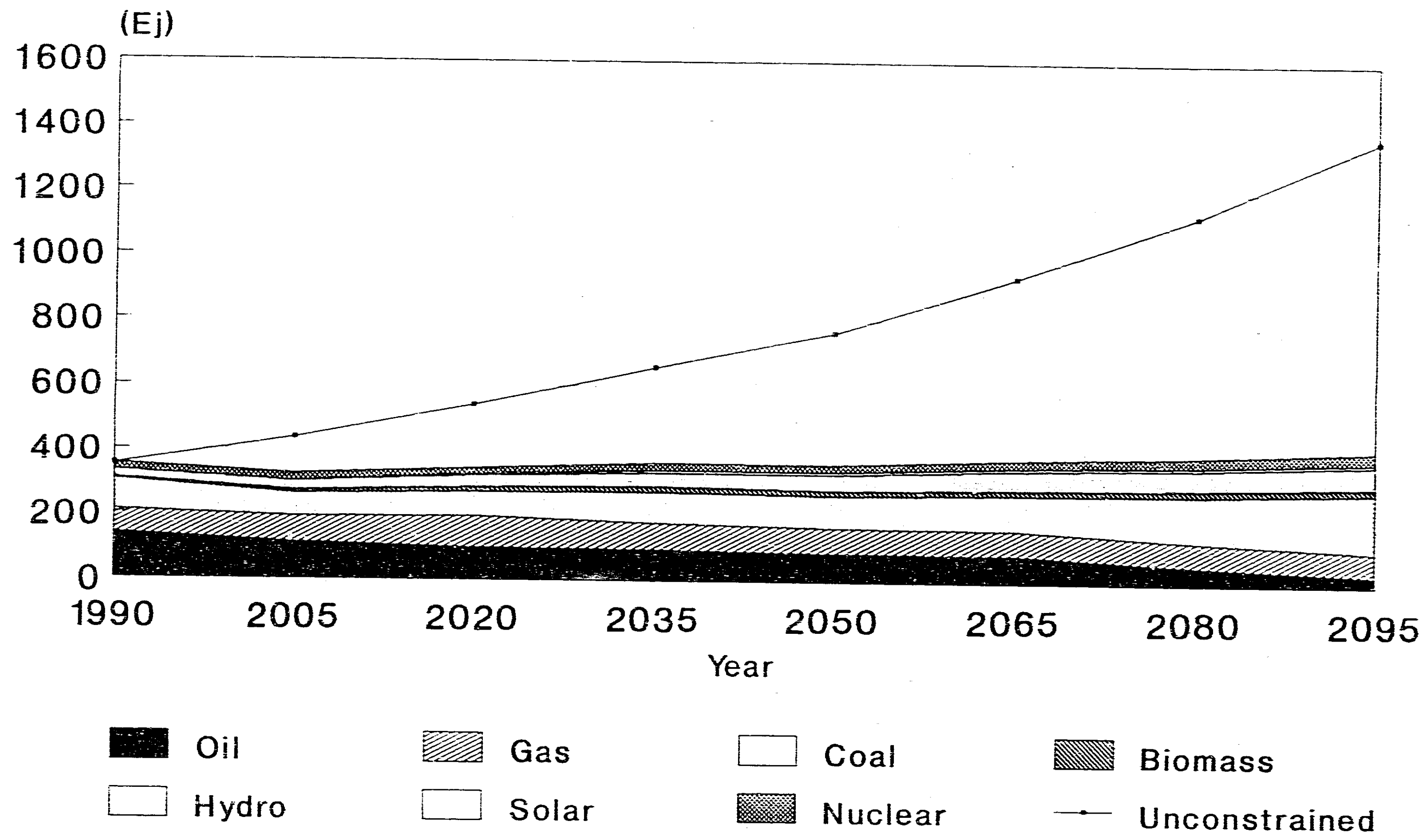


Figure 41. Case XIIID3-Sensitivity Run
Primary Energy Consumption
Low Rate of Technical Improvement (0.5%)

