Interdisciplinary Energy Modeling

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Introduction

Since 1990, IIASA's Environmentally Compatible Energy Strategies (ECS) Project has been studying global energy-related greenhouse gases

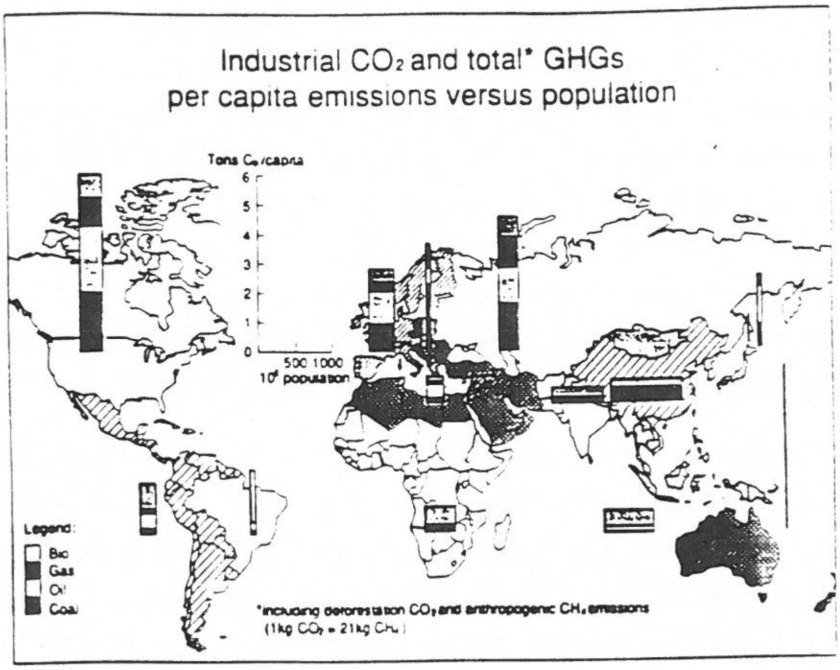

Figure 1. Greenhouse gases emissions and population in different world regions. Source: Nakićenović et al. (1993).

(GHG) emissions and ways to reduce them in the future. Figure 1 describes the present global situation of GHG emissions and population. It shows, for 13 world regions, the 1990 per-capita emissions of CO_2 and anthropogenic CH_4. The figure's bars represent total emissions in each of these regions as the product of population (bar width) and per-capita emissions (bar height). We see a clear distinction between population-rich developing countries and less populated industrialized countries which have high per capita emissions. Since the developed countries have larger economic and technological capabilities, they have the twofold advantage of not only being in a better situation to adapt to climate change but also of being able to achieve substantial reductions of CO_2 emissions if needed. In contrast, developing countries carry a twofold burden. First, they need to increase their per capita energy consumption if they are to improve the quality of life of their people and, second, they are also more vulnerable to the adverse consequences of climatic change.

The current levels of per capita carbon emissions differ between the North and the South by nearly an order of magnitude (3.3 tons of carbon per capita in developed countries versus 0.37 tons in developing countries). Even after including carbon emissions from tropical deforestation – currently estimated to range between 0.6 and 2.8 billion tons of carbon annually (IPCC, 1990; Houghton, 1990) – a significant gap remains (0.5 – 1.1 tons of carbon per capita in developing countries compared with 3.3 tons per capita in industrialized countries). In any case, it appears unavoidable that, with further development, global carbon emissions will continue to increase for some time to come.

The determinants of future energy-related CO_2 emissions can be represented as multiplicative factors as in the *Kaya identity** which explains energy-related CO_2 emissions in terms of population, per capita value added, energy consumption per value added and specific carbon emissions per unit of primary energy consumed (Yamaji *et al.*, 1991). Let us look at each of these four factors in turn.

