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Project Summary

Analysis of Historical Radiatively Important Trace Gases (RITG) Emissions: Development of a Trace Gas Accounting System (T-GAS) for 14 Countries

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In September 1989, a study was completed which focused on evaluating the feasibility of developing a country-specific CO_2 emissions forecast model. One objective of this 1989 study was to develop a pilot scale emissions model which could be used to estimate energy consumption and CO_2 emissions for specific energy end-use sectors in a country. Consistent with this objective, a pilot scale model was developed for Poland, South Korea, France, and India. The second objective of this study was to test or validate the methodology used in the model and, if the methodology proved to be viable, to develop a full scale model development plan. Analysis of the results from the pilot model showed that the methodology was a potentially viable tool for developing a country-specific global emissions model. Based in part of this finding, EPA decided to initiate a more comprehensive, Phase 2 study. This report summarizes the results of the Phase 2 study. The objectives of the Phase 2 study were to: (1) develop and test a CO_2 emissions model for 14 countries; (2) conduct a limited test of the model's forecasting capability by estimating and comparing emissions forecasts for Poland with forecasts developed by other models; and (3) use the model and accompanying global energy use databases to summarize and assess historical energy use and emissions patterns for the 14 countries. A key outcome of the Phase 2 study was the development of model algorithms and databases for the 14 countries. Other key outcomes were the development of software systems which facilitate the use of the algorithms and databases developed under this program, and which assist in the manipulation and analysis of the model resuts. These algorithms, databases, and software systems are referred to as the Trace Gas Accounting System (T-GAS).

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Identifying and assessing the most applicable and effective mitigation strategy for a country requires that country-specific emission patterns be examined and that country-specific mitigation studies be conducted. Those strategies which are ultimately identified as the best will vary from country to country depending on several highly country-specific factors such as its energy infrastructure, energy resource base, political and social system, economic system, level of development, and the general health of the economy. As the debate over greenhouse gases and mitigation strategies continues, the need to conduct representative country-specific case studies which are consistent with these and other factors will continue to increase. It is this need which prompted the research described in this report.

In September 1989, a study was completed which focused on evaluating the feasibility of developing a country-specific carbon dioxide (CO_2) emissions forecast model. Key objectives of the 1989 study were to develop a pilot scale emissions model for energy related sources and to test or validate the methodology used in the model to estimate historical and future CO_2 emissions. This study was referred to as the Pilot Study, and the results and recommendations for future research were summarized in a model development and implementation plan, which described the methodology used to develop a pilot scale emission model for Poland, South Korea, France, and India. The plan also summarized the results of an analysis performed to validate the country- and sector-specific emissions estimates developed by the pilot scale model. Finally, the plan laid the groundwork for a full scale model development program based on the results of the Pilot Study.

The methodology used to develop the pilot scale model differs from other techniques applied to develop energy related CO_2 emissions models. In general, the model consists of regression equations that estimate the demand for specific energy types (e.g., coal, oil, gas, electricity) in key energy end-use sectors of a country, including the industrial, transportation, residential, commercial, and agricultural sectors. The input variables for these regression equations include standard economic and demographic variables such as GNP,* fuel prices, population, and personal consumption expenditures. The equations are developed by performing regression analyses using historical energy, economic, and other data sets for each country. To estimate emissions for a country with the model, the demand for specific fuel types in each sector is first estimated by the regression equations for years for which economic and other input variables are provided. These energy demand estimates are then converted into CO_2 emissions using country-specific emission factors and information which characterize the performance and makeup of each country's secondary energy production system (e.g., electric utilities and refineries).

A validation of the results from the pilot model showed that the methodology used to develop the model represented a potentially viable basis from which a country-specific global emissions model could be developed. As discussed earlier, a model development work plan was prepared to guide future work at the conclusion of the pilot study. Based in part on these conclusions, EPA decided to initiate a more comprehensive Phase 2 study. This report summarizes the findings from this Phase 2 study.

* Gross national product.

Scope of the Phase 2 Study

In the Phase 2 study, the basic methodology developed under the Pilot Study was used to develop and validate CO_2 emission models for the 14 countries listed in Table 1. As for the Pilot Study, countries selected for the Phase 2 study represented a mix of differing economic, social, and developmental characteristics. The countries included those participating in the IPCC (Intergovernmental Panel on Climate Change) process.

A primary objective of the Phase 2 study was to develop and test the CO_2 emissions models developed for the 14 countries listed in Table 1. Other key objectives were to conduct a limited test of the model's forecasting capability and to use the models and accompanying global databases to examine historical energy and emissions patterns. The equations, databases, and computer software developed in support of these objectives are referred to as the Trace Gas Accounting System (T-GAS).

Consistent with the above objectives, three technical analyses were conducted:

- For each of the 14 countries, T-GAS regression equations were estimated and the model framework was developed. The representativeness of the results from the model was then examined by comparing T-GAS results with established energy and emissions databases. Where discrepancies were identified, assessments were conducted to identify the source of the discrepancies and, where possible, the model was revised.
- Historical energy use data from the OECD and historical CO_2 emissions estimates from T-GAS were developed and summarized for each of the 14 countries.
- T-GAS emissions forecast capability was examined by conducting a limited test forecast in which emissions were estimated for Poland from 1958 to 2030 with T-GAS and the results were compared to other model results developed for the IPCC.

Development/Performance of Models for the 14 Countries

The quantity and mix of fuels used to produce outputs vary greatly among sectors and nations. Nevertheless, the economic principles that guide a firm's technological decisions can be used to analyze fuel consumption and assess the potential for change. As the price of a fuel rises, the impetus for technological change increases and the resultant change can reduce the amount of fuel used to produce a unit of output. Similarly, as the price of one fuel rises relative to another, substitution allows firms to replace some fraction of the fuel whose price has risen with the fuel against which that price has been registered. The key factors influencing these changes can be identified and quantified based on an econometric analysis of historical data. By assuming that such opportunities for technological change and fuel substitution persist, the behavioral responses or response functions estimated from historical data can be useful in forecasting the effect of future changes.

The T-GAS model uses these response functions to estimate demand for coal, oil, gas, heat, and electricity. The results of the development of these response functions for each country are too complex to discuss in this summary but are discussed in detail by country in the full report. Instead, this summary examines the performance of the equations developed for each country.

The representativness and performance characteristics of T-GAS response functions were evaluated by comparing a "backcast" of CO_2 emissions from the model with an historical CO_2 emissions record developed for the U.S. Department of Energy (DOE)* for each of the 14 countries.

* Rotty, R.M. and G. Marland. Production of CO_2 from Fossil Fuel Burning by Fuel Type, 1860-1982. U.S. Department of Energy, 1984.

Table 1. *Countries in Phase 2 Study*

OECD Countries*	*Developing Countries*	*Other Non-OECD Countries*
France	*Brazil*	*China*
Italy	*India*	*Hungary*
Japan	*Mexico*	*Poland*
United Kingdom	*South Korea*	*Soviet Union*
United States		
West Germany		

* *Organization for Economic Co-operation and Development.*

T-GAS backcasts were calculated by using historical economic and other data as inputs to the regression equations in the model to calculate the fuel-specific demand for energy. The amount of CO_2 released was then estimated by multiplying these energy demand estimates by country-specific CO_2 emission factors.

This model validation exercise attempts to test the model's endogenous behavior, such as the regression equations which are used to estimate energy demand. The integrity of this validation is maintained in several ways. First, the nations used in this validation represent a wide range of economic systems, including developed economies, economies that have undergone rapid development, developing economies, and centrally planned economies. The equations for fuel intensity were estimated with data from the period 1971 to 1985, but the backcast extends to the late 1950s (in some cases) and early 1960s, depending on the availability of historical economic data. The timing of this break provides an additional test of the methodology. If the backcast reproduces the DOE historical CO_2 record, it may indicate that the dramatic price changes of the 1970s and 1980s did not change the behavioral relationship between energy use and economic activity. In fact, such stability does appear to occur and indicates that the behavioral relationship that prevailed in the 1970s and 1980s can be used to forecast into the 1990s and the beginning of the next century.

