Energy for the 21st Century: Towards Improved Efficiency and Environmental Compatibility

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Abstract

Economic restructuring imposes new requirements in the energy sector of all economies, both market based and those in transition. In market economies, further developments in energy efficiency and environmental characteristics of energy systems are primarily driven by the quest to further improve the productivity of resource use in production and consumption, and in response to environmental concerns including possible climate change. In reforming economies, a shift away from basic, smoke-stack intensive industries towards activities with higher value added and "lean" production requires high density and clean energy carriers in conjunction with efficient end-use applications. In addition, increased efforts have to be devoted to minimize risk and adverse local and regional environmental impacts from energy production and use.

The current energy situation in Central and Eastern Europe is characterized by: high basic materials (and energy) intensity of economic activities, low energy efficiency of industrial processes and end-use applications, risk hazards from some nuclear power stations, high sulfur and carbon intensity of the coal-dominated energy supply mix, and deteriorating regional cooperation and trade as exemplified by the energy sector.

At the same time, the potentials for improving energy efficiency in the region are vast. This can be achieved mostly by economic restructuring and replacing the most inefficient capital vintages by state-of-the art technology. Although processes and end-use applications tend to be less efficient than in the OECD countries, the overall systems' efficiency of energy use in the region is higher due to the structural characteristics of the energy supply system (importance of cogeneration and district heat systems) and of the structure of energy services demand (such as the importance of energy-efficient public mass transportation systems).

In order to improve energy efficiency, it is not only important to introduce more efficient end-use devices in industry and in private households, but also at the same time to try to maintain certain overall systematic advantages of the energy supply and end-use system, in particular cogeneration facilities and an attractive public transportation system. Access to know-how and state-of-the art technology will be critical. Under a deepening of economic structural change, energy demand is likely to contract or to remain flat in the short to medium term. Therefore, investments in energy supply are unlikely to be required for significant capacity expansion but rather for upgrading and environmental improvements of existing supply systems. Because of its environmental advantages, low capital requirements and flat economies of scale, natural gas (and gas related technologies like high efficiency combined cycle gas turbines) appear as a particularly attractive energy supply option. Related infrastructural requirements and diversified long-term supply options should receive particular attention from policy-makers.

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1. Introduction

Traditional concerns about the physical and economic availability of energy supply have given way to an increasing awareness of environmental impacts of energy production, conversion and end-use at all temporal and spatial scales: from short-term/local to long-term/global environmental issues. It is against this change in the energy development "paradigm" that the more acute problems of economic restructuring and alleviating local pollution levels characteristic for Central and Eastern Europe are addressed here. This is not to suggest that regional and global environmental concerns should take prerogative over solving the problems of economic transformation and its social impacts in the Region, but rather to highlight strategies which could yield a confluence between short-term national economic and long-term global environmental concerns. Improved productivity of factor input use, i.e., energy efficiency improvements, and restructuring the energy system in the direction of more efficient and environmentally benign energy carriers are considered strategies that could reconcile these divergent policy objectives.

Economic development is basically a process of permanent structural change in order to improve the productivity, output, and diversity of the economy at both levels of production and consumption. Such restructuring imposes new requirements in the energy sector of all economies, both market based and those in transition. In market economies, further developments in energy efficiency and environmental characteristics of energy systems are primarily driven by the quest to further improve the productivity of resource use throughout the economy (i.e., "dematerialization"), and in response to environmental concerns, such as mitigating the risks of possible adverse changes in global climate stemming from emissions of greenhouse gases, in particular CO_2 (i.e., "decarbonization"), as shown in Figure 1.

Since the onset of the Industrial Revolution, humanity has consumed fossil energy amounting to nearly 200 Gigatons (Gt) of carbon (C) and current annual emissions from fossil energy use amount to about 6 Gt (10^9 tons) C. Energy-related carbon emissions are the largest expression of the metabolism of human society, surpassing by several factors in quantity any other commodity produced, or effluent generated by human activity. Compared to the current emissions of 6 Gt C, the remaining "carbon wealth" accumulated over geological times and embodied in known (or inferred) energy reserves and resources is orders of magnitudes higher. Currently identified, economically recoverable energy reserves contain nearly 540 Gt C (as shown in Table 1). Additional 3,026 Gt C are contained in resources (i.e., identified quantities whose economic recoverability is uncertain at present) and further 5,200 Gt C are contained in additional occurrences (quantities inferred by broad geological information but with their economic and technical potentials remaining largely speculative). Remaining fossil energy resources thus range between 3,500 and 8,700 Gt C, compared to a current atmospheric carbon loading of about 760 Gt. This clearly illustrates that currently known fossil energy resources could be sufficiently large to raise atmospheric CO_2 concentrations by several factors. Perhaps this best illustrates the change in perception about the factors ultimately constraining future energy systems. The ultimate global resource could be the environment rather than the recoverable energy reserves and resources to support a growing population at higher levels of economic activities and consumption.

Thus, perceptions about factors ultimately limiting future energy growth have changed, while the driving forces are still the same – population and economic growth. Some of the measures and strategies that seemed to be desirable in the past, however, appear to be invariant to this shift in perceptions. Efficiency improvements and conservation are instrumental in reducing both fossil fuel requirements and emissions. In addition, structural changes in the energy system towards cleaner fossil energy sources (natural gas) and ultimately to zero emission technologies have been suggested as technological response strategies to the risks of global change.

2. Energy and the Environment in Central and Eastern Europe

Table 2 summarizes some demographic, economic and energy macro-indicators for European regional aggregates for 1990. More recent developments in the economy and energy system of Central and Eastern Europe will be discussed briefly below. Instead of the usual presentation of national statistics, we have aggregated national data into functional regions defined on the basis of similar levels of economic development and *degree* of economic and socio-cultural *integration*. Hence, we distinguish between an European Core and its Rim, in addition to Central and Eastern Europe and the former USSR. We adopt this three-tier structure mainly to illustrate how the intensity of economic activities and functional integration thins out towards the European periphery (including former Eastern Europe). Differences in energy and environmental (emission) *intensity* of economic activities and of resulting environmental impacts also mirror (inversely) this gradient between the affluent, energy efficient, and environmentally conscious European Core and more peripheral regions in Europe.

Using gross domestic product (GDP) as a proxy for the actual extent of economic activities shows that the highest level of development has been achieved in the core regions with GDP levels in excess of fifteen thousand dollars per capita. In comparison, the per capita GDP is only about one-third of that amount in the Southern European Rim (e.g., Portugal or Greece). While it is debatable how accurate are the relative assessments of economic development when measured by a rough and, in many ways, deficient indicator such as GDP, there are serious obstacles in determining any aggregate measure of economic activities in reforming economies. Currency convertibility, different price structure and, more recently, high inflation all make macroeconomic comparisons difficult. Using UNDP's estimates of purchasing power parity (PPP) GDP indicates for Central and Eastern Europe a level of economic development and consumption characteristic for the Southern European countries (the European Rim in our terminology).