Although the longer-term historical growth rates since 1800 have been about 1% per year, the world's global population presently grows at a rate of about 2% per year. Most of the population projections expect at least another doubling during the next century (e.g. World Bank and UN projections). Value added per capita has been increasing at about 2% per year since the beginning of industrialization due to growing labor productivity. In contrast, energy intensity per unit value added has been decreasing at a rate of about 1% per year since 1860 and at about 2% per year in most countries since 1970. CO_2 emissions per unit of

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* $CO_2 = P \times (GDP/P) \times (E/GDP) \times (CO_2/E)$, where P represents population, GDP the gross domestic product or value added, and E energy consumption.

energy have also been decreasing, albeit at the much lower rate of about 0.3% per year. According to the Kaya identity, these growth rates compound to a growth of energy-related carbon emissions of presently 1.7% per year.

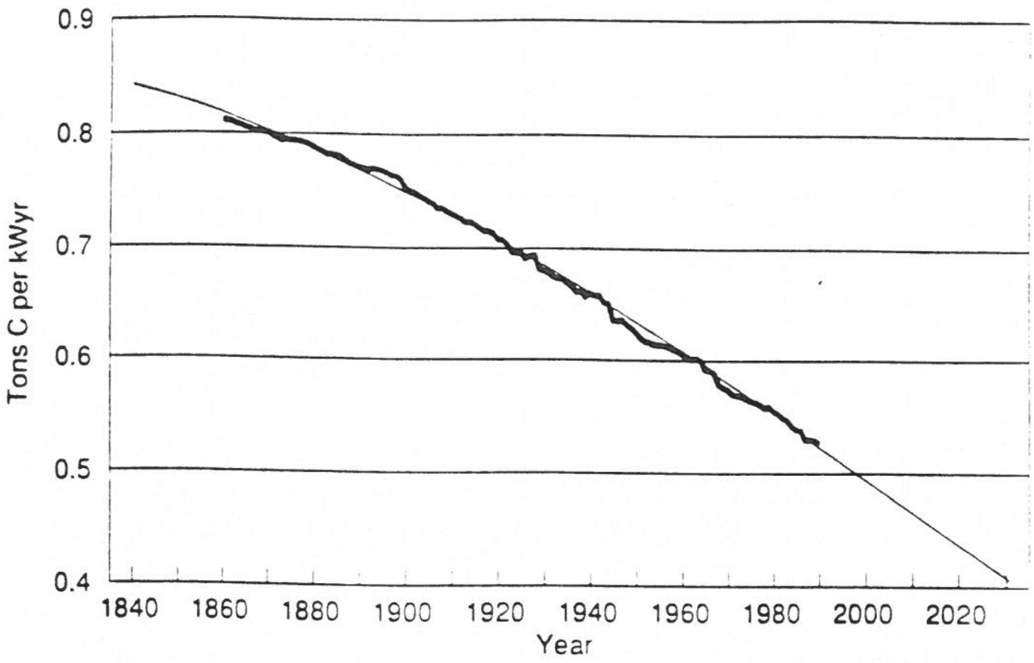

Figure 2. Decarbonization of global energy consumption since 1860 (in tons of carbon per kWyr). Source: Nakićenović et al. (1993).

Figure 2 illustrates the extent of "decarbonization", expressed in terms of average carbon emissions per unit of energy consumed globally since 1860. These specific emissions decrease due to the continuous replacement of fuels with high carbon contents, such as fuelwood and coal, by those with lower carbon contents such as oil, gas, and, recently, also nuclear energy.

Figure 3 shows the historical decrease of energy intensity per unit value added in a number of countries. Energy development paths in different countries have varied enormously and consistently over long periods, but the overall tendency is toward lower energy intensities. This figure also illustrates salient differences in the policies and structures of energy systems among countries. For example, Japan and