Figures 1 through 14 compare the emissions estimates developed by T-GAS with DOE emissions estimates. The figures show the percent difference between T-GAS DOE emission estimates for the years examined in this study. The percent difference is defined in the following manner:

percent difference =
([T-GAS - DOE]/T-GAS)*100.

The results for the 14 countries are presented in order of decreasing emissions significance; i.e., those countries with the greatest emissions are presented first. As the figures show, T-GAS results are generally in good agreement with the DOE emission estimates. For most countries examined, T-GAS emissions are usually well within 10% of the DOE emission estimates. The stated accuracy of the DOE record is ± 10%.

The difference between T-GAS and DOE emissions is consistently higher than 10% for a few countries, including South Korea, India, West Germany, and Mexico. For South Korea, the results presented in Figure 12 are somewhat misleading. Although the differences shown for the late 1950s and early 1960s are high, the absolute value of the difference between these two methodologies is relatively small. In fact, a detailed examination of the emissions results for South Korea shows that the model accurately predicts the rapidly increasing energy and emissions use trends which have occurred there since the early 1960s.

For India, agreement between the two methodologies is poor from about 1976 to 1985. In an effort to identify the reasons for this poor agreement, the reliability of the OECD energy data used to develop T-GAS response functions was examined. A comparative study was conducted to com-

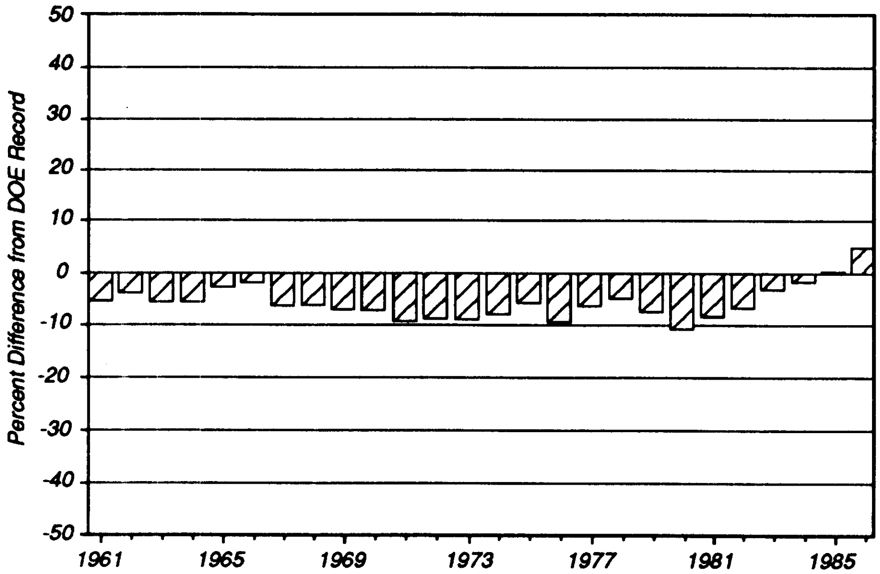

Figure 1. *Percent difference between T-GAS and DOE emission estimates for the United States from 1961 to 1986.*

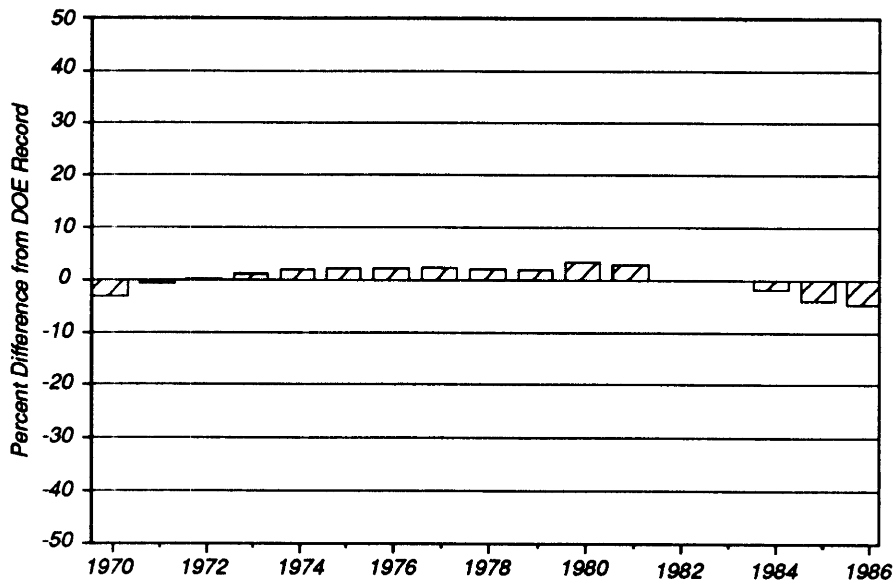

Figure 2. *Percent difference between T-GAS and DOE emission estimates for the Soviet Union from 1970 to 1986.*

* Rotty, R.M. and G. Marland. Production of CO_2 from Fossil Fuel Burning by Fuel Type, 1860-1982. U.S. Department of Energy, 1984.

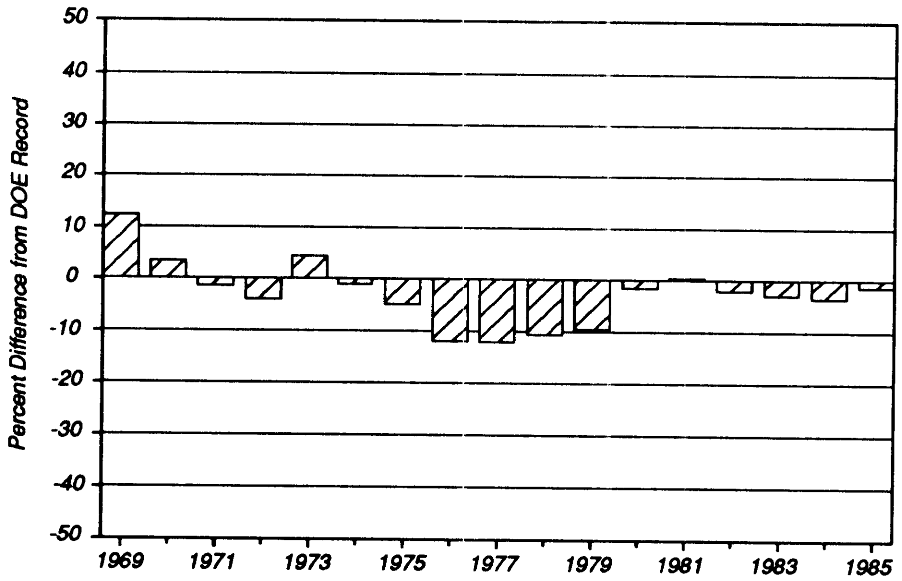

Figure 3. *Percent difference between T-GAS and DOE emission estimates for China from 1969 to 1985.*

