Energy strategies and greenhouse gas emissions

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Abstract: Concern about the availability of energy resources has given way in recent years to increasing awareness of the environmental impacts of energy production, conversion, and use. Future energy policies must be based on limiting and even reducing future emissions of greenhouse gases. Consequently, a number of national carbon dioxide reduction plans have been announced, which are aimed at stabilizing and in some cases even reducing further emissions.

Key words: energy strategies, environmentally compatible energy strategies, greenhouse gas emissions, mitigation measures.

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1 BACKGROUND

After nearly 20 years of many global, regional and national energy studies, perceptions of the major driving forces of the future evolution of the energy system have changed. Concerns about physical and economic availability of adequate energy resources have given way to increasing awareness of global and long-term environmental impacts of energy production, conversion and end-use. In particular, the energy-related emissions of greenhouse gases (GHGs) - and especially of carbon dioxide (CO_2) are an important cause of increasing concerns over the possibility of global change.

During the 1970s, the main focus of many global energy studies was on resource availability and the possible time horizons for introducing new energy supply sources. Special emphasis was often given to techno-economic measures for responding to the perceived scarcity of crude oil and increasing costs of energy supply. During the 1980s the emphasis shifted from supply aspects of future energy developments to demand management and more rational energy use. Perhaps even more important, these studies pointed to the large potential for efficiency improvements, particularly in energy end-use, and to the importance of the socio-behavioural perspective for future energy systems evolution.

Today, the predominant question is whether it would actually be possible to continue consuming energy resources at current or even higher rates in the future. What is dramatically different is that instead of energy resources the risk of adverse global change might constitute the ultimate limit of future development in energy systems. Thus, the ultimate global resource could be the environment rather than recoverable energy reserves and resources.

The current carbon dioxide content of the atmosphere is about 760 Gigatons (Gt) of carbon compared with annual emissions of about 6 Gt of carbon from fossil energy use. The atmospheric carbon content is less than four times the cumulative global emissions from fossil energy use of about 200 Gt of carbon. This illustrates the massive interference in the global carbon cycle. Compared to the historical carbon releases, the remaining 'carbon endowment' accumulated over geological times in form of fossil energy deposits is orders of magnitude larger. Table 1 shows that the economically recoverable energy reserves amount to 540 Gt of carbon and thus almost equal the total carbon in the atmosphere. Additional three thousand Gt of carbon are in the form of estimated resources (i.e., identified quantities with uncertain prospects for economic recoverability) and further five thousand Gt of carbon are estimated in additional occurrences (inferred quantities with largely speculative technical and economic potentials). This clearly shows that even the currently known fossil energy resources, if ever consumed, would be sufficiently large to raise the atmospheric carbon dioxide concentrations by at least an order of magnitude. Thus, future energy policies must be based on precautionary principles by limiting and even reducing future emissions of greenhouse gases. Consequently, a number of national CO_2 reduction plans have been announced, aiming to stabilize and in some cases even reduce further emissions.

2 CO_2 EMISSIONS AND GLOBAL ENERGY

For several years the prospects of global warming have been on the agenda of the Intergovernmental Panel on Climate Change [5] that has *inter alia* further extended the scientific knowledge in this area by analysing global greenhouse gas emissions, atmospheric concentrations, impacts and response strategies and has also developed a number of scenarios describing possible future developments of global greenhouse gas emissions. Under a 'business-as-usual' scenario, greenhouse gas emissions continue to increase leading to almost a tripling of the current concentrations by the year 2100. The energy-related carbon dioxide emissions path of this scenario is illustrated in Figure 1. The IPCC estimates that under such a scenario global mean temperatures would increase by 0.3 degrees Celsius per decade to reach a value of between 3 to 6 degrees higher than the pre-industrial levels. In view of the large degree of scientific uncertainty that surrounds global warming, the precautionary principle would deem emissions reductions as a prudent response to the potentially adverse consequences for humanity should current trends continue uninterrupted. Accordingly, other emissions scenarios were also developed by IPCC in which atmospheric concentrations of greenhouse gases are stabilized at a level less than a doubling of CO_2 equivalent and then further reduced. In particular, the Accelerated Policies Scenario (also given in Figure 1) defines a development path in which current carbon dioxide emissions from fossil energy use are approximately halved to about 3 Gt of carbon by the year 2050.