In contrast to the relatively low levels of economic development (in terms of estimated per capita GDP), energy consumption per head in Central and Eastern Europe is ample, even by the standards of the highly affluent European Core. In fact, Russia proper consumes more primary energy per capita [above 5 tons of oil equivalent (toe)] than the European Core region (3.8 toe/capita on average). This suggests that it is not the availability of energy *per se* that matters, but more on *how energy is used* throughout the economy, i.e., the *efficiency of energy use.*

This is exemplified when one looks at the energy intensity of economic activities which varies up to a factor of ten between different European regions and still by a factor of three when considering PPP GDP estimates (as perhaps more appropriate) indicator. Of course these regional aggregates mask even more dramatic differences in the value generation per unit of energy consumed between individual countries as a result of their different economic structure and efficiency of their energy system. On the extreme ends, the GDP (at market exchange rates) can exceed 8,000 $ per toe primary energy consumed (Switzerland) or be below 500 $ per toe as in the case of Romania and the CIS republics. These differences become somewhat reduced considering PPP GDP estimates, but remain nevertheless significant: economic output per unit of energy consumed can still vary by a factor five as the case between Switzerland and Romania.

However, the much higher energy intensities of economic activities prevailing in the Region do not necessarily imply that the overall efficiency of the energy system of Central and Eastern Europe is lower than in the West (cf. discussion below). Due to a number of structural features such as the importance of cogeneration or public transport systems, the overall conversion efficiency from primary to useful energy is in fact higher than in the OECD countries. This means that these structural features more than compensate the lower energy efficiency of individual conversion and end-use devices such as power plants, boilers or cars. Therefore, the main conclusion that can be drawn from the large differences in energy intensity is to point to the importance of economic structures and the efficiency of *energy use* (i.e., the conversion of useful energy to energy services) rather than to consider only the efficiency of energy supply (including end-use).

The particularly high energy (and environmental) intensities in Central and Eastern Europe can be attributed both to the structure of the energy system which relies heavily on coal use and to the structure of the economy relying heavily on the so-called primary sector, composed mostly of traditional smoke-stack industries. Both the low efficiency of energy use and the coal intensive energy supply mix result in extreme environmental burdens. This is exemplified in all energy-related emissions that result in environmental impacts ranging from urban smog to acid rain and global warming. Figure 2 shows the density of sulfur emissions in Europe derived from the Regional Acidification Information and Simulation (RAINS) Model developed at IIASA (Alcamo *et al.*, 1990). As the atmosphere does not respect political and national boundaries, dispersion of air pollutants from the coal production/consumption regions of Central and Eastern Europe pose a heavy burden not only to the local environment but equally to neighboring countries.

The differences in environmental impacts between the European core and the Central and Eastern Europe is most vividly exemplified in the CO_2 emissions (Figure 3): The highest per capita CO_2 emissions in excess of four tons per capita (5.6 tons/capita in the former GDR) are observed in the countries with the highest share of coal in the primary energy mix (former GDR, ex-Czechoslovakia and the Ukraine). In these countries, between one to 1.2 tons of carbon is emitted per each ton of oil equivalent of primary energy consumed. Conversely, the Western European average carbon intensity is with 0.7 tons C/toe, some 30 to 40 percent lower. It is interesting to point out that from all countries in the Region, only Russia has a similar favorable carbon intensity of its energy supply, primarily stemming from the importance of natural gas (and to a smaller degree also nuclear energy) in its primary energy mix. Even larger than the differences in the carbon intensity of energy supply are above discussed energy intensities, compounding thus further the differences between countries in their environmental (e.g., CO_2) intensiveness of economic activities. In the most extreme case, the carbon intensity of economic activity can vary by a factor of about 25 between Switzerland and the Ukraine. The CO_2 emissions are among the indicators which reveal the sharpest distinction between the relatively high efficient and service oriented economies of the European Core and the energy-intensive industrial structure of the Eastern periphery, resembling the industrialization path of the Core countries more than half a century ago.

3. Economies in Transition and Impacts on the Energy System

The most visible macro and microeconomic effects of the current restructuring of the former centrally planned economies in Central and Eastern Europe are a significant contraction in (industrial) output and in private consumption. The magnitude and duration of this contraction has been more severe than expected at the start of the reform process. In some countries, the economic output dropped by more than 30 percent in two years, a scale of contraction far larger than was experienced by market economies during the period of the Great Depression in the 1930s. Overall, estimates indicate that economic output declined by more than ten percent for the region as a whole over the 1990 to 1991 period. Most recent IMF (1992) projections expect a further decline of some twenty percent over the 1992 and 1993 period.

The situation is quite different between countries that are at various stages of economic reform and concommittant structural change. For instance, GDP levels decreased by up to 40 percentage points (of 1985 levels) between 1989 and 1991 in the former GDR, Poland and former Yugoslavia, and between 16 and 26 percentage points in Hungary, Romania and former Czechoslovakia. Industrial production decreased by typically 30 to 40 percentage points between 1989 and 1991, whereas industrial employment fell between 12 and 19 percentage points in Poland and Czechoslovakia over the same time period. Industrial employment in the former GDR territory fell to half of the 1985 level by 1991, and to 31 percent by mid-1992.

Macroeconomic stabilization policies, the breakdown of central planning, economic reforms, price liberalization, and progressive exposure to foreign competition are factors that have contributed to the drop in economic output of the Region. Moreover, a major factor behind the output collapse, particularly in the industrial sector was the dissolution of the trading arrangements within the Council for Mutual Economic Assistance (CMEA) in early 1991 and the sharp reduction of imports by the former GDR and the former Soviet Union. Intra-CMEA trade is estimated to have dropped by more than 50 percent in 1991 alone. This exogenous drop in trade was compounded by large terms of trade deterioration associated with a shift to world market prices, especially for energy imports. Natural disasters, political upheavals and civil strife also contributed to the drop in output as, for instance, in the case of Armenia, Georgia and the former Yugoslavia.

These macroeconomic developments have had profound implications on both energy demand and supply in the countries concerned. Despite the inevitable time lag in the availability of energy statistics, one can conclude that the reduction in economic activities is also mirrored in energy consumption figures, although as a rule energy consumption fell less than the corresponding activity levels either at the macroeconomic or sectoral level.

For instance, over the period 1988 to 1990, the primary energy demand in Poland dropped by nearly 22 percent and the final energy consumption even by 24 percent (for a GDP decline of over 25 percent). The most significant decline in final energy consumption (nearly halving the 1988 consumption levels) can be observed for solids (coal), whereas for high quality final energy carriers, such as electricity and district heat, the final energy consumption fell by less than 10 percent. Most of the decline in energy consumption occurred in industry as a result of the decline in production (–40% over the 1989 to 1991 period), economic structural change and rapid increases in energy prices. These price increases, however, happened in a period of rapid inflation and have been less pronounced on a real-term basis.

According to Kononov (1992), Russia's GDP dropped by 11 percent (of 1990 levels) in 1991, whereas the primary energy consumption dropped by some 1.6 percent only. For 1992, the decline in economic output was estimated to be between 20 to 30 percent with primary energy consumption dropping by up to 10 percent (Bashmakov, 1992). This low (downward) elasticity of energy demand exacerbates the much higher energy intensity of the Russian economy which is widening compared to Western European or US levels.