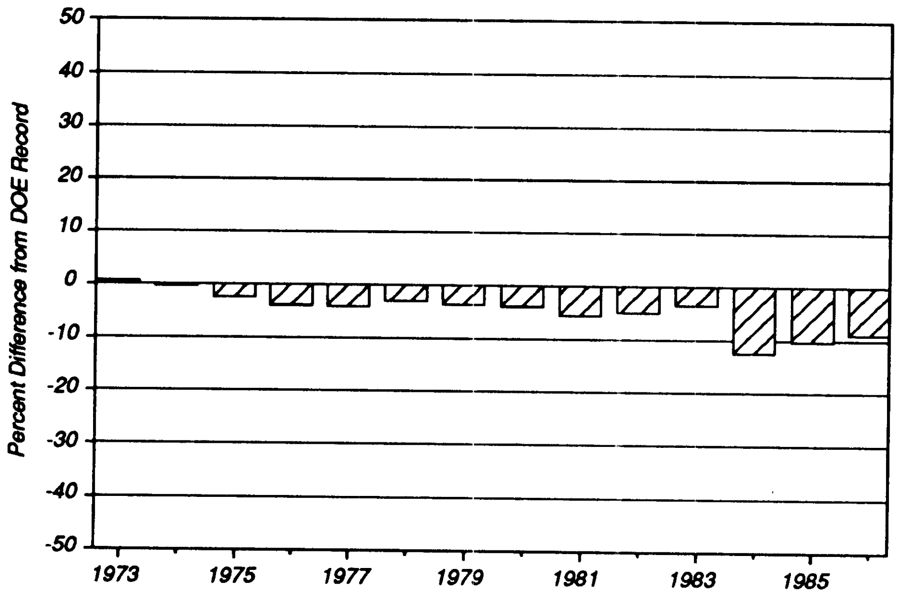

Figure 4. *Percent difference between T-GAS and DOE emission estimates for Japan from 1973 to 1986.*

pare OECD energy data with other energy databases developed for India. These comparisons revealed no serious discrepancies with the OECD database and indicated that the discrepancy between DOE and T-GAS emission estimates might be attributable to errors in the energy data used to develop the DOE data. The DOE data were developed in part from United Nations energy data statistics, and the energy data comparisons conducted in the T-GAS study reveal some unexplained data inconsistencies. A similar comparative study was conducted for Mexico and discrepancies were found between the OECD energy data used to develop T-GAS and the United Nations data sets used in the DOE record. Conclusions could not be reached as to which data set for Mexico was in error.

West German emissions estimates for oil use, a dominant fossil fuel source of CO_2 emissions in that country, agree reasonably well with DOE for all years (the difference is less than 10%). Coal use compares well in the early years but diverges significantly from the DOE values starting about 1970 (T-GAS is higher than DOE). This divergence in coal use is a primary cause of the poor agreement between the DOE and T-GAS total emissions estimates shown in Figure 5. Closer examination of the results shows that T-GAS total coal estimates appear to be overstated for many years in the 1970s and 1980s.

Summary of Historical Emissions and Energy Use Data

In the process of developing the emissions backcasts discussed earlier, a substantial volume of historical emissions data was developed for the 14 countries. These historical emissions data and the historical energy use databases used to develop T-GAS can be used to examine historical emissions patterns of individual countries and to identify the factors contributing to emissions changes within a country. By examining the factors which have influenced emissions changes in the past, valuable information can be developed concerning how best to reduce emissions in the future, and what changes might be expected as a result of implementing specific emissions mitigation strategies. Such detailed assessments could not be conducted within the scope of this study. However, a brief overview of the types of data developed in this study should provide the reader with a basis for assessing how such information could be used in performing such assessments in the future. A more comprehensive summary of the historical emissions and energy data developed for each country is presented for each country in the full report.

Figures 15, 16, and 17 present estimates of total CO_2 developed by T-GAS for the 14 countries evaluated. Figure 15 shows historical emissions for the four countries in this study that produce the most emissions. Figure 17 presents the historical emissions associated with several developing countries, while Figure 16 presents the historical emissions associated with several European countries. Although a detailed assessment of these data was not conducted, some interesting features in the data are noted. First, the data show that CO_2 emissions from several major countries (e.g., France, Brazil, Japan, West Germany, the United Kingdom) have been declining over the years. These emission reductions have occurred in spite of the fact that the economies of many of these countries continue to grow.

Several different and complex reasons for these emission reductions can be identified based on the data developed in this study, and each reason points to areas where further mitigation evaluations should be focused. Figure 17 compares CO_2 emissions for developing nations for various years. As the figure shows, Brazil's emissions trends are an anomaly compared to those of other developing nations: growth in emissions has decreased dramatically since the late 1970s. For many years, the Brazilian electric utility sector has steadily increased its use of non-fossil fuels (primarily hydropower) to the point that over 90% of the total electricity generated in the country comes from non-fossil fuel power plants. This, coupled with the fact that during the 1970s many energy end-use sectors (i.e., industrial, residential, and agricultural) in Brazil dramatically increased their use of electricity, has significantly contributed to reductions in the use of fossil fuels. Clearly, emissions mitigation strategies aimed at reducing electricity consumption in Brazil would do little to reduce CO_2 emissions. Instead, strategies aimed at reducing the consumption of fossil fuels in major end-use sectors seem more appropriate. For Brazil, this includes the transportation sector, which accounted for about 50% of the total fossil fuel consumption there in 1987. Within this sector, road transportation is the most significant, accounting for 87% of the total energy consumed. The second most significant consumer of fossil fuels is air transport (7%), followed by ship transport (3%).

Figures 18 and 19 show historical emissions and energy use trends associated with Japan and the U.S., respectively. For both countries, the figures can be used to examine historical changes in the overall CO_2 emission intensity for each country (i.e., the amount of CO_2 produced per unit of total energy consumed). As Figure 18 shows, total emissions in Japan have been increasing slowly relative to increases in total energy consumption. As a consequence, the emissions intensity in Japan has decreased significantly from a value of 0.73 tons of carbon per TOE* in 1973 to 0.60 tons of carbon per TOE in 1986 (almost a 20% reduction). On the other hand, the emissions intensity for the U.S. has changed very little since the early 1960s. Figure 19 shows that both total emissions and total energy use have steadily increased since the 1960s. In the early 1960s, the emissions intensity was 0.72 tons of carbon per TOE. By 1987, the value had decreased very little to 0.70 tons of carbon per TOE (less than a 3% decrease). There are several reasons that Japan has reduced its emissions intensity so significantly. As for Brazil, Japan has simultaneously expanded its use of non-fossil fuels at electric utilities and expanded the role of electricity use as a major fuel in several key sectors. Based on the regression analysis conducted to develop the response functions, it also appears that the energy intensity associated with several major sectors has been steadily decreasing in Japan. This indicates that energy is being used more efficiently and that the economy has steadily moved toward providing goods and services which do not require significant amounts of energy to produce (e.g., electronics).

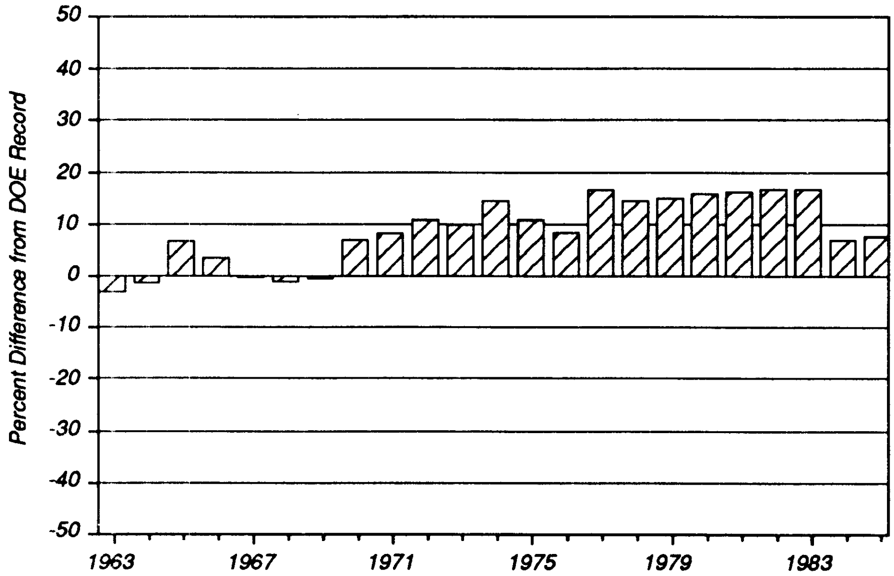

Figure 5. *Percent difference between T-GAS and DOE emission estimates for West Germany from 1963 to 1985.*