Table 1 *Fossil energy consumption, reserves and resources (Gt C):Accounting for historical, present and potential future carbon emissions from fossil fuel use in Gigatons carbon. Historical (1860-1987) and present (1987) carbon emissions from fossil fuel use by source and carbon content in identified, economically recoverable fossil fuel reserves, resources (identified quantities with uncertain prospects of economic recoverability), and additional occurrences (additional quantities inferred from geological information but with speculative technical and economic potential). Compared to historical fossil fuel use, the remaining resources in the ground represent a (perhaps even far too large) 'carbon endowment' which is more than a factor 10 as large as the total carbon pool in the atmosphere of around 760 Gt C (corresponding to a present CO_2 concentration rate of about 350 ppm) [4].*

	Coal	*Oil*	*Gas*	*Total*
1860–1987	114.9	58.2	24.5	197.6
1987	2.5	2.4	1.0	5.9
Reserves	391.6	92.1	58.5	542.2
Resources	2289	622	>115	3026
Additional occurrences	>3500	>1000	>700	>5200

Since 1981, Stanford University and IIASA have been jointly organizing the International Energy Workshop (IEW) with the aim to compare energy projections made by different groups in the world and to analyse their differences [6]. The median of global CO_2 emissions calculated from the IEW polls of global energy consumption or, in our interpretation, the current 'consensus view', corresponds to an annual growth rate of one per cent per year, i.e. to an increase from about 6 Gt today to some 9 Gt carbon by the year 2020, with a range between 8 to 10 Gt as shown in Figure 1. Although lower than the 'business-as-usual' scenario of the IPCC for the same year, the IEW poll range gives rise to concerns as to how such a trend could be 'bent' downwards, e.g. along the lines of the Low Emission and Accelerated Policy scenarios of the IPCC. This all strongly suggests that – in the absence of appropriate countermeasures – global carbon emissions will rise, perhaps beyond environmentally acceptable levels.

Thus, perceptions about factors limiting future energy use have changed while the driving forces are still the same – population growth and economic development. Some of the measures and strategies that seemed to be desirable in the past, however, appear to