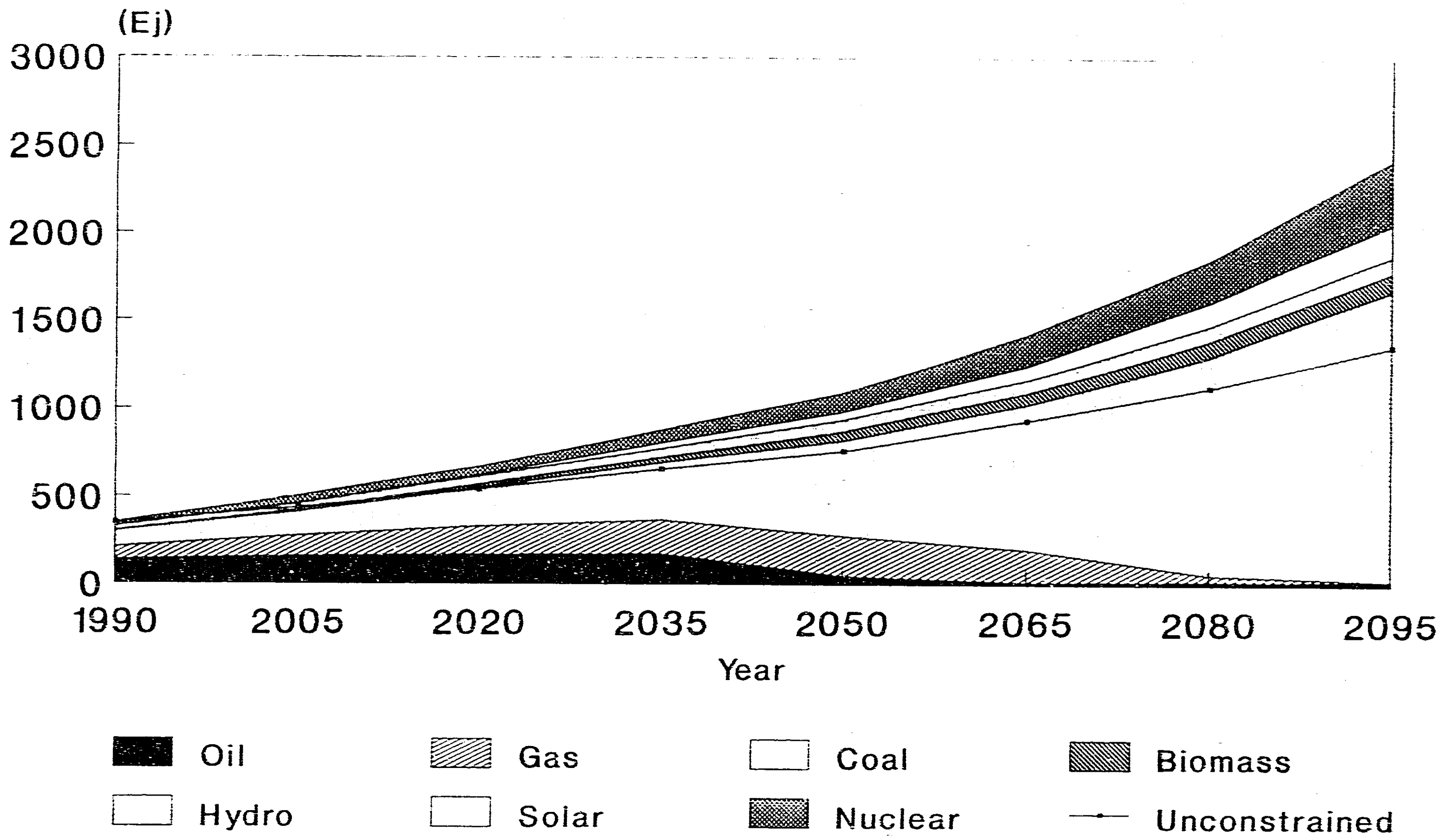


Figure 42. Case XIIID-Sensitivity Runs
Carbon Emissions
AEEI and Substitution Elasticities

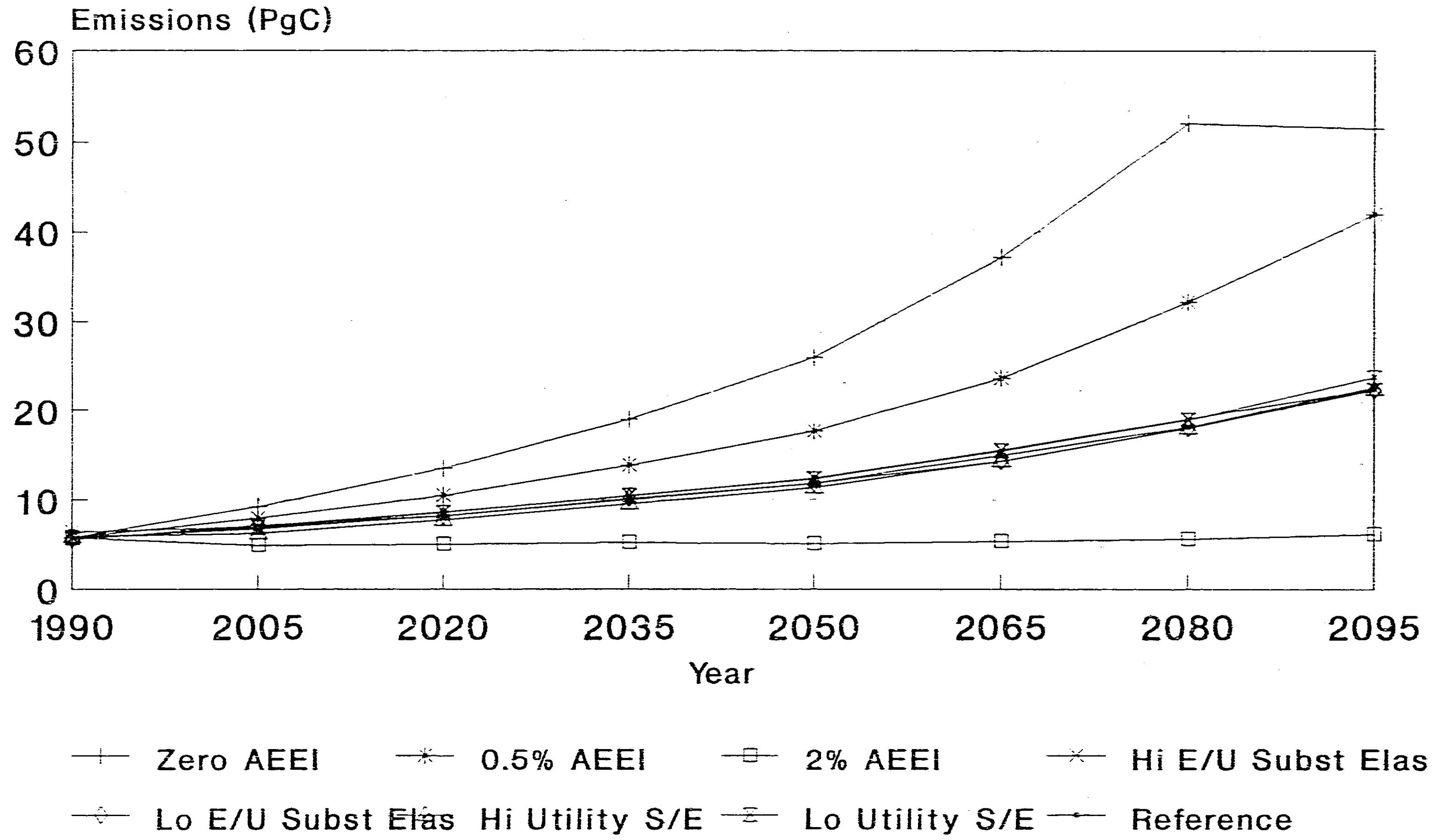


Figure 43. Case XIIID4-Sensitivity Run
Primary Energy Consumption
Low E/U Substitution Elasticity (-1.0)