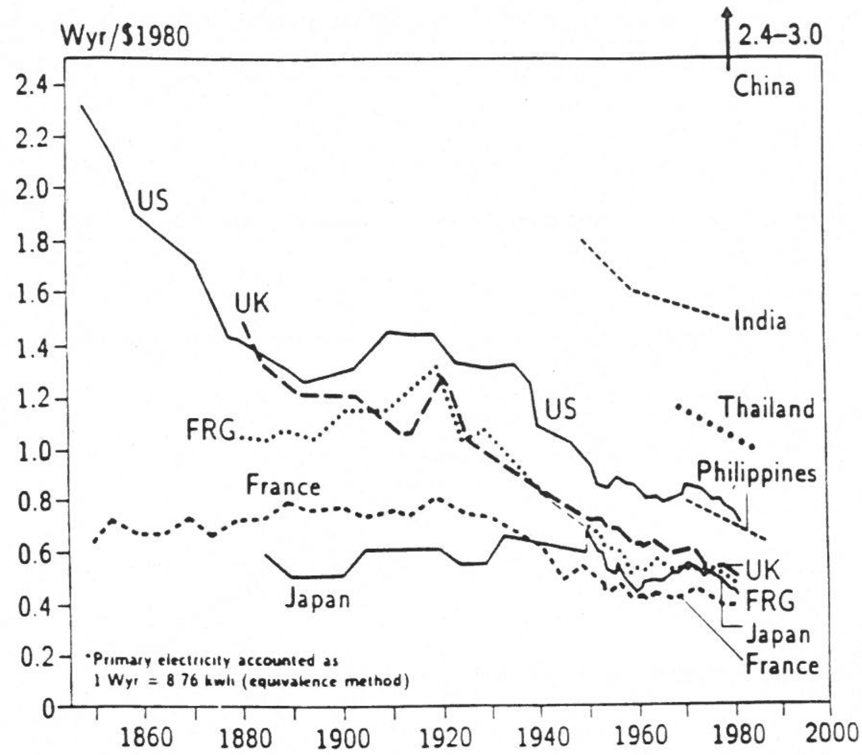

Figure 3. Primary energy intensity (including biomass) of value added (in Wyr per constant GDP in 1980 dollars). Primary electricity is accounted as 1 Wyr = 8.76 kWh (equivalence method). Source: Nakićenović et al. (1993).

France have achieved the largest degrees of decarbonization; in Japan this has been achieved largely through energy efficiency improvements over recent decades, while in France largely through vigorous substitution of fossil fuels by nuclear energy. The present energy intensity of Thailand resembles the situation in the United States in the late 1940s. The energy intensity of India and its present improvement rates are similar to those of the United States about a century ago.

For the readers very familiar with energy analysis it should be emphasized that our Figure 3 includes non-commercial energy. If this non-traded traditional form of energy supply is excluded from the analysis, primary energy intensity seems to peak. Since such peaks seem rather spurious, we prefer showing total primary energy intensity.

After this overview of historic carbon emission we turn to analyzing the prospects for their future developments.

Projections of Energy Intensity and Decarbonization

IIASA is a focal point of two international networks, the International Energy Workshop (IEW) and CHALLENGE*. Both networks are concerned with projections of energy demand and supply in countries, world regions, and in the world as a whole. Through an ongoing poll, these networks keep collecting information on projections of the international price of crude oil, GDP development, electricity generation, and energy-related carbon emissions. Scenario results are received in several classes of cases. From the data in the class with the biggest number of responses, i.e. the reference or base cases, indices of primary energy intensity and decarbonization can be derived. They are summarized in Figure 4 and Figure 5 respectively. Both show a curve of averages and, for each time period, an interval that is two sample variances wide, assuming a log-normal distribution**. The average annual decline rates of the (logarithmic) averages is very well in line with the historic rates. For the poll responses, they are 1.25% for energy intensity improvement and 0.35% for decarbonization.

The responses to the combined polls have been used as inputs to Global 2100, a global model of CO_2-energy-economy interactions (Manne and Richels, 1992). Taking the Manne-Richels scenarios as a basis, the combined IEW and CHALLENGE poll results were used to define scenarios of possible global developments of greenhouse gases emissions. The model results are thus based on a combination of published scenarios and inputs from many countries, emphasizing those that can be expected to have a crucial impact on the future development of

* This acronym for Common House ALternatives on Long-term ENergy Strategies under Global Environmental Concern reflects the original European focus of the project. For a more detailed description of the two networks' activities, see Manne, Schrattenholzer, and Marchant (1991) and Manne and Schrattenholzer (1993).