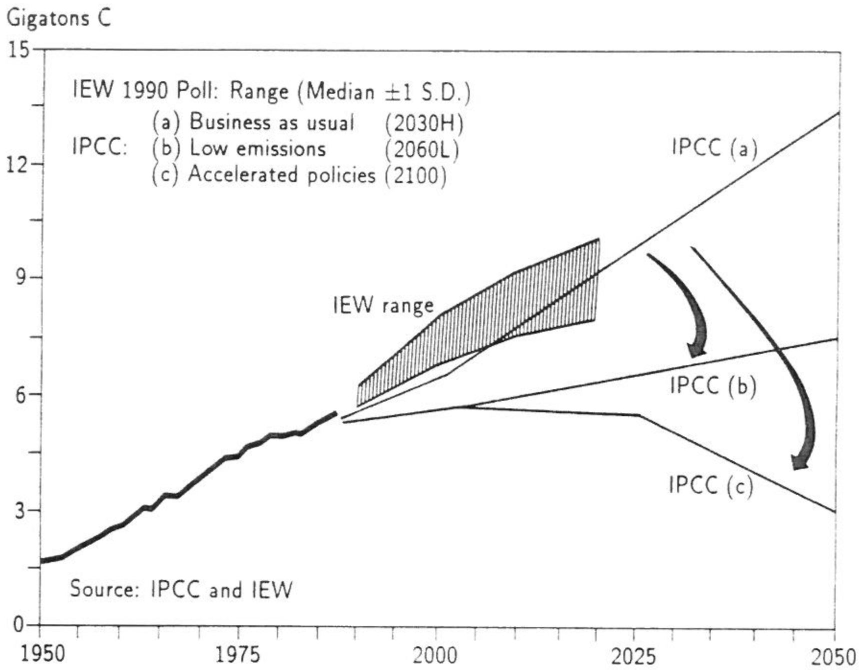

Figure 1 *Historical and future global energy-related CO_2 emissions: From 1950 to present emissions have increased on average at about two per cent per year. Possible future global energy-related CO_2 emissions are indicated by International Energy Workshop (IEW) poll-response range [6] and by three Intergovernmental Panel on Climate Change (IPCC) scenarios. IEW is jointly organized by Stanford University and IIASA with the aim to compare energy projections made by different groups in the world and to analyse their differences [10]*

be invariant to this shift in perceptions. For example, energy efficiency improvements and conservation are instrumental in reducing both fossil fuel requirements and the resulting emissions.

3 ENVIRONMENTALLY COMPATIBLE ENERGY STRATEGIES

The research effort in the area of energy and the environment at the International Institute for Applied Systems Analysis (IIASA) focuses on formulating long-term options and strategies for environmentally compatible energy development. The objective of this research at IIASA is to develop an analytical framework to evaluate the policy options and future global energy strategies directed at delaying or mitigating global change. In particular, the objective is to assess future potentials and rates of reducing energy and carbon intensity worldwide. Figure 2 shows historical improvements toward reducing carbon intensity in a number of selected countries. The aim is to analyse future trajectories that would lead individual countries and the world as a whole further toward lower specific emissions per unit value added as shown for the historical changes in Figure 2.

This research effort is based on a comprehensive assessment of a broad range of *options* (technologies, associated economic incentives and institutional frameworks for their implementation) that is needed for evaluating the global potential for stabilizing, ultimately reducing and perhaps even removing carbon dioxide and other greenhouse gases from the atmosphere [12]. Such a systems approach in assessing the contribution of individual technologies could lead to a better understanding of the aggregate potential in reducing emissions of greenhouse gases in the future. An important part of that work involves the development of an inventory of technologies for reducing carbon dioxide emissions. This inventory will provide information about technical characteristics of technologies, their cost structure and economies, and environmental profiles such as specific emissions. A special feature of this inventory is that it will also specify the applicability of mitigation technologies in different technological, economic or cultural settings, and will specify the time horizon of their availability and their forward and backward linkages to other enabling technologies in the energy system.