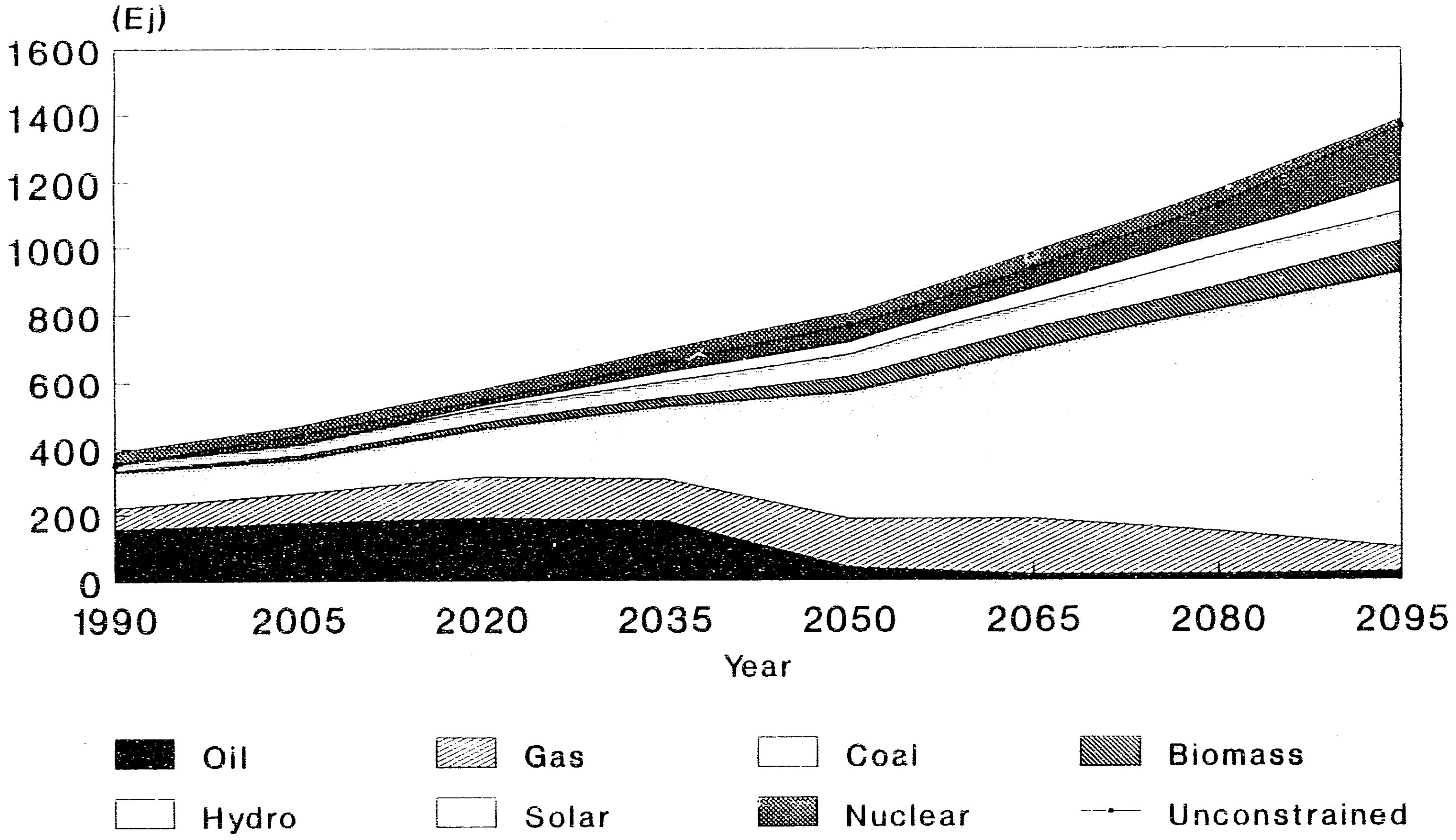


Figure 44. Case XIIID5-Sensitivity Run Primary Energy Consumption High E/U Substitution Elasticity (-7.0)