The most drastic reductions in energy consumption to date in any of the Central and Eastern European countries have occurred in the former GDR territory. Primary energy consumption dropped by one-third between 1987 and 1991, and nearly by 50 percent in 1992. Over the 1987 to 1991 period, the final energy consumption dropped equally by 30 percent with most of this decline being accounted for in the industrial and commercial (and military) sectors. Electricity consumption dropped from 11.1 million tons of coal equivalent (tce) in 1987 to 7 million tce in 1991, or by 37 (!) percent. Figure 4 shows the estimates of the evolution of industrial production (index) and energy consumption. Even if monetary output indices may overstate the decline in the absolute industrial production volume, a contraction of industrial output between one-third to one-half in a period of two years illustrates the scale of the economic transformation underway in the former GDR. The decline in industrial energy consumption was similarly dramatic, falling from some 1,000 PJ in 1989 to less than 500 PJ in 1991. It is also interesting to point out that similar far reaching changes can be observed with the energy supply of the former GDR. The consumption of coal more than halved between 1987 and 1992, nuclear energy was phased out completely, the country turned from a net importer to a net exporter of electricity, and oil consumption increased in absolute terms and even more so in relative ones (increase in the oil share in the primary energy balance from 13 percent to 28 percent over the 1987 to 1992 period). The structural changes in the electricity generating sector were similarly dramatic, resulting primarily in a reduction in the use of lignite for electricity generation in addition to above-mentioned phase out of nuclear energy.

Although perhaps an extreme example in scale and rapidity of structural change in both its economy and energy system, the former GDR nevertheless indicates that the overall evolution of economic activities is likely to be the dominant driving force for changes in energy demand and supply in Central and Eastern Europe in the short to medium term. These changes are likely to be so significant as to overshadow developments and constraints of the energy sector's development proper. The available data also suggest that the decline in energy consumption in reforming economies is less dramatic than the decline in macroeconomic and particularly in industrial output, implying a rising (industrial) energy intensity. This appears to be the result of a disproportionate decline in comparatively high value added industrial activities (in particular investment goods such as machinery) whereas more energy-intensive industrial activities, such as raw material production, declined less. Another factor in this rising energy intensity in industry is the decreasing capacity utilization of most industrial plants, implying frequent stop and go production schedules and thus reducing the efficiency of industrial energy use.

From such perspective, the initial process of economic restructuring is accompanied by a deterioration of the energy intensity. Improvements will only occur after consolidating the decline in economic and industrial output and after decommissioning the most inefficient capital vintages along with some investments into upgrading remaining equipment. With respect to energy supply, the structural changes that has been initiated and is likely to continue primarily implies a retreat from the massive reliance on coal in the Region, whereas high density and quality energy carriers such as electricity and natural gas will be less affected. However, policy emphasis will have to be given to improve regional economic cooperation and trade, particularly in energy. Those emphasizing immediate and comprehensive world market prices and hard currency payments for all energy trade should consider that the alternative to barter and other transitional forms of trade is no trade at all, i.e., a collapse of exports, especially as the market potentials towards Western Europe appear limited in view of a weak economy (and thus flat demand) and infrastructural limitations.

From an environmental perspective, both improved energy efficiency (i.e., declining energy intensity) and structural changes in energy supply (a move away from the use of coal particularly without pollution control) will be instrumental for improving the local environment. However, improved energy efficiency as a generic measure has an additional advantage over individual "add-on" pollution control measures as it can alleviate simultaneously a number of environmental impacts from the local up to the global scale. The potential for energy efficiency improvements appears to be large by any measure, although it is at present unclear how much and with what rate such potentials might be translated into actual improvements in energy intensity. The resulting likely reduction in energy demand however, could offer possibilities to decommission the environmentally most harmful energy facilities (in particular coal-based electricity generation) and/or to decommission the nuclear power plants with the highest risk potential without undue consequences on energy supply in the region. Yet another open question remains whether, in the face of declining energy consumption, the available productive capacity will not serve instead for energy exports (and hard currency earnings) to Western Europe provided appropriate infrastructures can be put in place.

4. Improving Energy Efficiency and Decarbonizing the Energy System

Figure 5 shows some longitudinal data on the long-term evolution of the primary energy intensity of economic activities in selected market economies and contrasts this with a range of energy intensities for countries in Central and Eastern Europe based on PPP and market exchange rate GDP estimates. Three noteworthy tendencies can be derived from Figure 5. First, for market economy countries, a clear long-term trend towards improved energy intensity (even in periods of low energy prices) can be discerned. Thus, improved energy efficiency is just another aspect of the long-term productivity increases of our economies that goes along with technological and economic structural change. Secondly, we observe persistent differences in energy intensity "trajectories" between countries as a result of their different resource endowments, industrial structures, settlement patterns and consumption habits of the population that have evolved, etc. These differences thus accrue from the cumulativeness of the process of economic development and cannot be only attributed solely to short-term economic variables such as relative price structure. Thirdly, the "efficiency gap" of Central and Eastern Europe can be put into a longer-term perspective: even in using the more favorable PPP GDP intensity indicator, Russia's energy intensity resembles that of the US some 50 years ago, and using an alternative indicator (based on "compromise" market exchange rates) the time shift in Russia's energy intensity compared to the US could well extend over 100 years.

At face value, these differences in energy intensity suggest a vast potential for efficiency improvement. For assessing these potentials that can be realized via measures related to energy supply and end-use, it is useful to first analyze the actual efficiencies of individual energy conversion and end-use devices and systems. For that purpose, detailed energy balances have been analyzed at IIASA to calculate the conversion efficiencies of a large number of energy chains and the weighted average efficiency of the whole energy system in a number of countries and regions (cf. Nakićenović, Grübler, *et al.*, 1993). The analysis does not end at the level of final energy but also includes the subsequent conversion of final energy to useful energy (lighting, or kinetic energy required for transportation purposes).

Figure 6 illustrates the estimated efficiencies of energy transformation from primary to useful forms for market economies (i.e., the OECD countries) and the reforming economies of Central and Eastern Europe. The highest efficiencies prevail in the conversion of fuels from primary to secondary energy forms. Refinery efficiencies are about 90 percent and on average, the conversion (including transport and distribution) to final energy forms of coal and gas also incurs rather low losses with efficiencies ranging from about 60 to almost 90 percent. Efficiencies in the generation, transport and distribution of electricity range typically between 20 to 35 percent. Overall, the primary to final energy conversion processes are quite efficient: on the average, about 70 percent of primary energy ends up as final energy delivered to the consumer. In comparison, the final to useful energy conversion efficiency is quite low: ranging from only 30 percent in the reforming economies to almost 53 percent in market economies. In general, natural gas and electricity have the highest end-use efficiencies. These results confirm that overall the largest energy conversion losses originate from end-use devices (boilers, cars, etc.) and not from facilities upstream the energy chain, pointing to the importance of efficiency improvement measures at the level of energy end-use.

The resulting average primary to useful energy efficiencies of the energy system were calculated to amount to 37 percent in the OECD region and 42 percent in the reforming economies. This implies that on the average only one-third of primary energy ends up as useful energy after the last conversion process in a large number of energy chains. The fact that the overall energy systems' efficiency is 42 in the reforming economies higher than in the OECD may appear paradoxical. All individual primary to useful energy chains are less efficient than in the market economies. However, the overall systems' energy efficiency is higher due to the *structural* characteristics of the energy system in reforming economies favoring collective, more end-use efficient forms of energy consumption. For example, people travel by public transport modes rather than private cars and they heat their homes using cogenerated heat rather than individual oil burners. Thus, while Russian buses are indeed less fuel efficient as German ones, Russian buses are nevertheless more energy efficient means of transportation than private cars in Germany!

The most important overall result from such an analysis is that energy end-use is the least efficient part of the overall energy system, and it is in this area that improvements would bring the greatest benefits. By taking the currently best efficiencies possible with existing technologies (e.g., a conversion efficiency of natural gas to electricity above 50 percent without considering cogeneration) and performing a similar analysis as reported in Figure 6, one can show that the average primary to useful energy conversion efficiency could be raised to some 60 percent without violating any thermodynamic limits, indicating that there is much room left for efficiency improvements in all economies: reforming and market based alike.