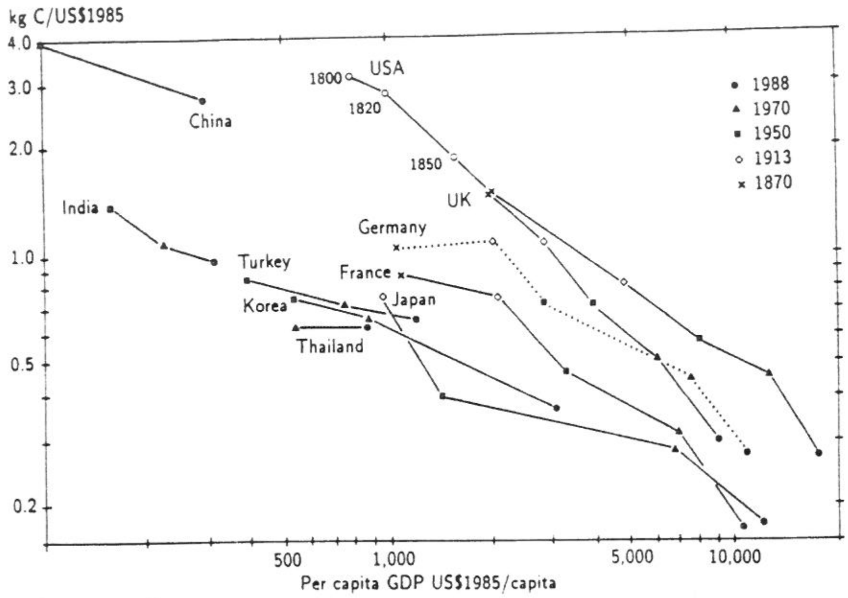

Figure 2 *Energy CO_2 emissions intensity per constant GDP, in kg per constant 1985 US$ versus per capita GDP in constant 1985 US$: Energy data include also non-commercial sources such as fuelwood. In general, carbon intensity of economic activities improves as a function of an increasing level of economic development but there remain large differences between countries for similar per capita GDP levels. It shows that developed countries had higher specific emissions per unit GDP during early development phases that are comparable to current emission intensities of GDP in developing countries [3].*

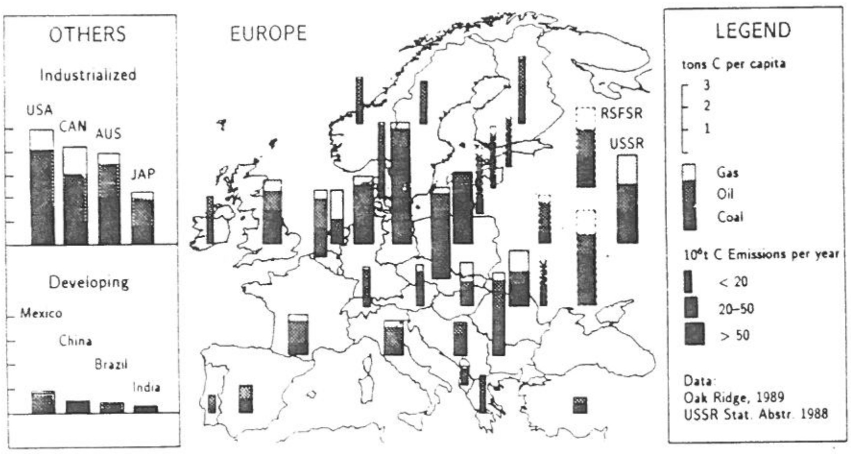

Figure 3 *Per capita CO_2 emissions from commercial energy use, by source and for selected countries (in tons carbon per year per capita): A graphical representation of per capita carbon emissions from energy use reveals extreme disparities and heterogeneity. These are the result of differences in degree of economic development, level and efficiency of energy consumption and the structure of the energy supply system (i.e. its carbon intensity). The figure illustrates vividly the significant North-South divide in energy related CO_2 emissions. Also noticeable are the high per capita emission levels in Eastern Europe, most of them stemming from coal use. Even in cases when per capita emissions are of similar magnitude, they are often so for entirely different reasons. For example, both the USA and the former GDR have per capita CO_2 emissions in excess of 5 tons carbon per year per capita. In the case of the USA this is due to high energy consumption and energy intensive lifestyles, like the high oil consumption for private transportation. In the former GDR it is due to a different level and structure of consumption and supply of energy, stressing the basic material production sector and a high share of brown coal in the energy balance [12].*

The second objective is to identify constraints and boundary conditions of *strategies* for achieving environmentally compatible paths of economic and social development. The development strategies will outline different paths of techno-economic, socio-behavioural and institutional adjustments reflecting differing technological, economic and cultural characteristics of industrial market economies, transforming economies and developing countries. Figure 3 illustrates the high degree of heterogeneity in the world today with respect to the level of energy-related CO_2 emissions. It compares per capita CO_2 emission for different countries indicating varying characteristics of energy systems, structure of the economic and social and cultural settings. For example, both the USA and the area of former GDR have the highest per capita CO_2 emissions in the world in excess of 5 t carbon per year but for fundamentally different reasons. At similar levels of affluence, some other West European countries and Japan emit much less carbon indicating that decarbonization and development are not mutually exclusive provided an appropriate policy mix is found. Especially striking is the large 'North-South' disparity in energy-related carbon emissions. Current per capita carbon emissions differ by nearly a factor of 9 (on average 3.3 tons of carbon per capita in the more developed countries compared with 0.4 tons in developing countries). The burden of the developing countries is two-fold. While they need to increase their per capita energy consumption in order to improve the quality of life, they are also more vulnerable to adverse consequences of climate change. Industrialized countries are in a better position to achieve emissions reductions compared to the rest of the world both because they have relatively high per capita emission levels and larger economic and technological capabilities. At the same time, industrialized countries are in a better situation to respond and adapt to climate change.