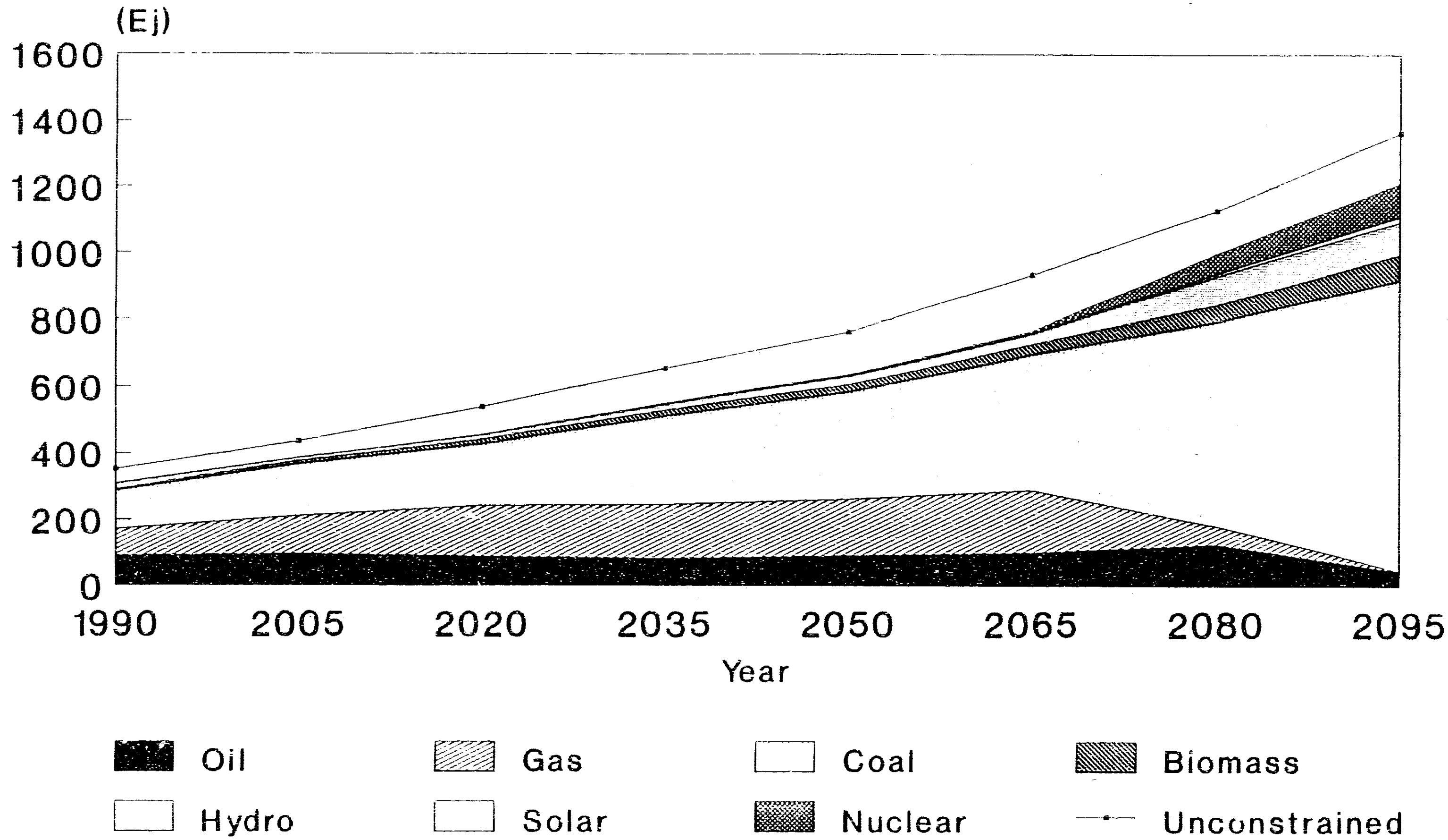


Figure 45. Case XIIID6-Sensitivity Run
Primary Energy Consumption
Low Utility Subst. Elasticity (-1.0)

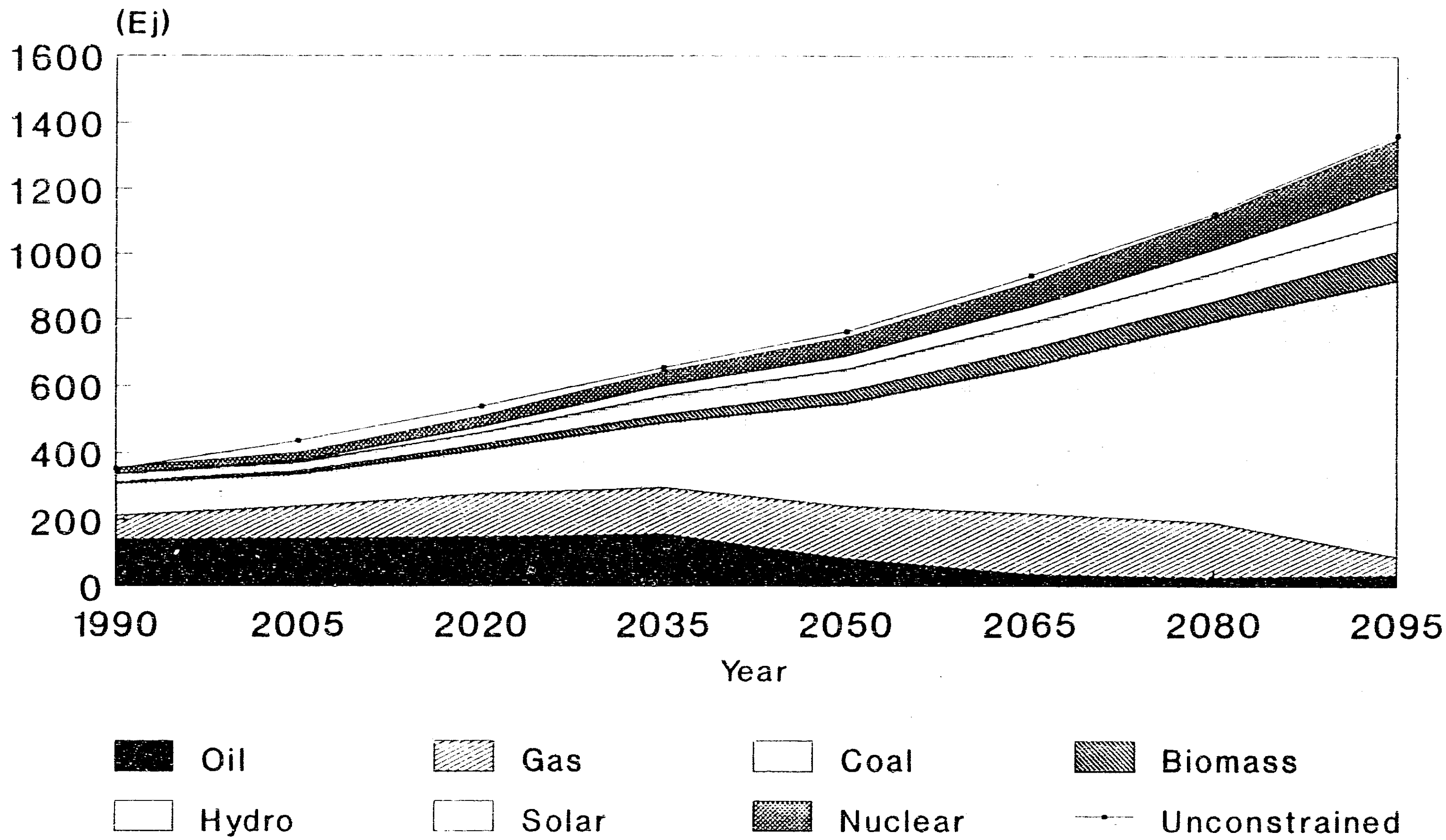


Figure 46. Case XIIID7-Sensitivity Run
Primary Energy Consumption
High Utility Subst. Elasticity (-6.0)