** If the poll responses are indeed log-normally distributed, these ranges cover about two-thirds of the responses at a given time period.

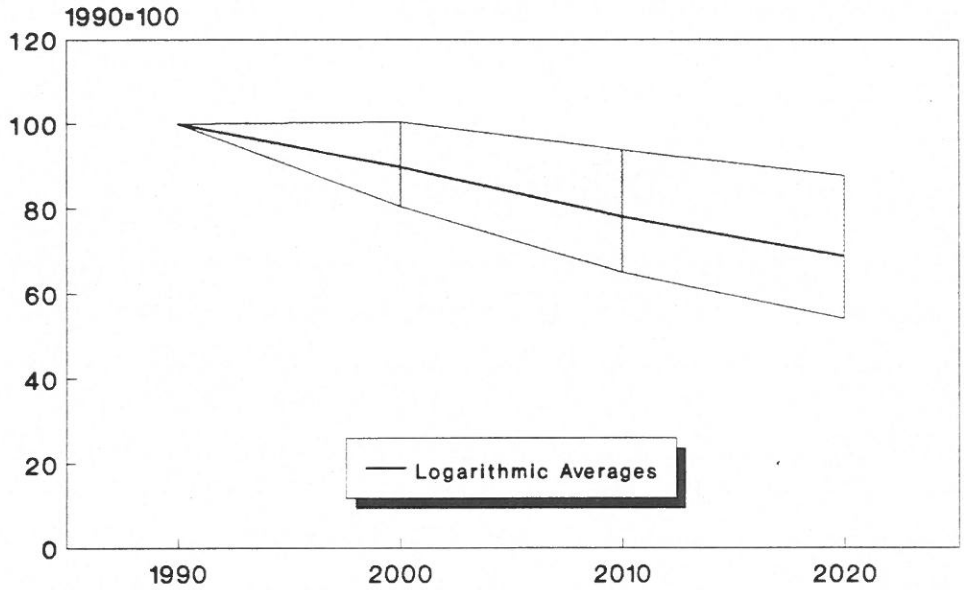

Figure 4. Primary Energy Intensity, IEW and CHALLENGE Poll ranges and averages.

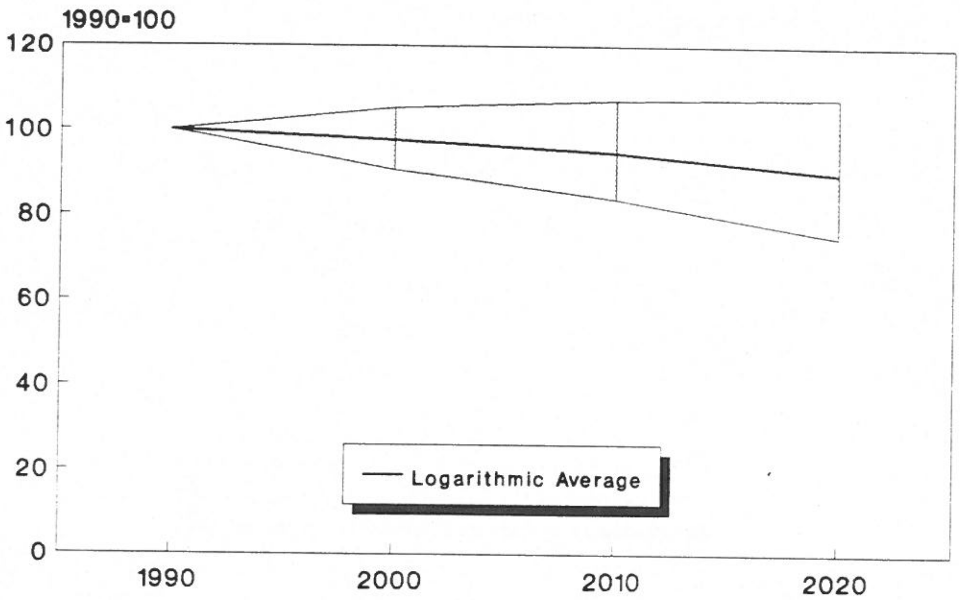

Figure 5. Decarbonization, IEW and CHALLENGE Poll ranges and averages.

carbon emissions.