These considerations suggest that in the absence of appropriate countermeasures global emissions of greenhouse gases will continue to increase well into the twenty-first century, perhaps beyond environmentally acceptable levels. Thus, it might be prudent to reduce the sources of greenhouse gases to the greatest extent possible and at the same time to increase the natural sinks of carbon dioxide and create new ones for storage of carbon removed from fossil fuels. It will make a big difference whether paths of energy efficient economic development will be followed that rely on carbon-poor sources and carriers of energy or whether less energy efficient and coal intensive ones continue to predominate in the world. Also, there are other important problems facing humanity so that the limited resources available for investment and consumption have to be distributed. A comparative assessment of different strategies for mitigating and adapting to possible global warming is therefore required. Such an evaluation constitutes the main part of the on-going study of environmentally compatible energy strategies at IIASA.

4 INVENTORY OF MITIGATION MEASURES

Options and measures for environmentally compatible development, particularly in energy, encompass a wide range of techno-economic and socio-behavioral adjustments and responses. They include technological and economic measures to minimize energy-related GHGs emissions. There is a need for a comprehensive evaluation of innovative technologies with an account of their current status, implementation prospects, applicability in different geographical, economic and cultural settings, transfer to developing countries, cost structure, technical performance, market potential, time horizons of their availability and their forward and backward linkages to other enabling technologies. Such an assessment could be used to produce an inventory of the full range of technological and economic measures spanning efficiency improvements, conservation, enhanced use of low-carbon fuels, carbon free sources of energy and other options such as afforestation and enhancement of carbon sinks.

The analysis of mitigation measures covers the whole energy system from primary energy to actual energy sources including various conversion, transport, distribution and end-use systems. This is important for assessing the overall mitigation potential and possibilities. For example, energy end-use is the least efficient part of current energy systems so that it becomes of crucial importance to include end-use technologies that provide transport, industrial or residential energy needs into the mitigation assessment. A detailed energy and exergy efficiency assessment of the OECD countries shows that the conversion from primary energy to final energy forms required by the consumer is about 70 per cent. In contrast, the efficiency with which final energy forms are applied to provide useful energy and services is much lower resulting in an overall conversion efficiency of not much more than 10 per cent. In developing countries and reforming economies in Europe, the overall systems energy efficiency is lower. The efficiency of the system is still lower if different 'quality' characteristics of various energy carriers and delivered forms are taken into account. Figure 4 shows that the overall exergy efficiency in the OECD countries is at most a few per cent compared with the theoretical maximum and perhaps as low as one per cent in