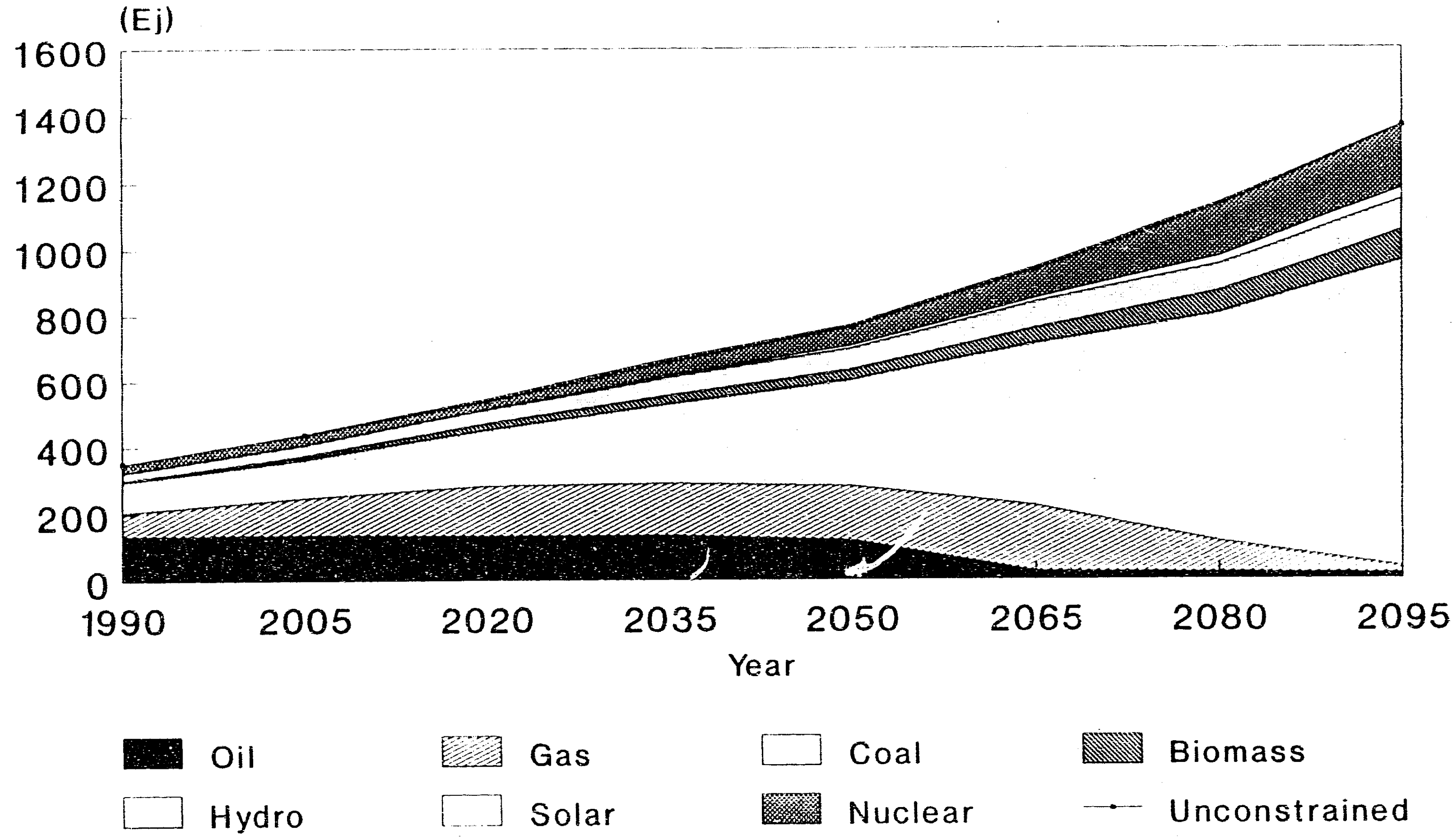
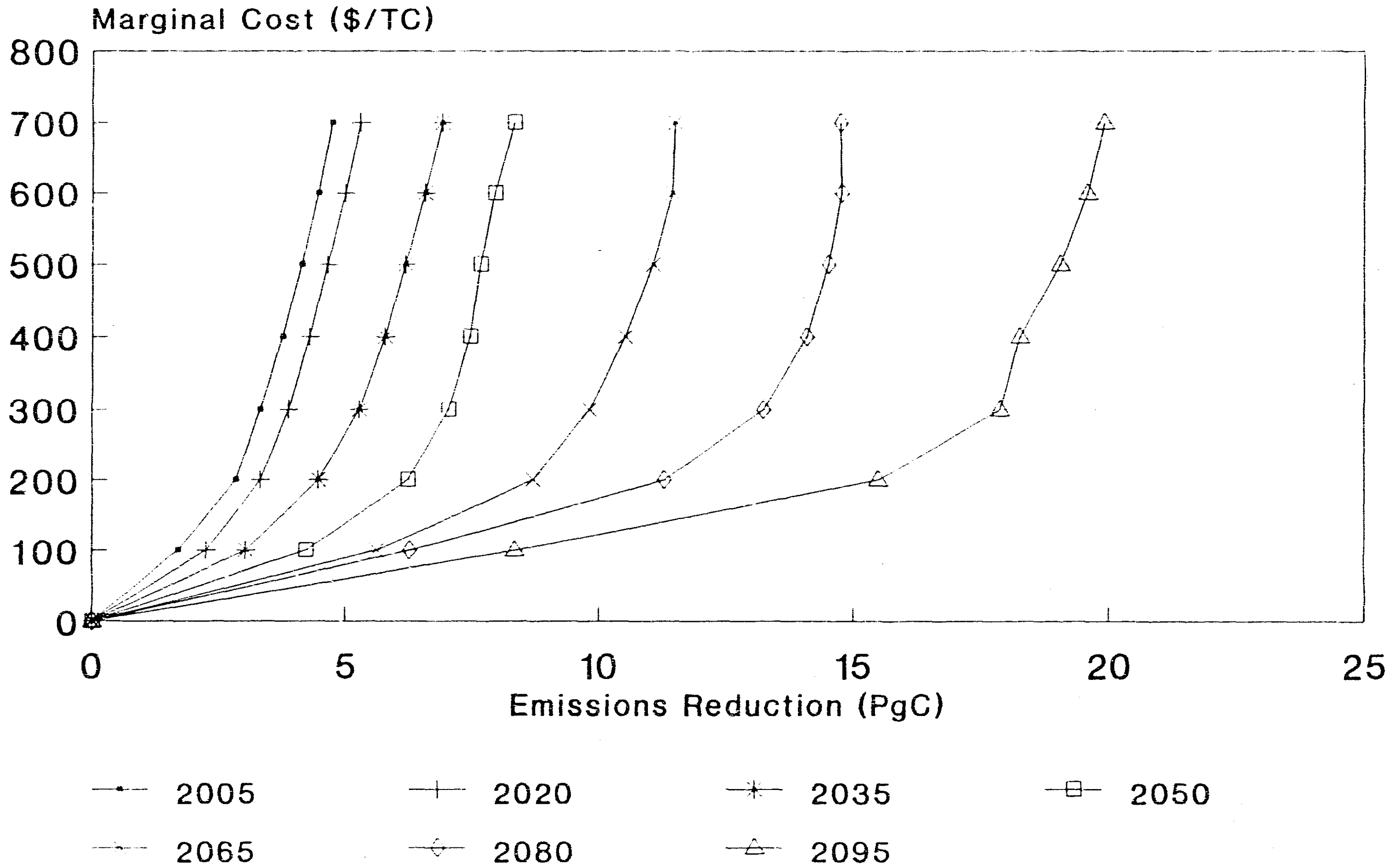