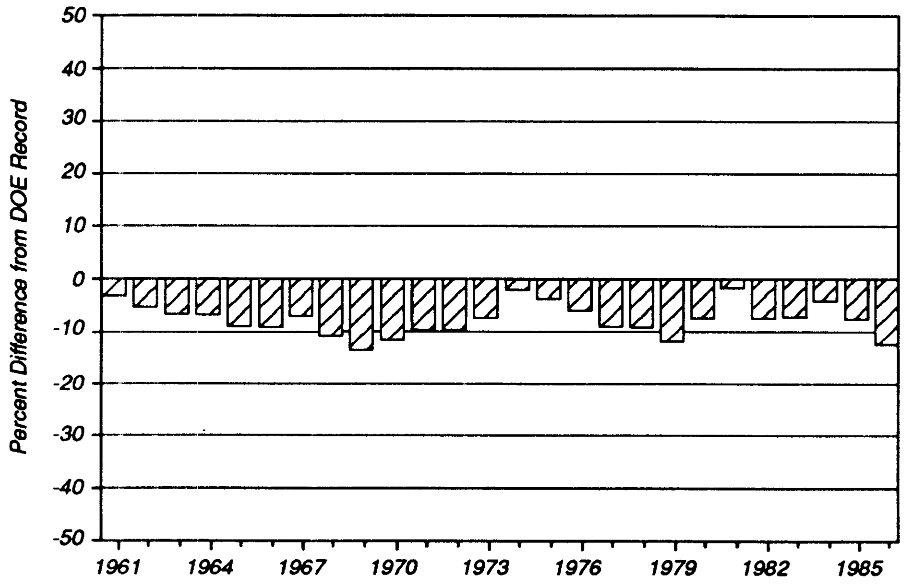

Figure 6. *Percent difference between T-GAS and DOE emission estimates for the United Kingdom from 1961 to 1986.*

* Ton of oil equivalent.

Development/Analysis of an Emissions Forecast for Poland

Although the model was used in this study primarily to estimate and assess historical CO_2 emissions, it can also be used to estimate future emissions if values for future economic and other variables are provided as inputs. Key objectives of the Phase 2 study were to examine the model's forecasting capability and to assess its ability to perform emissions mitigation evaluations. The results of such an effort are presented for Poland. In general, Poland was selected for this component of the study for several reasons: (1) it is an important case study in the mitigation evaluations conducted under the IPCC; and (2) the energy, economic, and political structure in Poland poses challenges to the development of a representative emissions model for the country.

The Response Strategies Working Group of the IPCC conducted an emissions mitigation study for Poland. In the IPCC study, several future emissions scenarios were developed and evaluated using a different emissions model. Using the T-GAS model developed for Poland, an attempt was made to reproduce and compare the model results obtained in the IPCC study by using scenario assumptions from the IPCC study as inputs to T-GAS.

Two different emission scenarios were examined: the base case scenario and the structural change scenario. Both provide forecasts of emissions of CO_2 from 1985 to 2030. In the base case scenario, the IPCC study assumed the continuation of current trends; i.e., no important changes in current trends in the overall structure of the economy, patterns of energy end-use demand, or energy efficiency. Depending on the year, base case economic growth assumptions in the Polish economy range from 2.0 to 2.6% annual growth in GNP. The structural change scenario was developed as an IPCC case study in part to assess the impact that restructuring the Polish industrial sector would have on emissions. Structural change is simulated by adjusting the growth rates of five industrial subsectors included in both the T-GAS model and the IPCC study model (e.g., iron and steel production, chemical manufacturing). Since the most energy intensive industries are assumed to grow more slowly than in the base case, the structural change scenario generally simulates a shift toward less energy intensive industries (e.g., away from steel production). In general, growth rates for the five industrial subsectors are lower here than in the base case scenario. The structural change scenario takes into consideration improvements in living conditions, increases in the production of consumer goods, and reduced reliance on heavy industries. The overall level of economic activity in the structural change scenario is greater than in the base case.

The emissions forecast for the base case scenario is illustrated in Figure 20. Emissions from 1958 to 1985 (i.e., the non-forecast years) are also shown in the figure to provide the reader with an historical context from which to examine the trends in future emissions. Total base case emissions in Poland were estimated by T-GAS to be 194,100,000 metric tons of

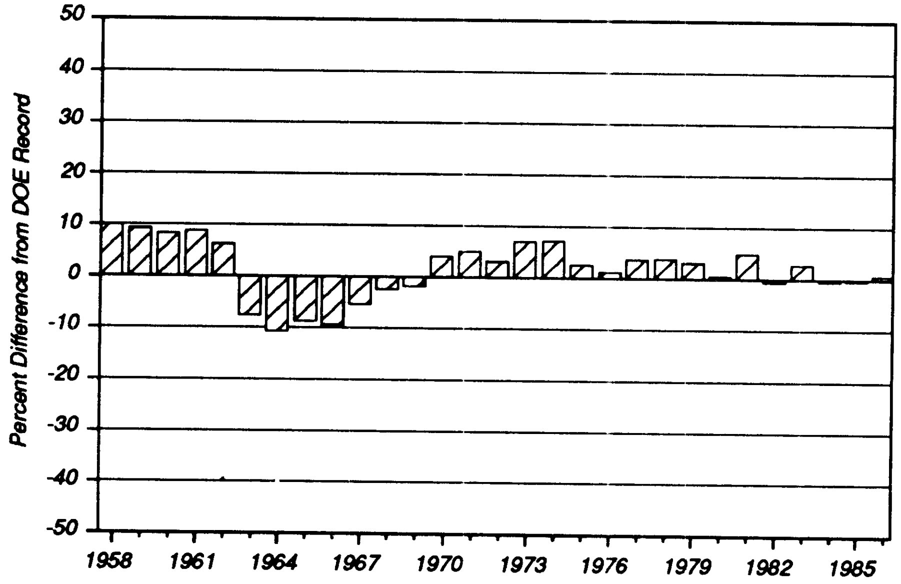

Figure 7. Percent difference between T-GAS and DOE emission estimates for Poland from 1958 to 1986.

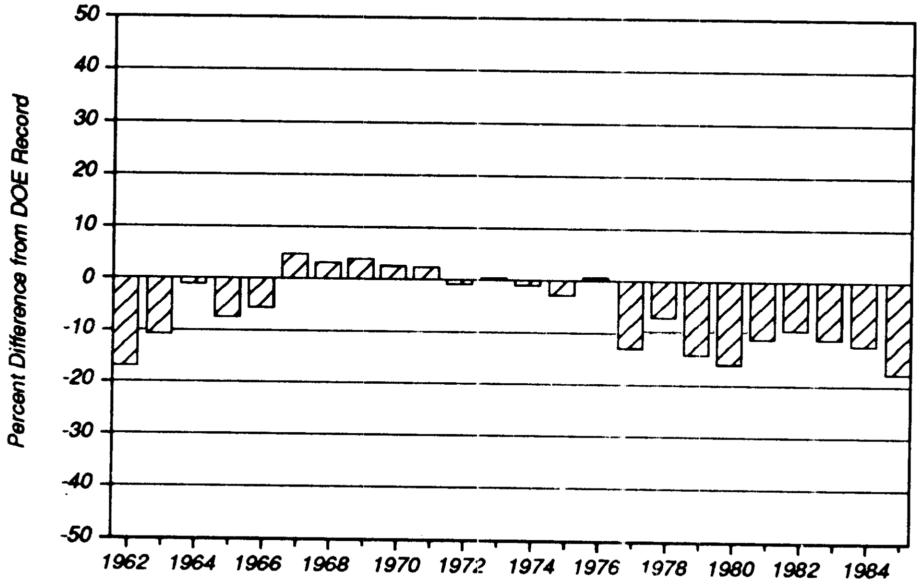

Figure 8. Percent difference between T-GAS and DOE emission estimates for India from 1962 to 1985.

carbon by 2030. This represents an overall 60% increase in emissions from 1985, or an annual average increase of 1.2% per year. This increase is on the low side of the historical annual average increases seen in Poland since the late 1950s. About 84% of the emissions are associated with the use of coal, 11% with the use of oil, and the remaining 5% with the use of gas. This is very similar to the current distribution of emissions by fuel type and is consistent with historical fuel mix patterns seen in Poland. This fuel mix forecast can be considered reasonable if it can be assumed that Poland has sufficient energy reserves over the next 40 years to satisfy the level of fossil fuel demand estimated by the model. For coal, this assumption may be optimistic.