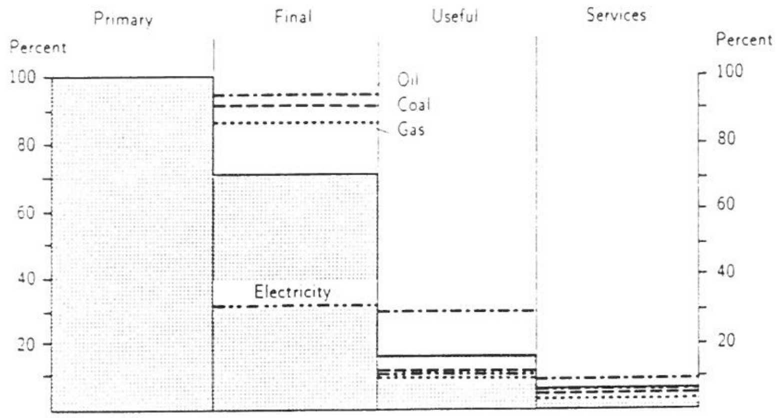

Figure 4 *Exergy balances for the OECD countries in 1986 (in per cent of primary exergy): A second-law analysis of the exergetic efficiency of the exergy (and energy) system in the OECD countries shows that while the efficiency in the provision of final exergy is already quite high, efficiencies at the end-use side, and in particular in the provision of services are low. The overall exergetic efficiency of the OECD countries is estimated to amount only to a few per cent. Figures for the USSR and developing countries are probably even lower. This indicates the large theoretical potential for efficiency improvements of between a factor 20 to 100. Realization of this potential depends on the implementation of many technological options and organizational innovations. Their different tradeoffs, the cost and timing involved need detailed study [13].*

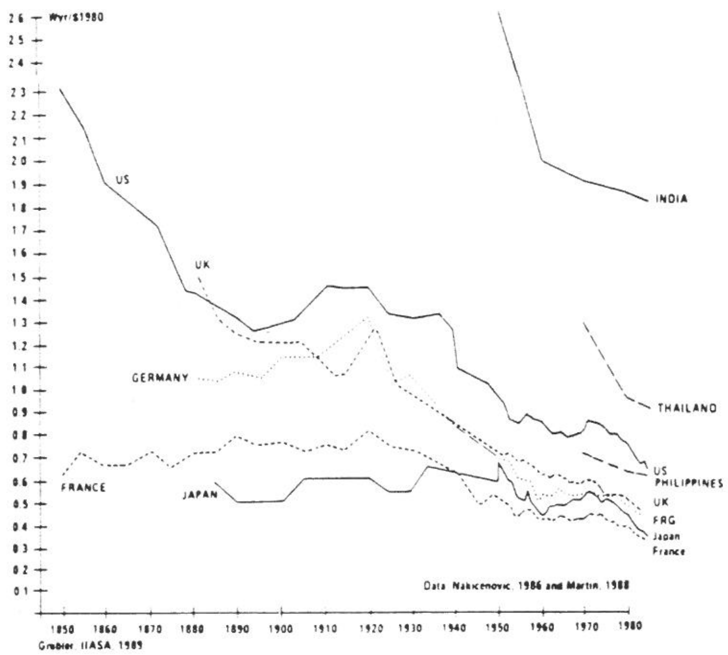

Figure 5 *Primary energy intensity (including biomass energy) per constant item (Wyr/yr constant [1980] US $): Historically, the energy intensity declined at an average rate of one per cent per year. This means that a dollar item is produced today with only one fifth of the primary energy consumption some 200 years ago. Since the early 1970s the energy intensity has improved at rates of 2 to 3 per cent annually. Also visible from* Figure 2 *are distinct differences in the industrialization paths between various countries. The actual performance of an economy in terms of its energy consumption per unit of value added is thus path-dependent. Present intensities, as well as future improvement potentials are deeply rooted in the past, in the particular industrialization path followed, the settlement patterns that have developed, consumption habits of the population, etc. The fact that the US consumes about twice as much energy per dollar item than countries in Western Europe or Japan does not necessarily imply that improvements are easier to achieve than in other countries. Developing countries have energy intensities similar to the industrialized countries at times of comparable levels of economic development and per capita income many decades ago [13]*

developing countries. This shows that there are large possibilities for more efficient energy use and in particular for improvement of end-use technologies. The inventory of mitigation measures and the technology database are specifically designed to integrate current and possible future individual conversion, transport, distribution and end-use systems into energy (or exergy) chains giving the whole bundles of technologies that define a particular reduction strategy.