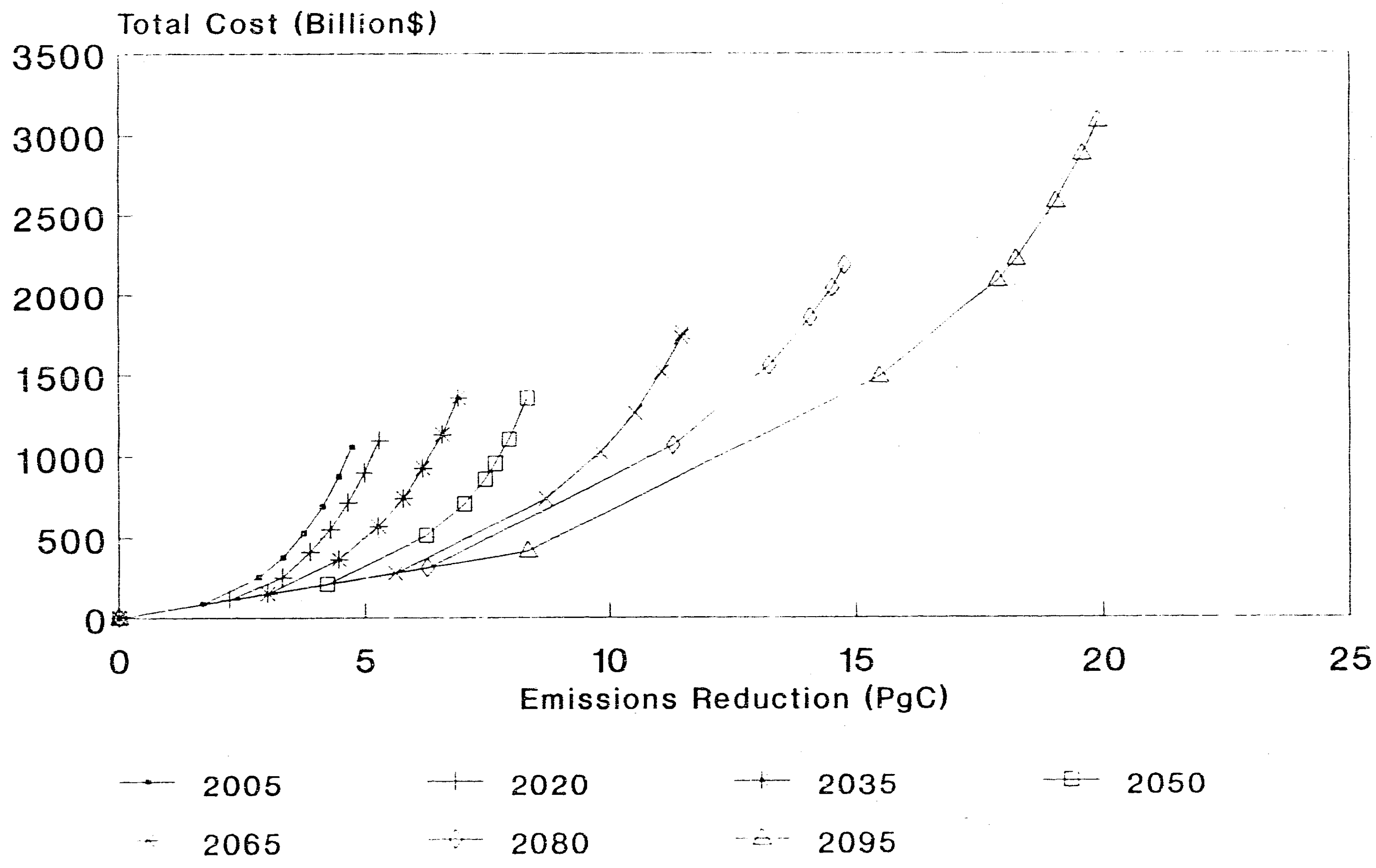