The T-GAS estimate of total emissions for the base case is significantly lower than the estimates developed for the IPCC case study. In the IPCC base case, total emissions were estimated to be 263,700,000 metric tons of carbon by 2030. This estimate is 35% higher than the T-GAS estimate for 2030. An investigation was conducted to identify the possible source of this discrepancy. Several potential reasons were identified. First, in the IPCC model it was assumed that no improvement in energy efficiency would occur over the efficiencies which existed in 1985 for each sector. In T-GAS, energy efficiency improvement is allowed to occur in a manner which is consistent with changes in the factors that have influenced Polish energy efficiency change in the past. That is, the model allows a "business as usual" or base case efficiency improvement to occur. This is a key difference with the IPCC methodology and could result in T-GAS estimating lower energy consumption and subsequent emissions. It seems reasonable to assume that some improvement in energy efficiency will occur in Poland by 2030.

A second potential source of discrepancy is that the IPCC model is not capable of projecting the future mix of primary energy (e.g., coal, oil, gas, nuclear, hydro). Instead, the mix is assumed. In T-GAS, fuel mix is estimated based on the regression equations developed from historical data sets. This is a key difference in the way IPCC and T-GAS models work and could cause significant variations in fuel mix and subsequent emissions estimates.

Figure 21 shows the emissions estimated for the structural change scenario. A comparison of the base case results with the structural change results shows that emissions decrease only slightly under the structural change scenario. For example,

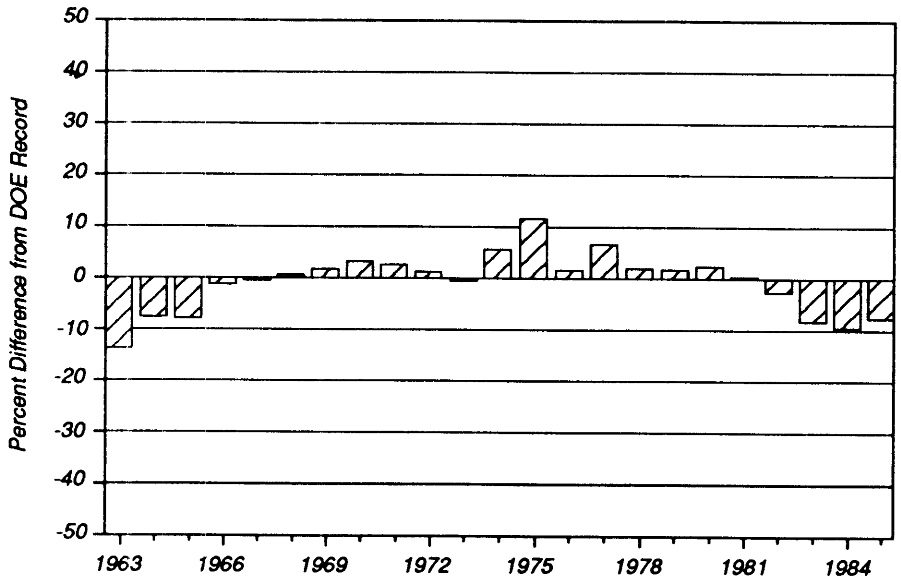

Figure 9. *Percent difference between T-GAS and DOE emission estimates for France from 1963 to 1985.*

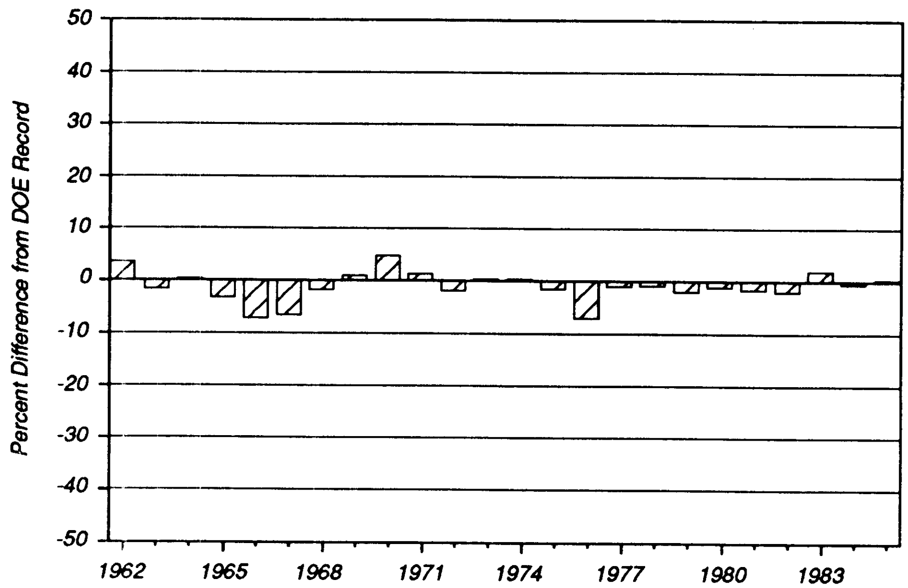

Figure 10. *Percent difference between T-GAS and DOE emission estimates for Italy from 1962 to 1985.*

total emissions in 2030 under the base case scenario were estimated by T-GAS to be 194,100,000 metric tons of carbon. Total emissions for 2030 under the structural change scenario were estimated by T-GAS to be 182,314,000 metric tons of carbon; about 6% less than the base case. An analysis of the results indicates that, although some actions were taken to reduce emissions under the structural change scenario (i.e., efficiency gains in industry and transportation and reduced growth in energy intensive industrial subsectors), high growth in the overall economy resulted in significant energy increases that in some cases overshadow the energy reductions associated with the efficiency improvements specified for structural change. For example, the consumption of total energy (solid, liquid, and electricity) in the transportation sector in 2030 was estimated to

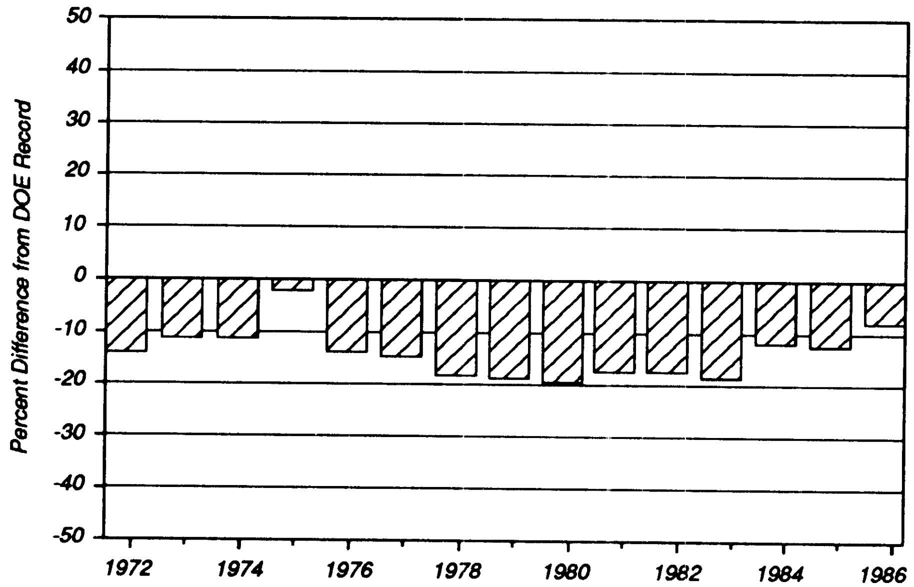

Figure 11. ***Percent difference between T-GAS and DOE emission estimates for Mexico from 1972 to 1986.***