The rates at which such efficiency improvements can be achieved are to a large extent dependent on the age distribution of the capital stock in the economy, rates of diffusion of new technologies and technology transfer. The long-term improvement in the energy intensity of GDP shown in Figure 5 was about one percent per year in the industrialized countries. However, this is a historical average over 200 years containing periods of more rapid improvement such as since the early 1970s with 2 to 3 percent per year, but also periods of stagnation and even reversals with increasing energy intensity as the case today in a number of developing countries. With improvement rates of 2 to 3 percent per year, i.e., at a similar rate as economic growth, energy demand in most OECD countries has remained flat since the early 1970s. Over longer time periods, the improvements in energy intensity have averaged one percent per year. The difference to the long-term rate of economic growth of 3 percent yields the observed long-term growth rate of primary energy consumption worldwide of about 2 percent annually.

Efficiency improvements have been faster in certain areas/sectors than in others. For example, over the past twenty years, aircraft manufacturers have managed to improve the energy efficiency of commercial jet transports by 3 to 4 percent annually. In electricity generation, this improvement has been 2.5 to 3 percent per year over the period between 1930 and the early 1970s. These are about the upper boundary values to be expected in efficiency improvements in the medium term. With an improvement in the energy intensity of 3 percent per year, a dollar of GDP could be produced fifty years from now with only 20 percent of current energy requirements; this figure would be lower in terms of carbon emissions if energy substitution is also taken into account.

Figure 7 shows the typical age distribution of the capital stock in Germany and the ex-USSR indicating that about 80 percent of the capital stock is younger than 20 years, i.e., is turned over within less than two decades. Taking the results from Figure 6 which indicate a potential to improve the primary useful conversion efficiency of current energy systems in the OECD and Central and Eastern European countries to some 60 percent between primary and useful energy (i.e., an improvement of around 50 percent compared to current levels) and a capital turnover rate of 20 years would yield an annual improvement rate in energy efficiency of 2 percent. This calculation delineates the range of efficiency improvements possible with currently available technologies and normal rate of capital turnover.

In order to improve energy efficiency, it is however not only important to introduce more efficient end-use devices in industry and in private households, but also at the same time to try to maintain certain overall systematic advantages of the energy supply and end-use system Central and Eastern Europe, in particular cogeneration facilities and an attractive public transportation system.

While efficiency improvements are a fundamental measure for reducing environmental impacts especially in the near to medium term, there is a clear need to shift to clean energy sources in the long run. This means first a progressive shift to environmentally more benign fossil fuels such as natural gas, and ultimately to those without sulfur, nitrogen or carbon emissions whatsoever, such as hydro, solar, nuclear, and the sustainable use of biomass. These structural changes in the energy supply mix towards an environmentally "lighter" menu are again not inconsistent with historical experience. Figure 8 shows the long-term trend in the carbon intensity of the global primary energy consumption indicating that on the average the global fuel mix has "decarbonized" at a rate of about 0.3 percent per year. This was primarily the result of a gradual shift to fossil fuels with a higher hydrogen to carbon ratio, such as natural gas (4 hydrogen atoms per carbon atom), and also to carbon-free sources of energy such as hydropower and nuclear energy. In fact, Western Europe and Japan have decarbonized their energy systems over the last two decades at rates between 0.8 to 0.9 percent annually (Ogawa, 1992) due to *inter alia* a significant market penetration of nuclear energy in the power plant sector.

5. Technology Assessment

There are indeed a multitude of options to improve the efficiency of energy use and to further enhance its environmental compatibility, for instance in decarbonizing energy systems. However, these options need a systematic and careful evaluation with respect to their ultimate potentials, costs involved, and possible diffusion horizon before conclusions on their desirability and applicability in different economic and social contexts can be drawn.

Such an evaluation constitutes the main part of an ongoing study within the Environmentally Compatible Energy Strategies (ECS) Project at IIASA. In order to make the technology assessment transparent and open to critical evaluation, the activity includes the development of an integrated database for a comprehensive inventory of technological options for mitigating energy related CO_2 emissions: the CO2DB. The database covers 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 inventory of mitigation measures and the associated technology database are specifically designed to provide a uniform framework for assessment of ultimate impacts from the introduction of new technologies over different time frames and in different regions. 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 energy technologies with emphasis on those offering opportunities for CO_2 reduction and removal.

The database also enables the assessment of CO_2 reduction strategies by combining many individual technologies together, i.e., to analyze measures throughout the energy chain from primary energy extraction to improvements in energy end-use efficiencies often called full-fuel-cycle analysis. Thus, the CO2DB enables analysis of options encompassing whole bundles of technologies that define a particular energy or environmental strategy.

Figure 9 illustrates an analysis of the cost, CO_2 emissions and energy requirements of different energy chains that provide the same service -- lighting. Each of the seven bars depicts a different combination of technologies that can now or could in the future provide lighting: conventional incandescent bulbs versus energy-efficient compact flourescent bulbs; power generated by a conventional power plant burning hard coal versus a highly efficient combined-cycle natural-gas turbine, with or without CO_2 scrubbing. The bottom bar in each graph compares one of the six US energy chains with an identical chain in Austria: analyses using CO2DB show to what extent identical technological systems can have different costs and consequences in different situations.

Figure 9 illustrates several other features of the CO2DB inventory. First, it depicts all parts of an energy chain. Second, it gives a breakdown of the costs and emissions attributable to each step in the chain: in these examples costs to deliver the same service differ by about 30 percent, while CO_2 emissions to provide that service differ by more than 90 percent. Third, it allows analysis of trade-offs: for instance, the potential to reduce CO_2 emissions by concentrating on energy end-use -- in this case, the type of bulb -- versus energy supply, and the approximate costs of changing any part of the chain.

6. Environmentally Compatible Energy Strategies

Four types of technological strategies can be distinguished for improving the environmental compatibility of current and future energy systems. The first is an incremental one, emphasizing energy efficiency improvements. In this case, devices or operational practices are replaced by more efficient ones without major changes in the technology of the device itself or technologies upstream of the energy chain. For example, this could mean replacing a refrigerator or a gas-fired power plant by more efficient vintages while using the same electricity and fuel supply chains. The other three strategies are more radical. They include changes in the design and operational practices of technologies with and without changes in the energy chains. We refer to these as changes in technological "trajectories". In the simplest case, the end-use technology is changed but keeps the same upstream energy chain, e.g., switching from a gasoline to diesel car. Alternatively, the end-use and conversion technologies may stay the same but the primary energy input changes, such as switching from an oil to a gas-fired combined-cycle power plant. Finally, it is possible to change the "trajectories" of end-use, conversion and primary energy supply technologies, such as switching from a gasoline car with oil as the primary energy source to an electric vehicle with photovoltaic panels.

There is a clear ranking of the four different technological strategies with regard to costs. The incremental improvements have the lowest cost because they do not require changes in technological trajectories. These are also the easiest to implement and take the shortest time. They are followed by measures that involve a change in the primary energy source and those involving changes in end-use technologies. Generally, the most difficult and costly measures to implement will be those where both end-use and primary energy supply technologies have to be changed. Here, changes are required in all related components of the energy system, meaning that new energy chains have to be entirely developed and built up: new energy supply systems, infrastructures, diffusion of new end-use devices and delivery outlets.