Figure 47. Marginal Cost-Uniform Tax
EMF 12 Data



EMF-12

Figure 48. Global Total Cost-Uniform Tax
EMF 12 Data



EMF-12

Figure 49. Global Total Cost-Uniform Tax
EMF 12 Data

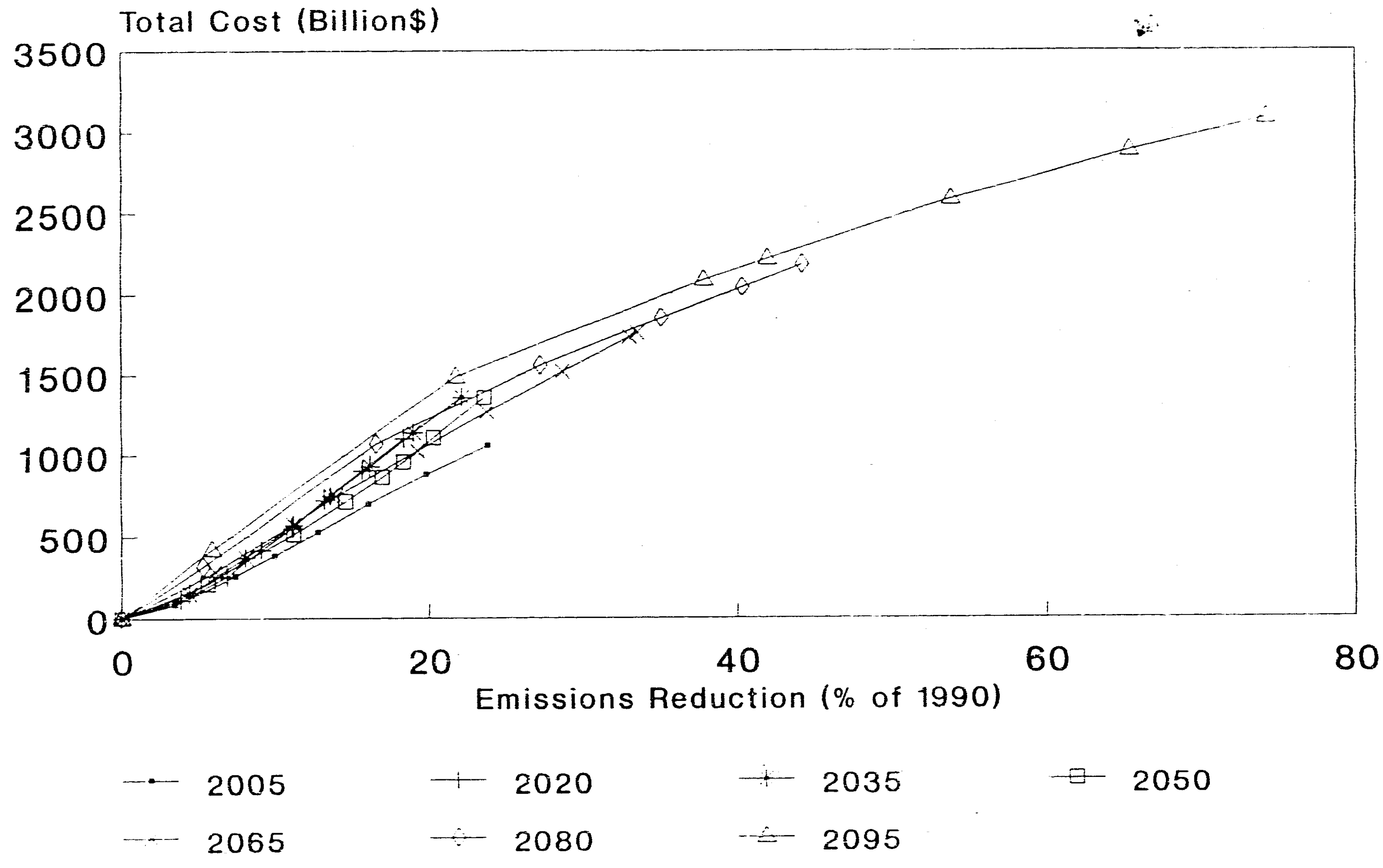