For five globally exhaustive world regions, Global 2100 describes a reference case and – as the most illustrative representative of carbon emission reduction cases – a scenario including carbon emission reduction measures up to US$200 per ton of carbon reduced. The results of these two scenarios in terms of global carbon emissions between 1990 and 2020 are shown in Figure 6, where they are compared with the highest and the lowest of six emission scenarios by the Intergovernmental Panel on Climate Change (IPCC 1992). If the poll-based Global 2100 Reference case is indeed a "do-nothing" case, i.e. a scenario in which no special mitigation measures are taken to avoid climate change, then the range spanned by the IPCC scenarios looks overly pessimistic – both on the low and the high side. In contrast, energy-related carbon emissions in our Reference case grow from 6 billion tons of carbon in 1990 to 9.1 billion in 2020, i.e. at an average annual rate of 1.4%. The Reduction case shows that, according to Global 2100, global carbon emissions can be stabilized between 1990 and 2020 at a marginal cost of US$200 per ton of carbon (tC). This is not the place to discuss whether

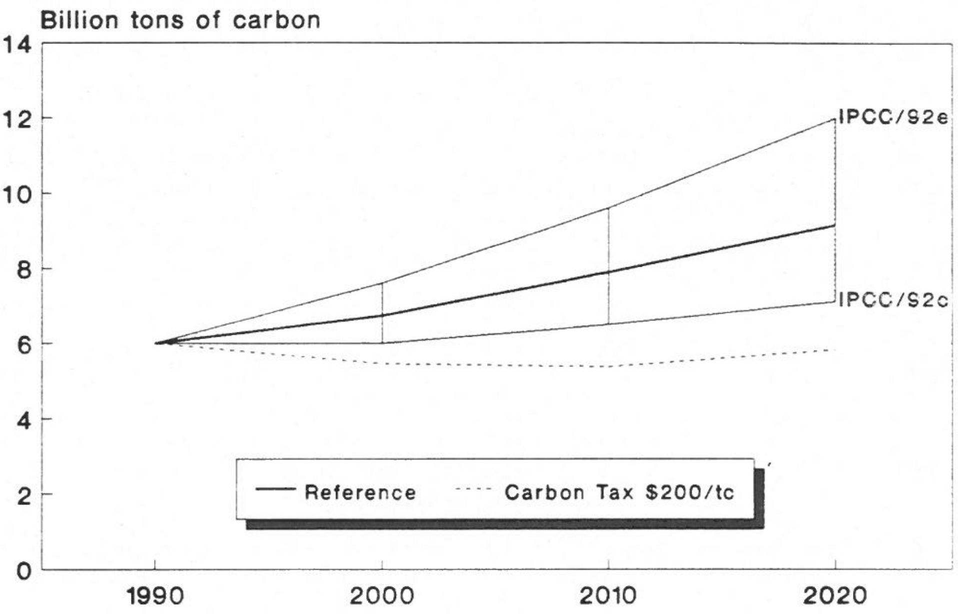

Figure 6. Global Carbon Emissions, Global 2100 results and two IPCC scenarios.

this is a high or a low price to pay. To put it into some perspective, however, it should be compared with the original plan of the Clinton Administration to increase U.S. gasoline prices by 5 cents per gallon (approximately 20$/tC) which, at least for the time being, turned out politically infeasible.