Under a deepening of economic structural change, energy demand in Central and Eastern Europe is likely to contract or to remain flat in the short to medium term. Therefore, investments in energy supply are unlikely to be required for significant capacity expansion but rather for upgrading and environmental improvements of existing supply systems. An open question is whether perennial capital shortages and related limited access to energy efficiency and pollution prevention/clean-up technologies will enable to achieve these desirable objectives. Recognizing that both regional and global environment are shared resources might be a first step towards cost effective internationally coordinated strategies addressing simultaneously the issues of economic transformation *and* environmental protection.

Because of its environmental advantages, low capital requirements and flat economies of scale, natural gas (and gas-related technologies such as high efficiency combined cycle gas turbines) appear as a particularly attractive energy supply option in the Region. Policy-makers should pay particular attention to related infrastructural requirements and diversified long-term supply options. Increased reliance on natural gas is also an interesting transitional energy option from a global change perspective. There are three reasons for this. First, natural gas is the fossil fuel with the most favorable hydrogen to carbon ratio and thus the lowest specific carbon emissions per unit energy. Secondly, gas, next to (cogenerated) direct heat, is the most efficient technology chain to convert primary to useful energy. Thirdly, increased reliance on gas could open strategies for active CO_2 recovery (e.g., from steam reforming) and disposal, closing thus the energy carbon cycle.

Both technological and economic structural change will be of fundamental importance for efficiency improvement and for lowering emissions in order to achieve environmentally compatible pathways of socioeconomic development. The strategies outlined in this paper aimed to illustrate that there might be a significant confluence between economic and environmental objectives which should be explored in more detail in periods of rapid structural change, such as currently the case in Central and Eastern Europe.

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Table 1. Fossil energy consumption, reserves and resources (Gt C).

	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

Table 2. Area, population, GDP, energy and carbon emissions of European regional aggregates ca. 1990.

	Core[a]	Rim[b]	Eastern EU[c]	Western CIS[d]	Russia	Rest of ex-USSR
Area, 10^6km^2	2643	1580	1340	845	17075	4308
Population, 10^6	307	118	131	66	147	68
Inhabitants/km^2	116	75	98	78	9	16
GDP, 10^{12} \$88[e]	4900	540	260	130	350	80
PPP-GDP, 10^{12} \$87[f]	3870	670	610	370	1030	240
GDP/capita, 10^3 \$	16.0	4.6	2.0	1.9	2.4	1.2
PPP-GDP/capita, 10^3 \$	12.6	5.7	4.7	5.7	7.0	3.5
Primary energy consumption, mtoe	1065	182	382	269	832	205
toe per capita	3.8	1.5	2.9	4.1	5.7	3.0
kgoe per \$	.22	.34	1.45	2.10	2.35	2.49
kgoe per PPP \$	.28	.27	.63	.72	.80	.85
Carbon emissions from energy, Mt C	756	107	351	254	562	155
tons C per capita	2.5	.9	2.7	3.8	3.8	2.7
kg C/kgoe, primary energy	.72	.59	.92	.94	.68	.90

Notes:

a) Core: EEC 9 (Germany includes former GDR) and EFTA.

b) Rim: Greece, Ireland, Portugal, Spain.

c) EEU: Albania, Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovak Republic, ex-Yugoslavia.

d) West-CIS: Byelorussia, Moldavia, Ukraine.

e) Based on "compromise" exchange rates. Source: Economist, 1991.

f) Source: UNDP, 1990.

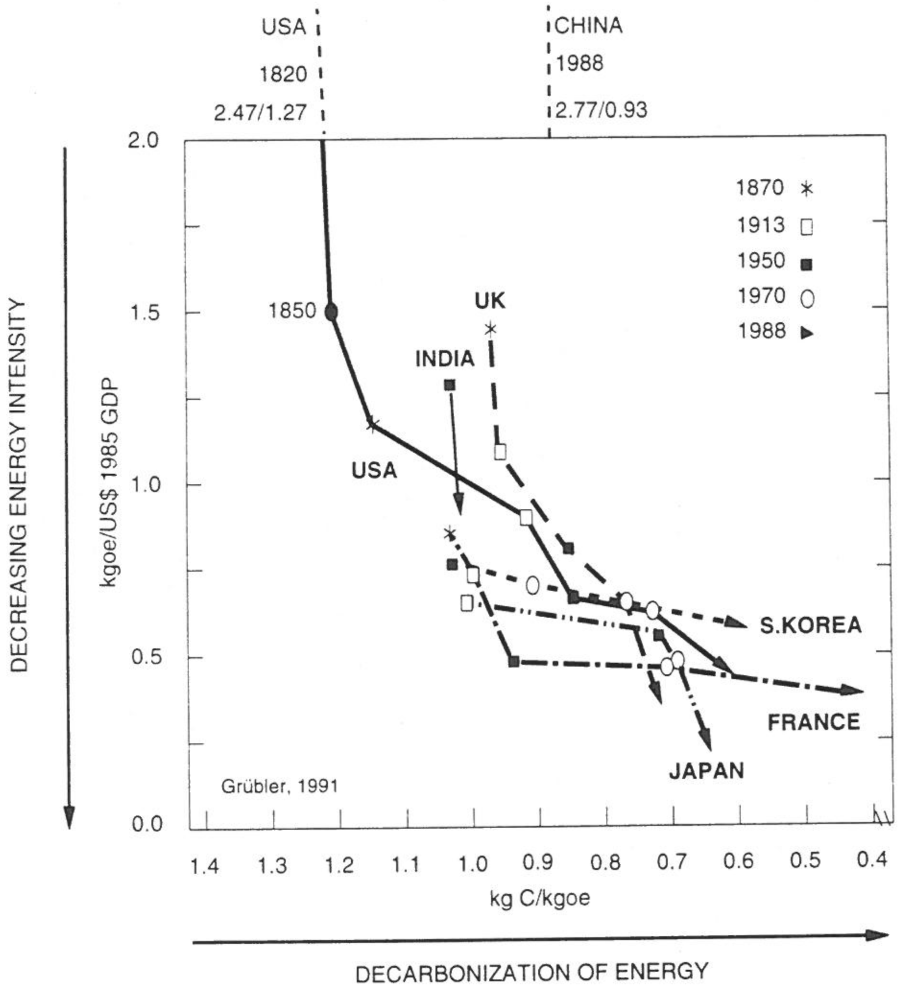


Figure 1. Trends in selected countries towards decreasing energy (kgoe/$ 1985 GDP) and carbon (kg C/kgoe) intensity.