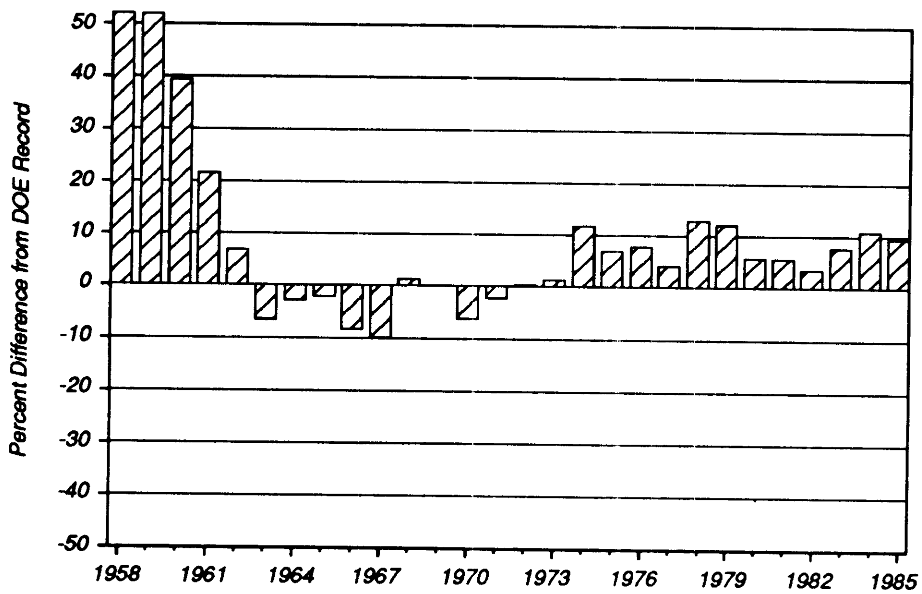

Figure 12. ***Percent difference between T-GAS and DOE emission estimates for South Korea from 1958 to 1985.***

be 17.8 MTOE* for the base case scenario. Total energy consumption in the transportation sector was estimated to be 21.4 MTOE for the structural change scenario even though greater energy efficiency improvements were assumed to occur in road transportation compared to the base case. In general, T-GAS estimates that, as the Polish people become more wealthy relative to the base case (as indicated by the rapid increases in GDP** relative to the base case), the demand for increased mobility and other consumer related energy activities will increase significantly in Poland and could overshadow the benefits associated with improved energy efficiency.

A comparison of the T-GAS and IPCC results for the structural change scenario shows that T-GAS estimates are again lower than the results from the IPCC case study. In the IPCC case study, total emissions were estimated to be 231,000,000 tons of carbon. Although this is about 20% higher than the T-GAS results, it is less of a discrepancy than existed when comparing the base case results, where a 35% difference was identified.

Summary/Conclusions

The forecasting exercise for Poland described above suggests that T-GAS is capable of developing representative and credible emission estimates up to at least 2030. Although the results obtained from T-GAS were consistently lower than the results from the IPCC model, the likely reasons for the discrepancy were explained. In at least one case, the T-GAS estimates may be more representative than the IPCC case study assumptions (i.e., in the base case, IPCC assumes no efficiency improvements will occur, while T-GAS allows a "business as usual" efficiency improvement to occur). These results also show that T-GAS is a useful analytic tool. For example, an analysis of the results from the structural change scenario showed that even moderate increases in the overall economic activity of the country (i.e., as measured by GDP) can overshadow the emission reductions associated with a variety of major technological improvements.

The results above also demonstrate that T-GAS is capable of performing detailed emissions mitigation evaluations for individual countries. Recall that, in the structural change scenario, a complex set of scenario assumptions were represented in T-GAS which were intended to simulate the effects of simultaneous changes in technology efficiency, economic activity, and industrial restructuring. Specifically, technology change aimed at improving energy efficiency was simulated for several sectors and subsectors (e.g., road transportation, iron and steel production, chemical manufacturing, pulp and paper production, light industry). Industrial restructuring was simulated by adjusting the economic growth rates of energy intensive industries downward (e.g., iron and steel) and adjusting the economic growth rates of less energy intensive industries upward.

* Million tons of oil equivalent.

** Gross domestic product.

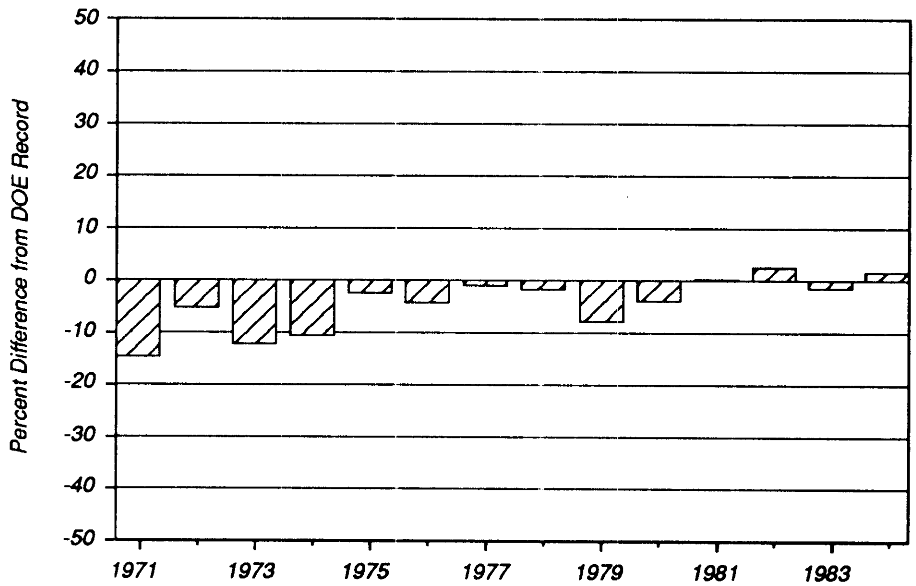

Figure 13. Percent difference between T-GAS and DOE emission estimates for Brazil from 1971 to 1984.

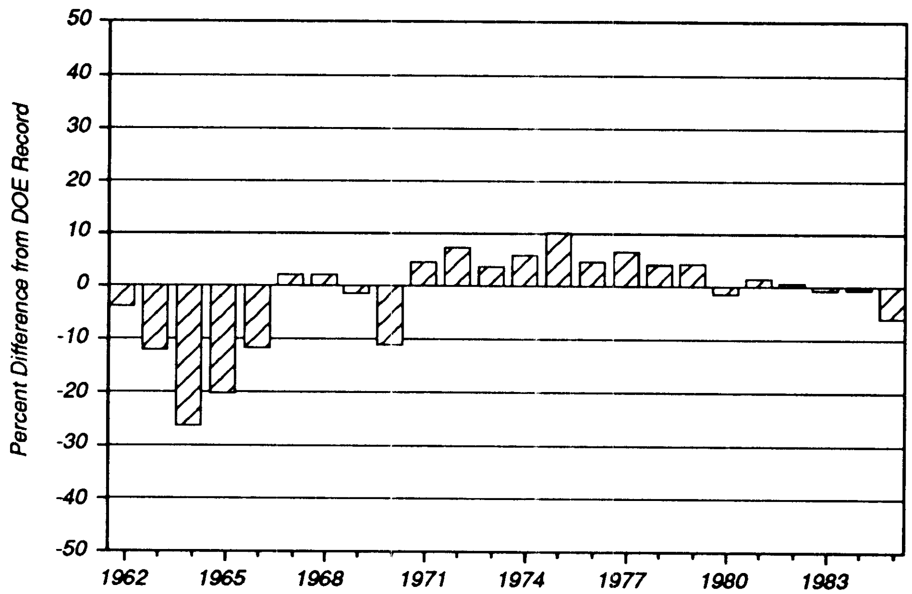

Figure 14. Percent difference between T-GAS and DOE emission estimates for Hungary from 1962 to 1985.