The overall efficiency of the OECD countries would be nearly doubled by application of the most efficient technologies available today. The database will serve to assess such potential with greater consistency worldwide. The rates at which such efficiency improvements can be achieved are to a large extent dependent on the vintage structure of the capital stock of our economies, rates of diffusion of new technologies and technology transfer. Figure 5 shows that long-term improvement in energy intensity of item was about one per cent in the industrialized countries. However, this is a long-term historical average over 200 years containing periods of more rapid improvement (2 to 3 per cent per year), but also periods of stagnation and even reversals with increasing energy intensity as is the case today in a number of developing countries. Improvement has been faster in certain areas than in others. For example, over the past twenty years, aircraft manufacturers have managed to improve energy efficiency of commercial jet transports by 3 to 4 per cent annually. In electricity generation, this improvement has been 2.5 to 3 per cent per year over the period between 1930 and the early 1970s. These are about the upper boundary values observed over more recent history. With an improvement in the energy intensity of 3 per cent per year, a dollar of item could be produced fifty years from now with only 20 per cent of current energy requirements; this figure would be lower in terms of carbon emissions if energy substitution is also taken into account.

While efficiency improvements are a fundamental measure for reducing carbon emissions especially in the near to medium term, in the long run there is a clear need to shift to energy sources with low carbon content such as natural gas, and ultimately to those without carbon whatsoever, such as hydro, solar, and nuclear energy, and the sustainable use of biomass. Thus, technological and economic structural change will be of fundamental importance for improvement of efficiency and lowering of carbon emissions. The inventory of mitigation measures and the associated technology database is specifically designed to provide a uniform framework for assessment of ultimate reduction potentials over different time frames and in different regions including efficiency improvements, conservation, enhanced use of low-carbon fuels, carbon free sources of energy and other options such as afforestation and enhancement of carbon sinks.

The database includes detailed descriptions of the technical, economic and environmental performance of technologies as well as data pertinent to their innovation, commercialization, and diffusion characteristics and prospects. Additional data files contain literature sources and assessments of data validity and concurrent uncertainty ranges. It is an interactive software package designed to enter, update, and retrieve information on CO_2 reduction and removal technologies [8, 9].

The particular merit of the database developed at IIASA is that it can provide a ranking of mitigating measures at the global level and thus contribute in a fundamental way toward assessment of global tradeoffs involved in reducing CO_2 emissions and their economic impacts. The comprehensive catalogue of options to be developed in the subsequent phases of the study could allow for analysis and assessment of the most economical and technologically efficient global strategies for reducing climate impacts of the future energy systems.

The database can facilitate the assessment of CO_2 reduction strategies by combining many individual technologies together, i.e. to analyse measures throughout the energy chain from primary energy extraction to improvements in energy end-use efficiencies. Figure 6 shows an applications of the inventory of mitigation technologies to assess overall carbon dioxide emissions of passenger cars [14]. This figure illustrates that substantial carbon dioxide reduction potentials exist for passenger vehicles by means of a shift to alternative fuels. The specific carbon emissions include both the direct releases from the vehicles themselves and all the emissions that result from the rest of the energy supply system such as conversion of primary energy into fuels, transport of fuels and distribution to end-use. A shift to hydrogen or electricity in passenger cars would not only reduce the overall emissions but would also move the bulk of them from vehicles to conversion facilities when the removal and storage of carbon are possible and perhaps even cost-effective. Such a comparative assessment of different options and measures for reducing and removing emissions might identify future technological systems and development paths with low specific energy requirements and low adverse environmental impacts. Progress has been achieved in improving efficiency and in decarbonizing economies, as illustrated in Figure 7. All countries shown have achieved improvements in both domains. The overall objective of this research area at IIASA is to assess the conditions that would direct the future development trajectories toward further decarbonization and energy disintensification in the world.