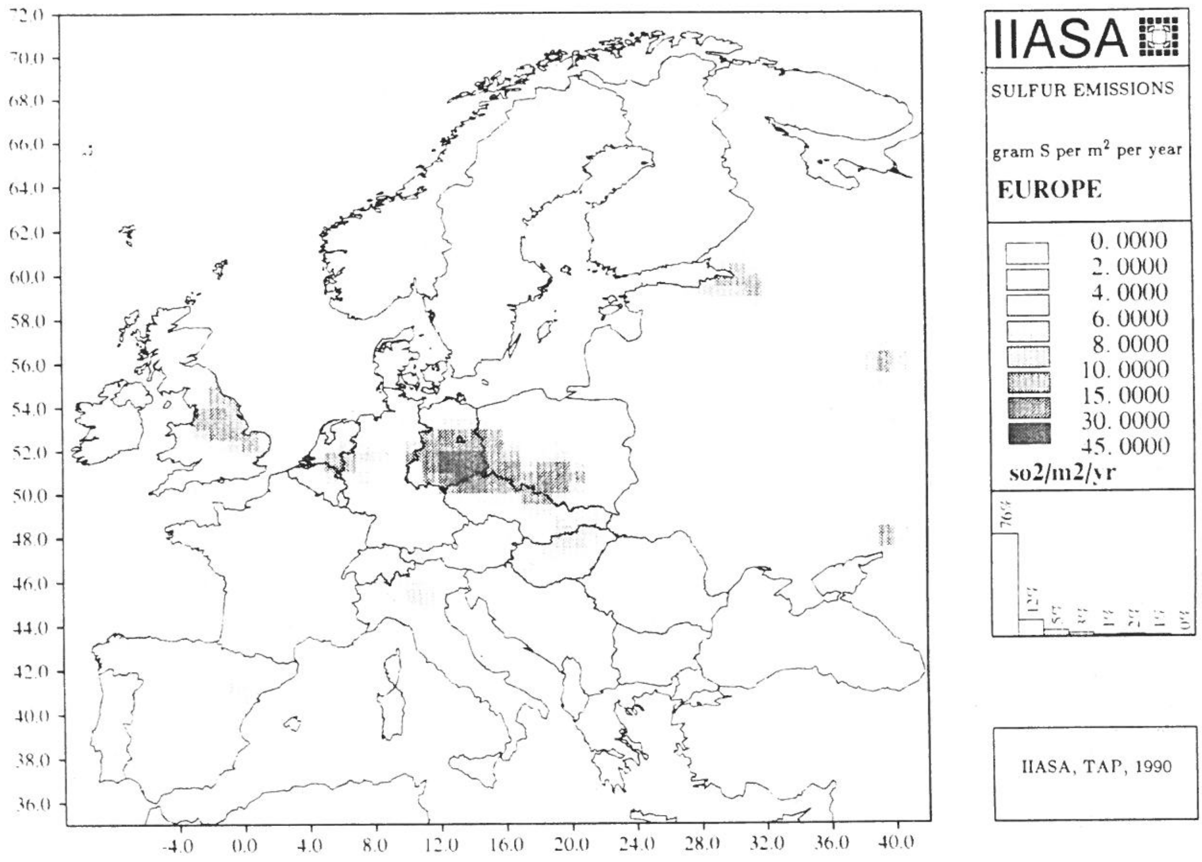


Figure 2. Spatial density of sulfur emissions from energy conversion and end-use in Europe (gram S/m^2). Source: Alcamo *et al.*, 1990.

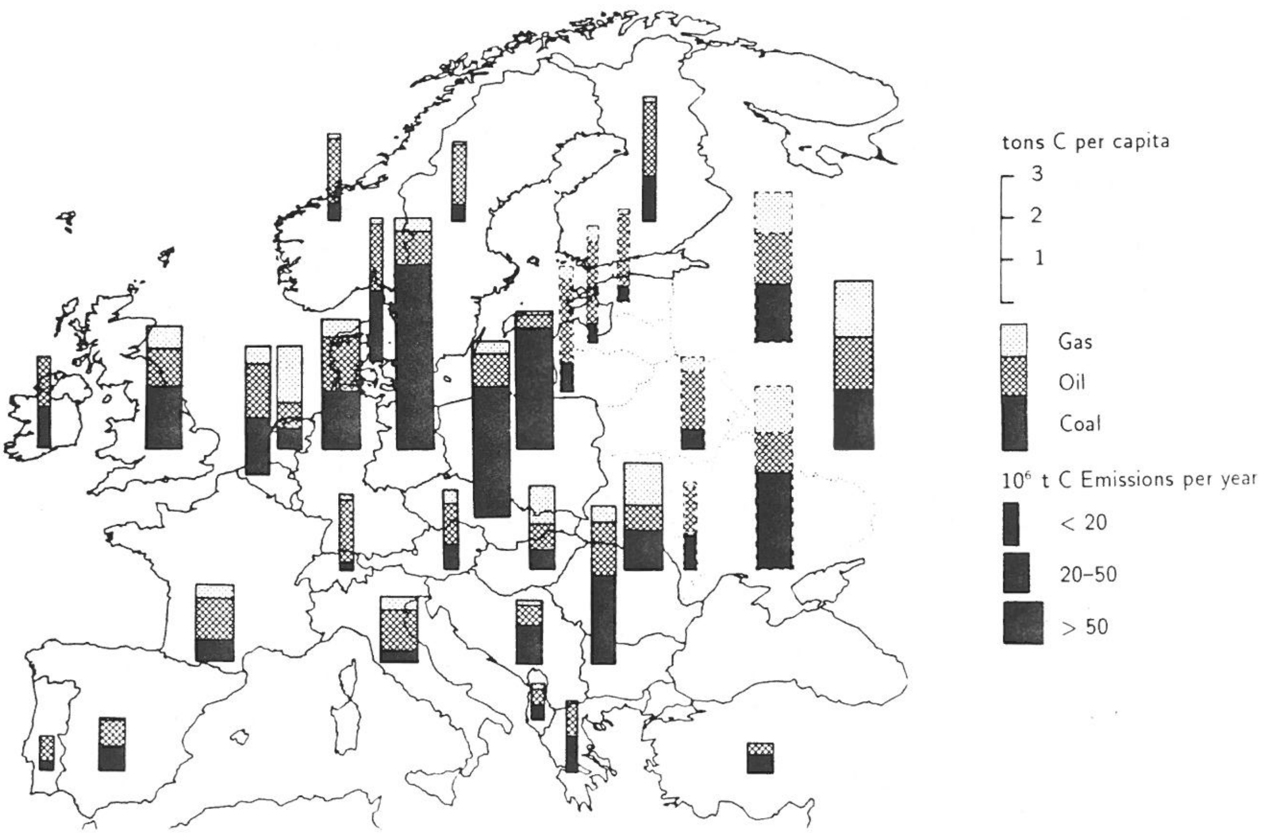


Figure 3. Energy-related carbon emissions for European countries in 1989, per capita and by source (tons C per capita).