Engineering and Economics in Energy Modeling

The Reduction case described in the previous section is consistent with the economists' view that reductions of carbon emissions always cost a positive amount of money. This view is challenged by several engineering-type studies that claim that large quantities of energy, and thereby carbon emissions, can be saved reducing costs at the same time. A typical example of such a result is reproduced in Figure 7. It says that by investing in energy saving measures in the U.S. residential sector, mostly in the field of space heating, 50% of the reference emissions (the actual values of 1989) could be avoided at "negative costs", i.e. net

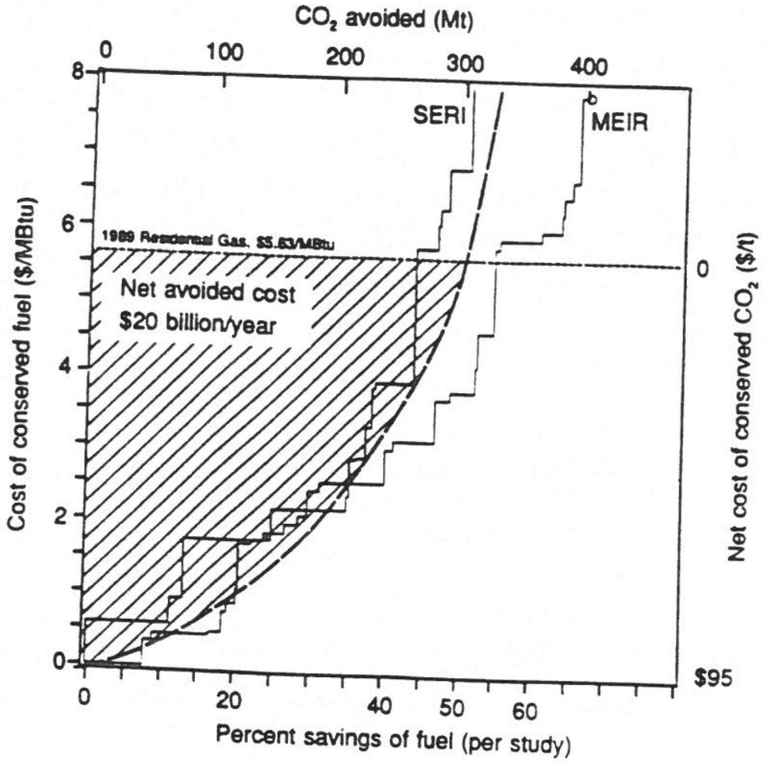

Figure 7. Cost of conserved energy and net cost of conserved carbon dioxide for the U.S. residential sector. Source: COSEPUP (1991).

savings of 20 billion U.S. dollars per year. The question arises: Can the economists and the engineers be right at the same time?

What at first sight looks like a clear impossibility, reveals some interesting aspects when analyzed in more detail. First, it should be realized that the two types of analysis address two different questions. The economists ask: *By how much does a given energy price increase (e.g. through an carbon tax) reduce energy demand and thereby carbon emissions?* In contrast, the engineers' question is: *How can a given emission reduction task be achieved with minimal costs?* Clearly, these two questions are not equivalent. To begin with, only the economists' question explicitly addresses the problem of forecasting. The engineers' question and the resulting savings potential (as shown in the previous figure) cannot have immediate predictive power, because if they had, at least some of the theoretical potential would have been realized already.

The obvious next question therefore becomes: *Why is it that a significant energy savings potential is not realized by the consumers?* One possible answer is that the market discount rates often used in engineering studies to annualize investment costs are often unrealistically low for adequately describing consumer behavior and that they therefore underestimate costs and overestimate potential savings. This possibility has been suggested by Hausman (1979), who calculated implicit discount rates by observing consumer decisions trading off initial investments against later savings when purchasing air conditioners*. His results are

Income Class, US$(1979) per Year	Implied Annual Discount Rate, %
6,000	89.0
10,000	39.0
15,000	27.0
25,000	17.0
35,000	8.9
50,000	5.1

Table 1. Implied discount rates, calculated from purchases of air conditioners in U.S. households. Source: Hausman (1979).

given in Table 1. They show that consumer behavior, particularly in low income classes, is consistent with discount rates that are very much higher than bank rates. But not only private consumers can act as if their individual discount rate is very high. According to Ross and Steinmeyer (1990), a typical criterion for U.S. companies to decide whether they should invest into energy saving measures or not is an estimated pay-back time of 2 to 4 years. This criterion corresponds to discount rates of the order between 25 and 50%.