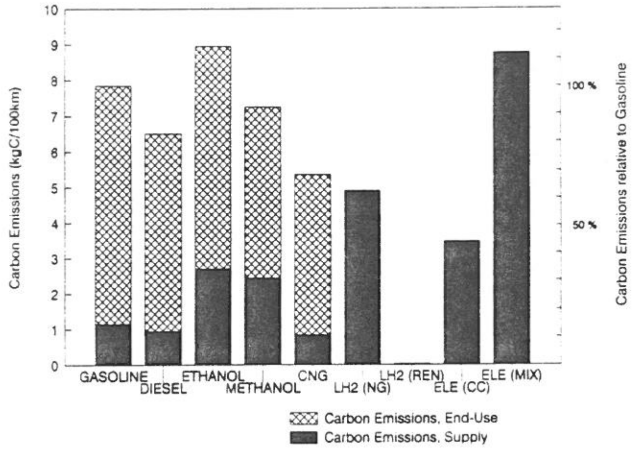

Figure 6 *Carbon emissions for different transportation fuels - gasoline, diesel, CNG: Compressed natural gas, ethanol is assumed to be produced from sugarcane, methanol and hydrogen derived from natural gas (SR-NG: autothermal steam reforming of natural gas, LH2 (REN): liquid hydrogen from renewables, ELE (CC): electric vehicle with electricity from a natural gas fired combined cycle power plant and ELE (MIX) from an average power plant with the current US fuel mix [14].*

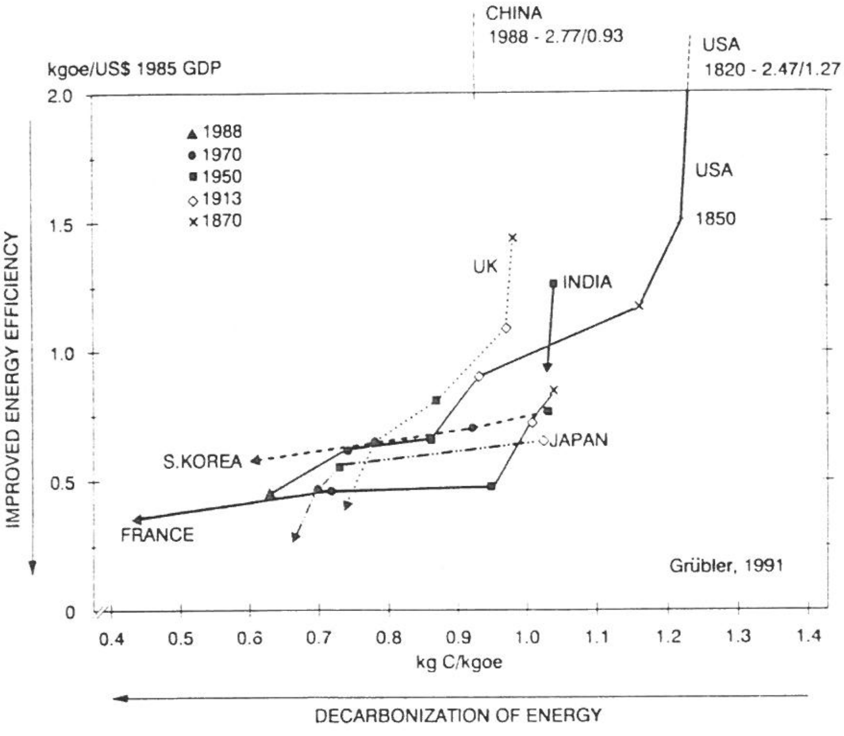

Figure 7 *Historical trends in energy (kgoe per 1000 US$ GDP) and carbon intensity (kg C per kgoe) of various countries: Improved energy efficiency (lowering the energy intensity) and interfuel substitution (lowering the carbon intensity of energy use) are two important options for lowering carbon emissions. The graph shows the diverse policy mix and strategies followed in different countries over the time horizon considered. France appears to follow a decarbonization strategy, whereas Japan mostly follows an efficiency improvement strategy. All countries shown achieved improvements in both domains. The objective of research at IIASA in the area of Energy and the Environment is to assess the conditions that would direct the future development trajectories of most countries further toward the origin of this figure [4]*

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