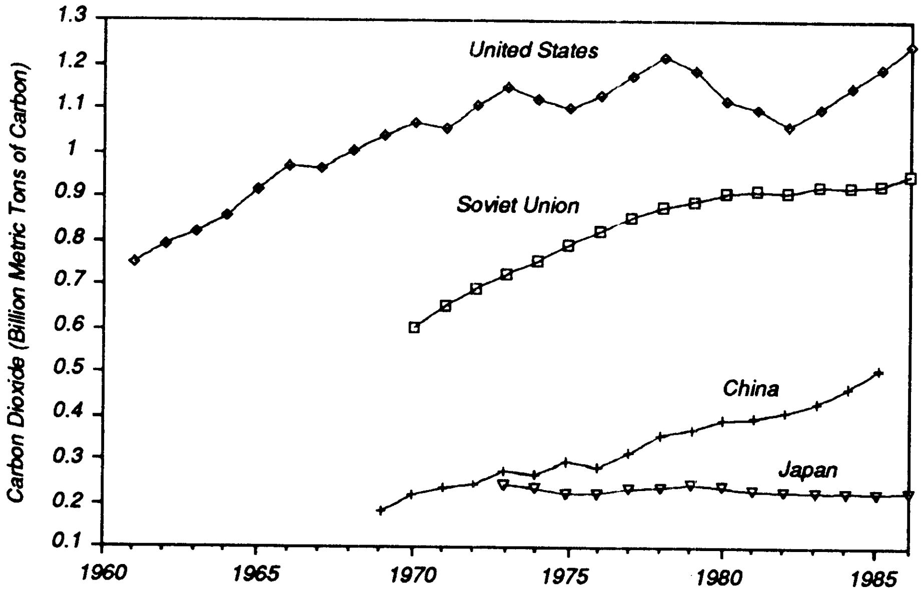

Figure 15. **Comparison of CO_2 emissions for various years from the four largest emission sources evaluated in the study.**

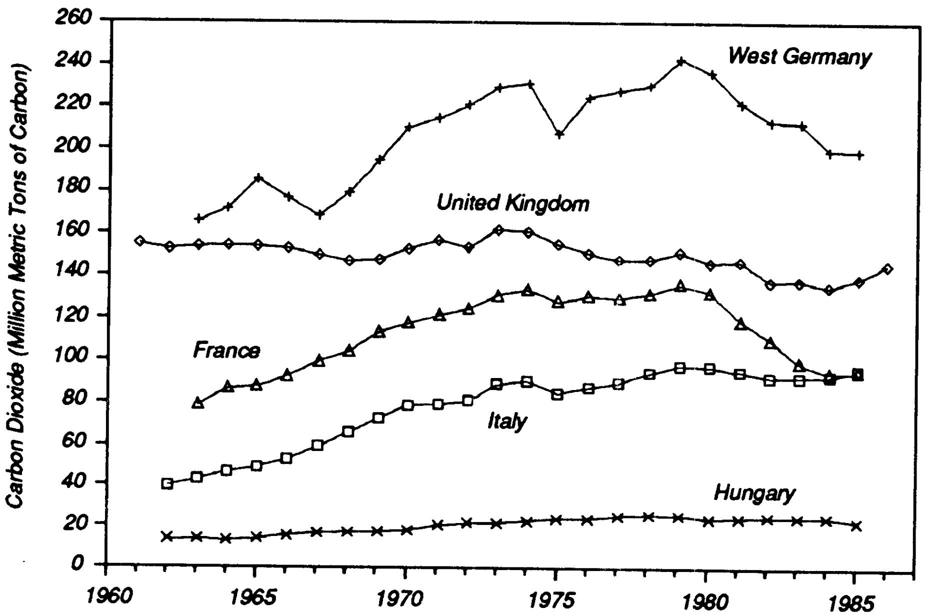

Figure 16. **Comparison of CO_2 emissions for various years from selected European countries.**

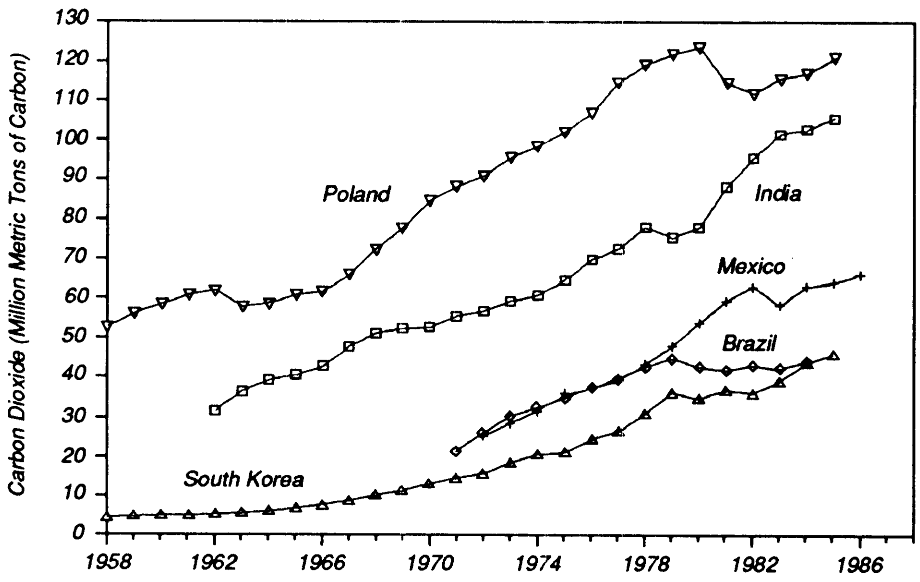

Figure 17. Comparison of CO_2 emissions for various years from the four developing nations.

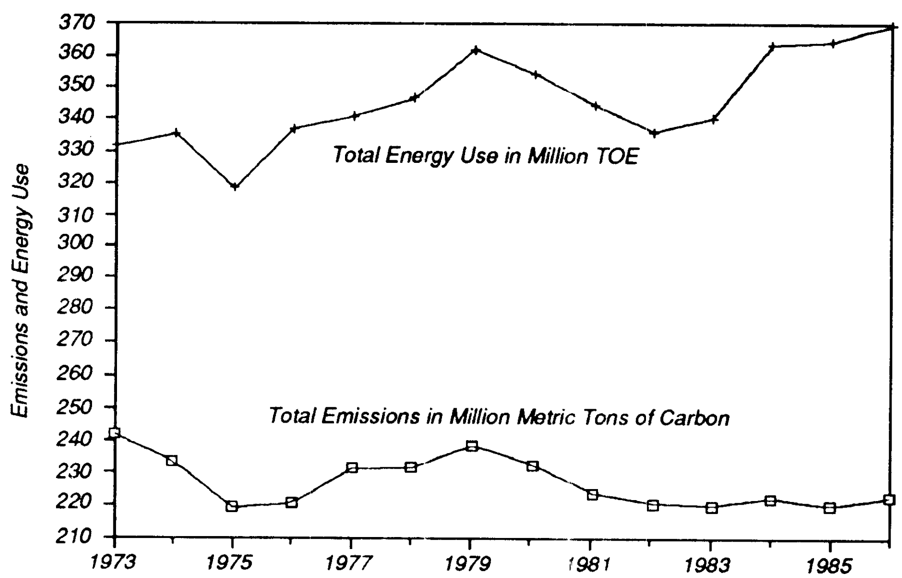

Figure 18. Comparison of emissions and energy use data for Japan from 1973 to 1986.