* Meanwhile, this phenomenon has been investigated further, and more examples have been reported. See, e.g. Train (1985).

Does this mean that economic agents behave irrationally? This question cannot be answered by a simple analysis of these figures because there are several kinds of non-monetary costs (e.g. transaction costs) involved in buying energy-efficient equipment. If they are not explicitly added to the market price, they have an influence on the implied discount rate. For households, such transaction cost can arise in the form of inconveniences when a home is retrofitted with better insulation. Another, more abstract example of non-monetary costs is the effort to collect enough information to make an economically rational decision. The latter problem is addressed by demand-side management (DSM) programs which have been initiated, e.g. by electric utilities in the U.S. In these programs, consumers are provided with energy-saving equipment for which they pay, in effect, by sharing subsequent electricity cost savings with the utility.

But even when a theoretical saving potential is actually realized, the resulting overall reduction of energy demand can be less than

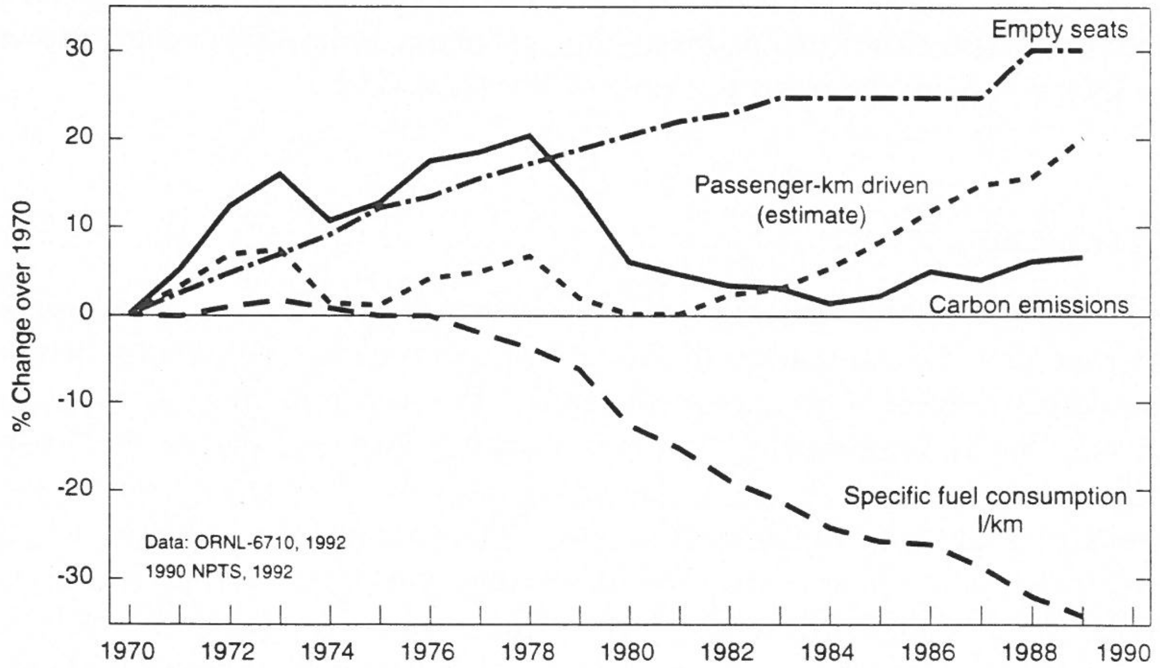

Figure 8. Carbon emissions from U.S. passenger cars. Source: Grübler, IIASA, (1993), unpublished.

expected. This is exemplified by Figure 8, showing that a more than

30% reduction of specific gasoline consumption by U.S. passenger cars between 1970 and 1989 did not achieve a reduction of their carbon emissions. The offsetting factors preventing it were an increase of the passenger kilometers driven and a decrease of the average number of passengers per ride.