Figure 50. GNP Reduction-Uniform Tax
EMF 12 Data

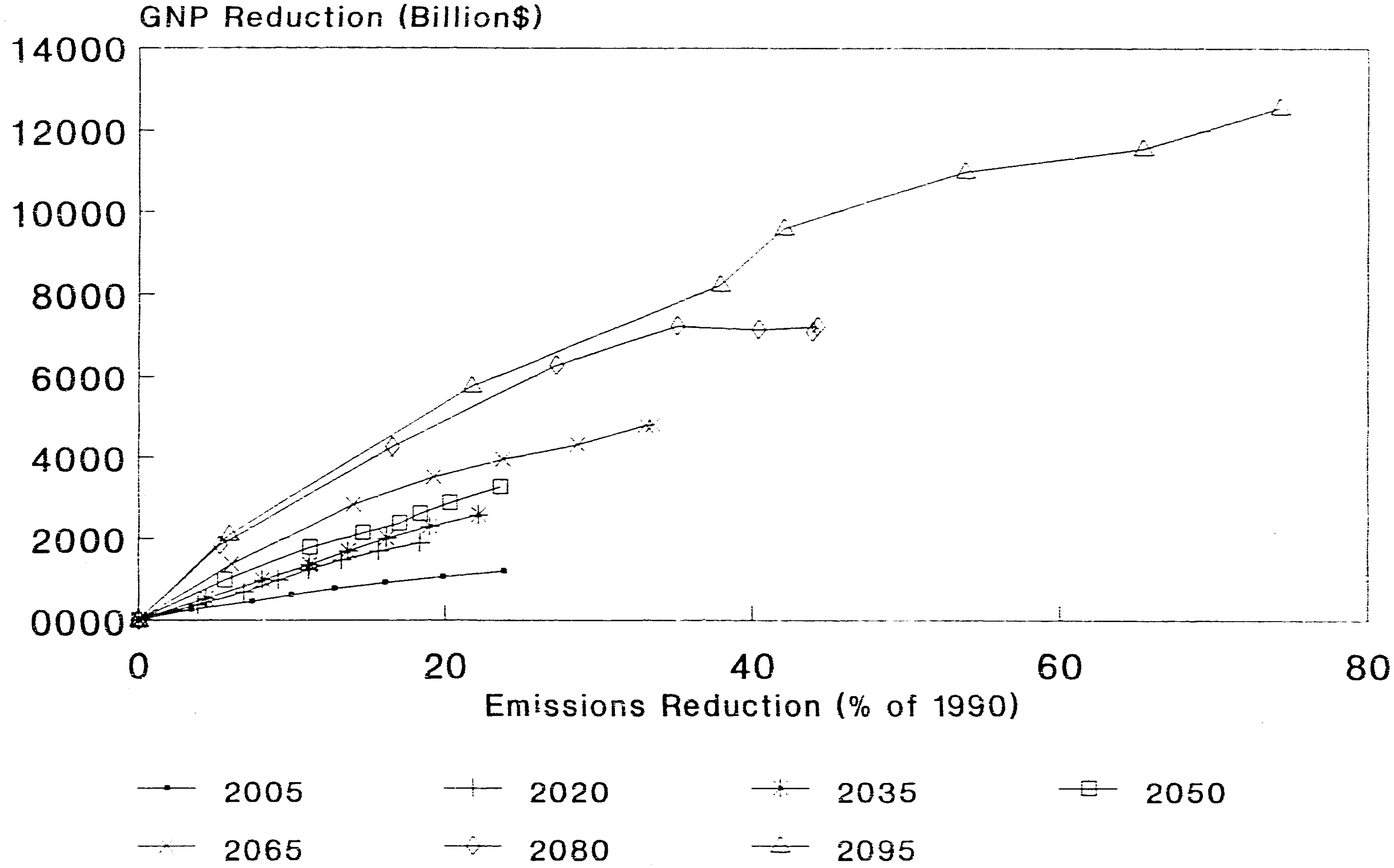
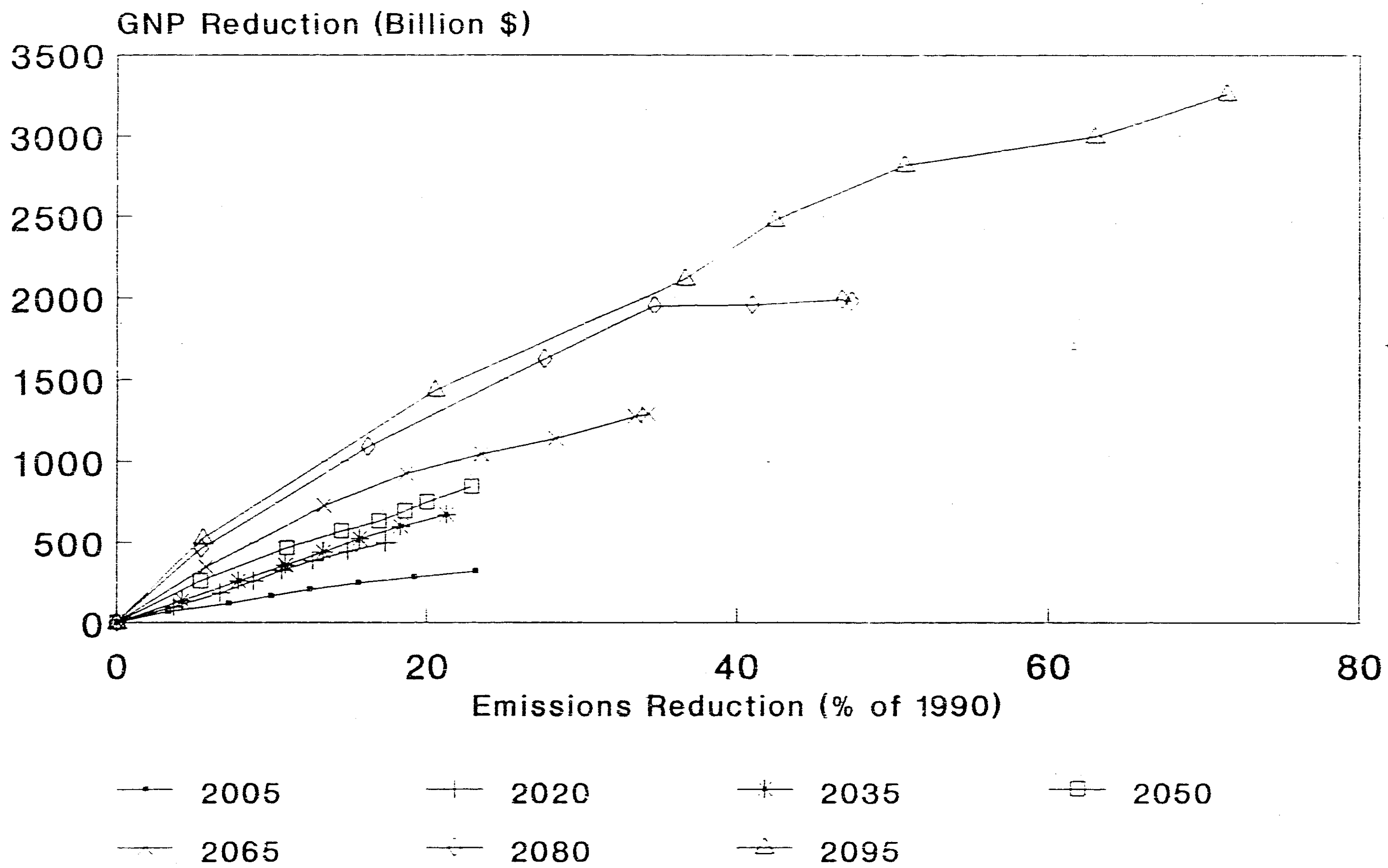


Figure 51. GNP Reduction-Uniform Tax
EMF 12 Data-Low GNP Feedback Elasticity



EMF-12

END

DATE FILMED

5/5/92