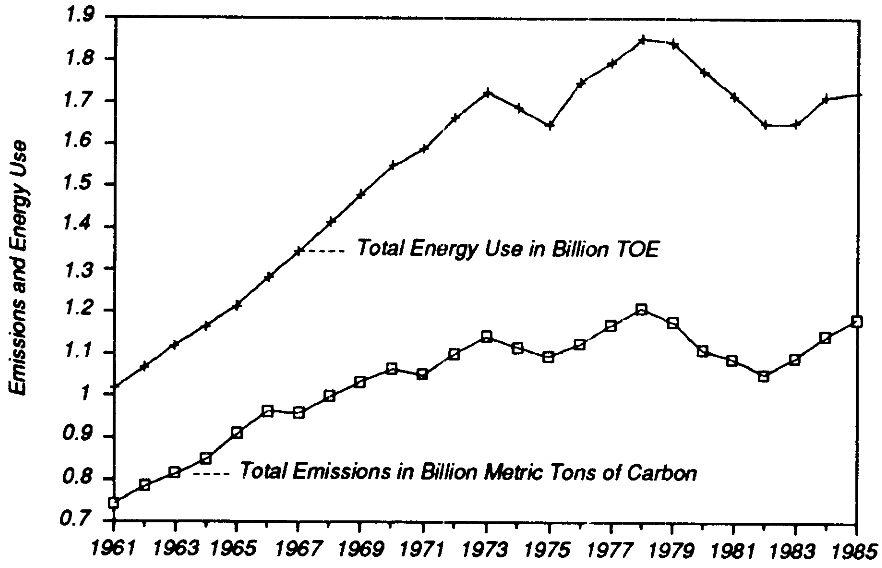

Figure 19. *Comparison of emissions and energy use data for the United States from 1961 to 1985.*

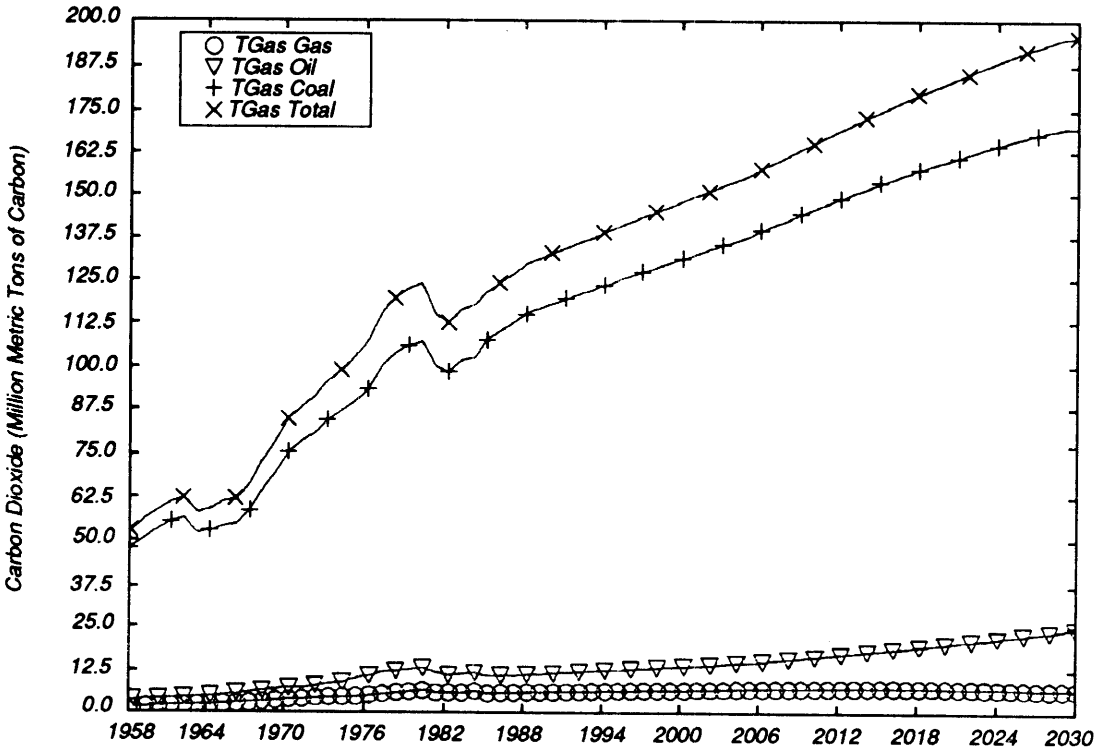

Figure 20. *T-GAS emissions estimates for Poland from 1958 to 2030 under the base case scenario.*

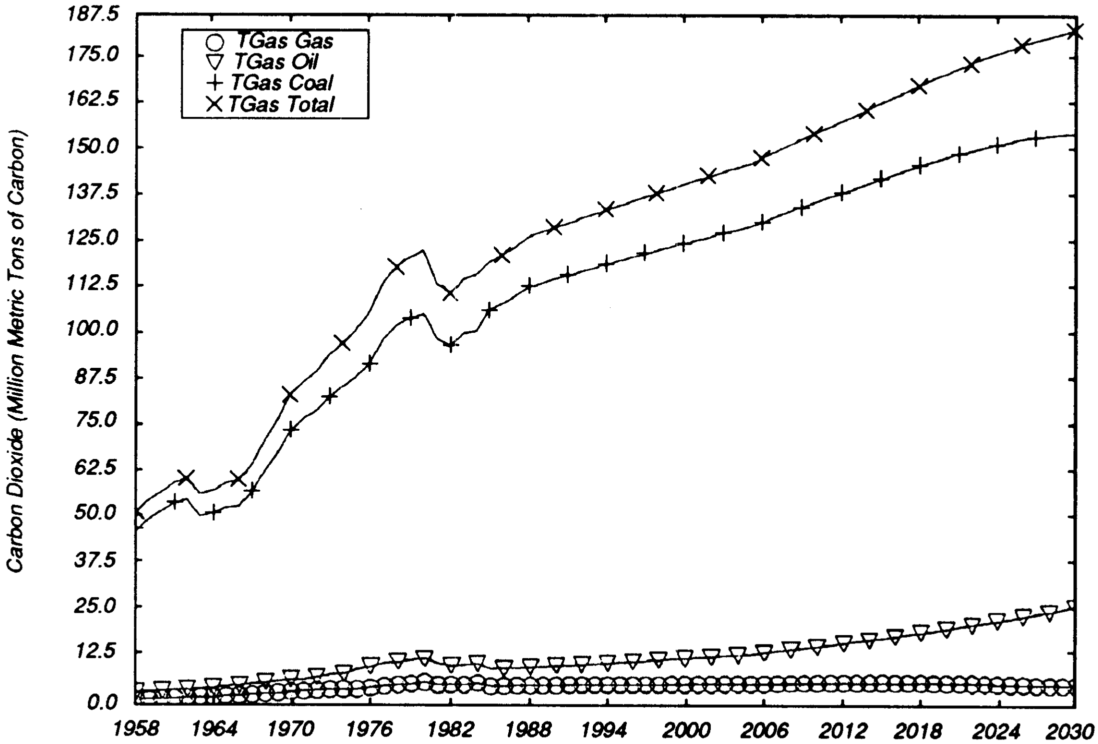

Figure 21. *T-GAS emissions estimates for Poland from 1958 to 2030 under the structural change scenario.*

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The complete report, entitled "Analysis of Historical Radiatively Important Trace Gases (RITG) Emissions: Development of a Trace Gas Accounting System (T-GAS) for 14 Countries," (Order No. PB91-216325/AS; Cost: $39.00, subject to change) will be available only from:

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