These points explain some of the differences between the two types of modeling approaches by qualifying results of engineering-type models. But there is also a response by the economic models which acknowledges, at least indirectly, the existence of a potential for cost-effective energy savings. Most economic models describing the long-term development of energy demand include a factor called *Autonomous Energy Efficiency Improvement* (AEEI). This factor aims at quantifying reductions of energy intensity of economic output that is realized over and above the effect of price-induced energy savings. The AEEI factor is measured in percent per year, and a typical value used by economic modelers is 0.5 (Manne and Richels 1992), expressing the assumption that, in the absence of price changes, energy demand (in industrialized countries, the situation in developing countries is less favorable) grows by half a percentage point per year slower than GDP.

Conclusions

Analyzing the dynamics of global energy-related carbon emissions we find that a continuation of the secular growth rates will bring further increases of greenhouse gases emissions. We also find that, in contrast to superficial impressions, analyses showing large potentials for cost-effective emission reductions cannot be taken to indicate an automatic break of this trend in the near future. The way from a potential to its realization is long and winded. A savings potential merely acts as a force (in the physical sense) that induces some acceleration towards energy saving. And even in cases where technology provides us with the means to use energy more efficiently, we can observe offsetting effects of less conscious use of energy. In my view, this last observation is also the key to addressing the problem of promoting the intelligent use of energy, that is, the general awareness of the consequences of unrestricted emissions would be the most promising factor to lead to effective counter measures. This means that physicists and engineers have a double role to play. Professionally, they should develop the knowledge and teach the skills to use energy intelligently. Privately, they should promote the intelligent use of energy in their social environment, most effectively by setting examples.

References

Committee on Science, Engineering and Public Policy (COSEPUP), 1991, *Policy Implications of Greenhouse Warming: Report of the Mitigation Panel*, U.S. National Academy of Sciences, U.S. National Academy of Engineering and Institute of Medicine, U.S. National Academy Press, Washington, DC, USA.

Hausman, J.A., 1979, Individual discount rates and the purchase and utilization of energy-using durables, *Bell Journal of Economics* **10**:33–54.

Houghton, R.A., 1990, The global effects of tropical deforestation, *Environmental Science and Technology* **24**(4):414–422.

Intergovernmental Panel on Climate Change (IPCC), 1990, *Climate Change, The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC), 1992, *1992 IPCC Supplement*, February, Geneva, Switzerland.

A. Manne and R. Richels, 1992, **Buying Greenhouse Insurance**, MIT Press, Cambridge Massachusetts.

A. Manne and L. Schrattenholzer, 1993, Global Scenarios for Carbon Dioxide Emissions, *Energy*, forthcoming.

A. Manne, L. Schrattenholzer and K. Marchant, 1991, The 1991 International Energy Workshop: The Poll Results and a Review of Papers, *OPEC Review* **Winter**: 389-411.

N. Nakićenović, A. Grübler, A. Inaba, S. Messner, S. Nilsson, Y. Nishimura, H.H. Rogner, A. Schäfer, L. Schrattenholzer, M. Strubegger, J. Swisher, D. Victor and D. Wilson, 1993, Long-Term Strategies for Mitigating Global Warming, *Energy* **18**(5): 401-609.

M. Ross and D. Steinmeyer, 1990, Energy for Industry, *Scientific American* **263**(3): 46-53.

K. Train, 1985, Discount Rates in Consumers' Energy-Related Decisions: A Review of the Literature, *Energy* **10**(12): 1243-1253.

Yamaji, K., 1991, *Lifestyle Factors in Japan's Energy Demands*, Paper presented at the International Workshop on Social Behavior, Lifestyles and Energy Use, 24–26 June 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.