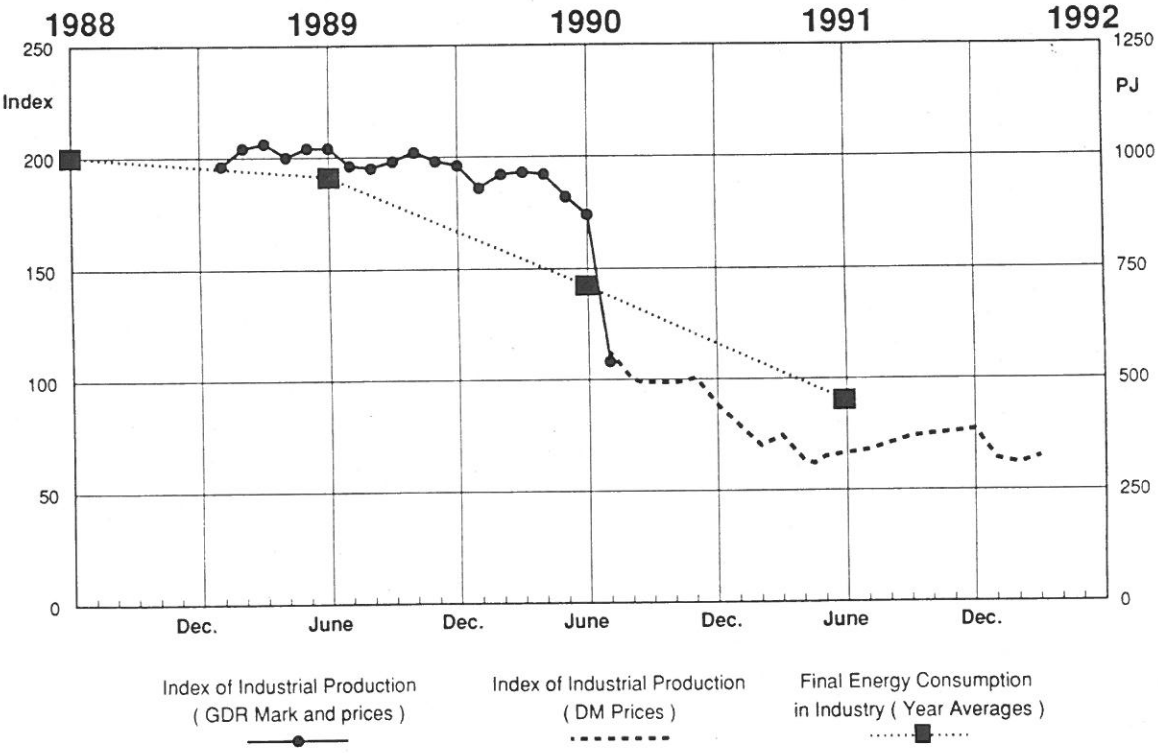


Figure 4. Evolution of industrial output (value index) and energy consumption (PJ) in the former GDR.

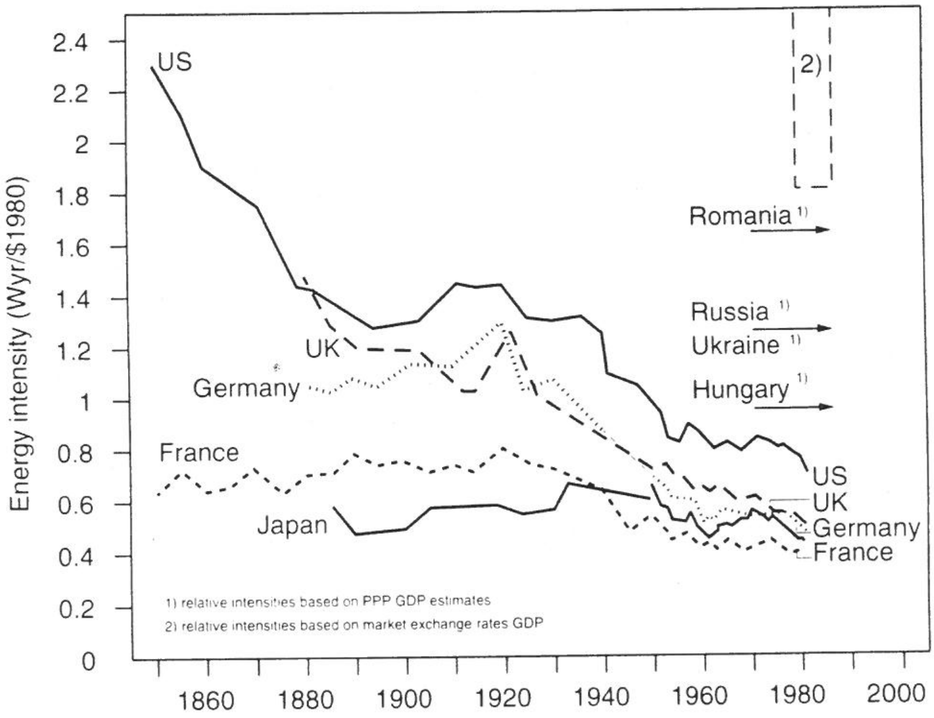
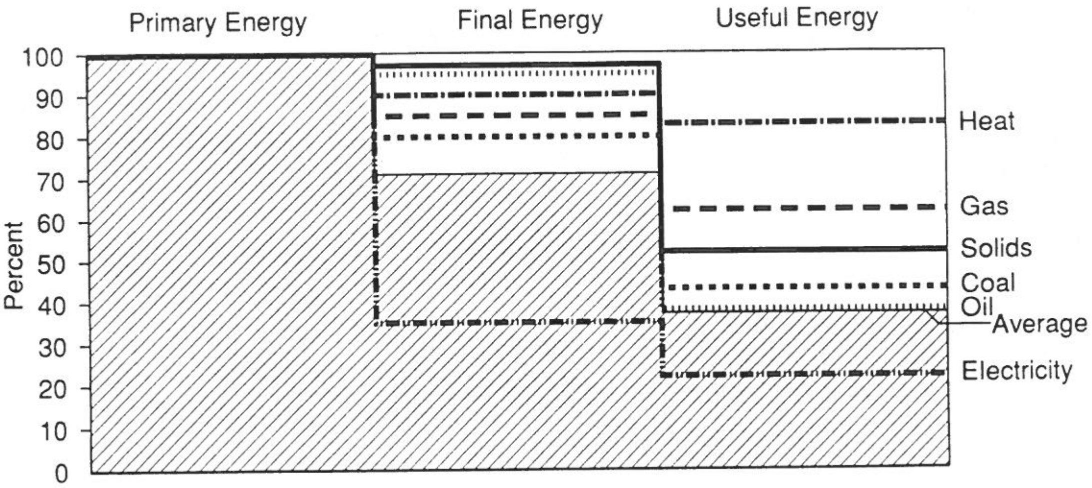
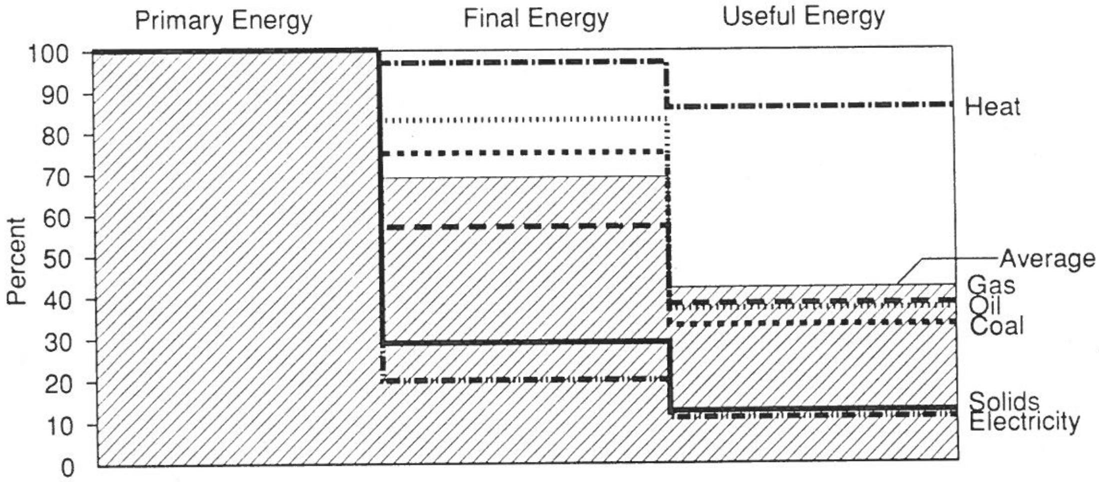


Figure 5. Primary energy per constant GDP (Wyr/$ 1980) for selected countries. Note that primary energy includes also non-fossil sources and fuelwood. Hydro and nuclear electricity accounted for with thermal equivalent of kWh. Relative intensities of Central and Eastern European countries based on PPP GDP and market exchange rate GDP estimates.



* Vector specific efficiencies exclude cogeneration; average includes district heat and cogeneration



* Vector specific efficiencies exclude cogeneration; average includes district heat and cogeneration

Figure 6. Energy efficiency in percent of primary energy in market economies (top) and reforming economies (bottom). Vector specific efficiencies exclude cogeneration; average includes district heat and cogeneration.

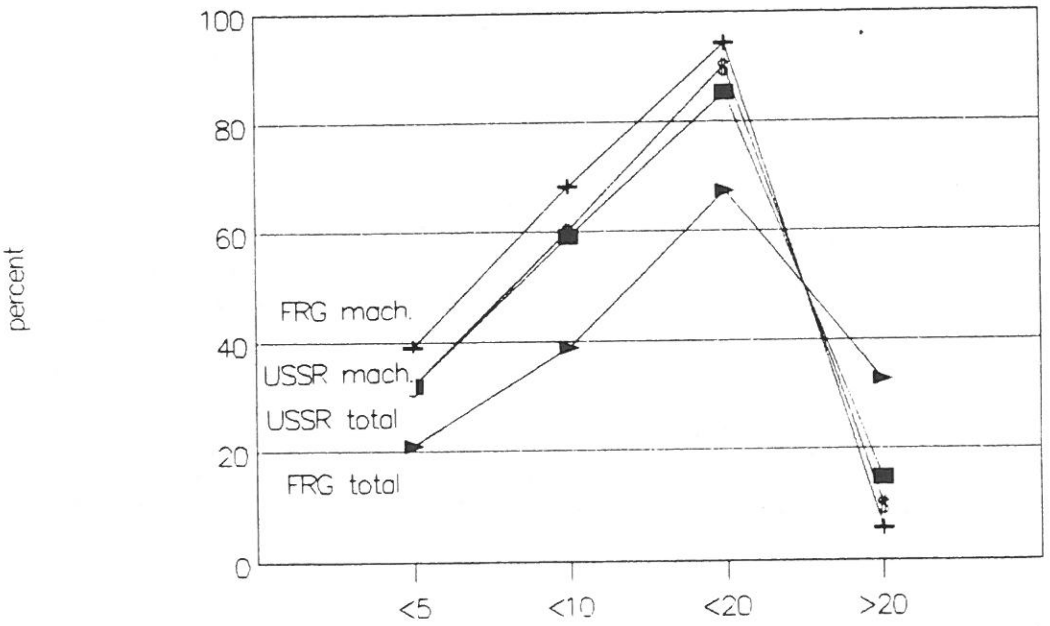


Figure 7. Age distribution of capital stock (total excluding buildings, and machinery) for ex-USSR and FRG, in percent per age category.

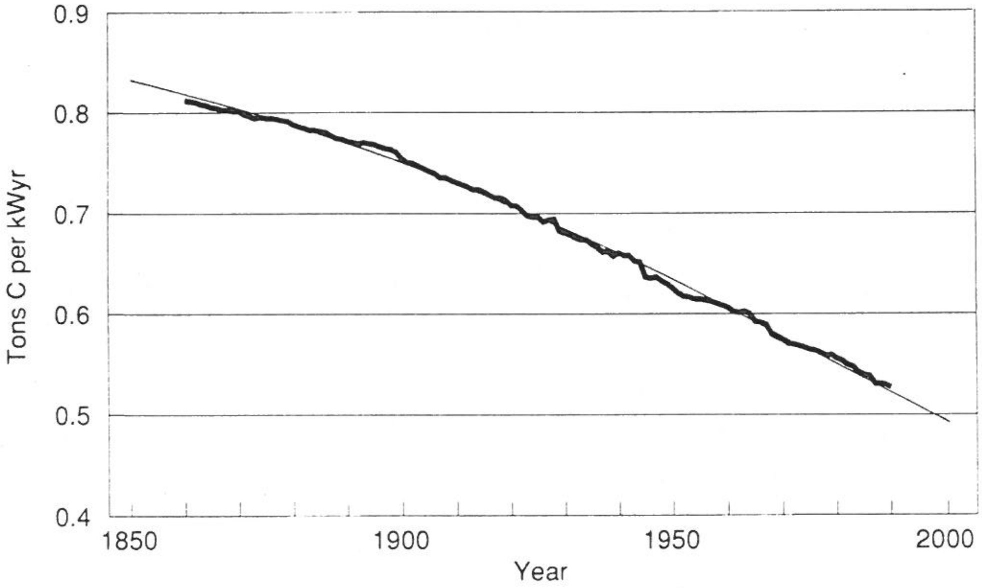


Figure 8. Carbon intensity of global primary energy consumption (tons C per kWyr).

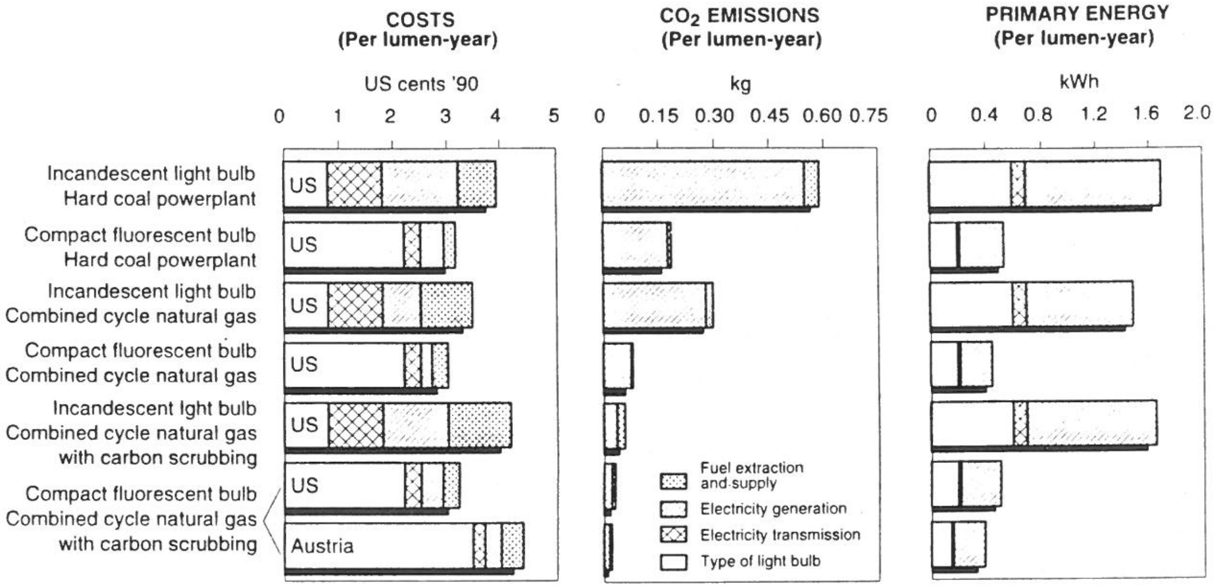


Figure 9. Primary energy, CO_2 emissions, and costs (US cents 1990) for alternative energy chains providing lighting (all units per lumen-year). Source: IIASA CO2DB.