The Future of Natural Gas in Europe

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1 Introduction

The increasing concerns about the possibility of anthropologically induced global climate change have caused reevaluation of the future role of natural gas as a more environmentally benign fossil energy source. The combustion of natural gas results in lower carbon dioxide emissions compared to other fossil energy sources. For example, natural gas emits roughly one half of the carbon dioxide in comparison to coal for the equal amount of energy. However, natural gas consists mainly of methane and is a very potent greenhouse gas if released into the atmosphere. Fortunately releases of uncombusted methane can be controlled by appropriate mitigation measures, so that prudent use of natural gas can result in substantially lower energy-related emissions of greenhouse gases. Thus, a possible shift to a methane economy during the next decades offers a genuine mitigation strategy for anthropologically induced global warming. Beyond that, natural gas could pave the way for more environmentally compatible energy systems of the distant future. Such systems could use hydrogen and electricity, both of which are carbon-free energy carriers, that could be produced by non-fossil sources of primary energy. This transition to the methane age and beyond that to carbon-free energy systems and the hydrogen economy would enhance the reduction of other adverse impacts on the environment by human activities.

Greater reliance on natural gas in the future would represent an evolutionary strategy reducing the necessity of radical shifts in the energy policy during the next decades that would be mandated if the reduction of greenhouse gas emissions would be based solely on the rapid introduction of renewable energy or nuclear power. Wider use of natural gas would be consistent with the need to improve the efficiency of energy conversion and use, and to enhance advances in energy conservation. Natural gas conversion technologies and end-use devices are generally more efficient than those relying on other fossil energy sources. They also have higher efficiency improvement potentials. For example, advanced aero engine derivative gas turbines can achieve efficiencies in access of 50 percent at very low cost compared to other alternatives. They can be produced in large numbers and hold a promise of substantial cost reductions along the learning curves as cumulative output increases. An attractive and very efficient conversion technology of a more distant future are fuel cells.

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The attractiveness of these systems is not only their efficiency and modular design but also low capital costs and flexibility in use. The major new infrastructure requirements would consist of constructing additional gas pipe-lines and distribution networks. Wider use of natural gas in Europe would for example necessitate additional pipeline capacity from Siberia, the North Sea, and probably also from North Africa and the Middle East. All of these components of the methane age energy system, such as the gas turbines, fuel cells, and pipeline networks, could also be used in the hydrogen economy of the more distant future. Perhaps the most important feature of the evolutionary transition to the wider use of natural gas is that it is consistent with historical development of the energy system from a carbon rich fuel mix to less carbon intensive sources of energy: from fuelwood and coal to oil and natural gas. A shift to natural gas would represent a continuation of the long-term decarbonization of the global energy system and those in most of the European countries. Among the many challenges that the possibilities of a methane economy poses, the most important might be the availability of natural gas resources at economic costs and the determination to keep the methane seepage from energy extraction, conversion and end-use systems to less than a few percent of total consumption. The latter is a technical, organizational, and institutional issue that in principle can be resolved. The former, however might cause a greater barrier to future use of natural gas especially at regional levels because it would require assurance of security of supply and cooperation at the regional and even global level.

In the first part of this paper, we will illustrate to what extent this strategy of wider natural gas use in the future would be consistent with the decarbonization of the energy system and with the known and speculative natural gas resources. In the second part of the paper, we present a scenario of energy systems development in Western Europe to the year 2050. In this scenario we have attempted to enhance the reliance on natural gas in Europe and have also included some of the more efficient natural gas conversion and end-use technologies. The paper is in part based on the ongoing research activities at IIASA in the area of global energy perspectives and climate change. An important component of this research effort is the assessment of Environmentally Compatible Energy Strategies (ECS Project) and this also includes the evaluation of the future role of energy gases and the development of global energy scenarios.

2 Decarbonization

In general, the instrumental determinants of future energy-related carbon dioxide emissions could be represented as multiplicative factors in the hypothetical equation that determines global emission levels. The *Kaya identity* establishes a relationship between population growth, per capita value added, energy per value added and carbon emissions per energy on one side of the equation, and total carbon dioxide emissions on the other (Yamaji *et al.*, 1991)[1]. Two of these factors are increasing and two are declining at the global level.

Figure 1 illustrates the extent of this decarbonization in terms of the ratio of average carbon dioxide emissions per unit of primary energy consumed globally since 1860. The

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[1] carbon dioxide = (carbon dioxide/E) x (E/GDP) x (GDP/P) x P, where E represents energy consumption, GDP the gross domestic product or value added, and P population. Changes in carbon dioxide emissions can be described by changes in these four factors.

ratio decreases due to the continuous replacement of fuels with high carbon contents, such as coal, by those with low carbon contents and most recently also nuclear energy. Figure 2 shows the historical decrease in 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 towards lower energy intensities. For example, France and Japan have always used energy more efficiently than the United States, the United Kingdom or Germany. This should be contrasted with the opposite development in some of the rapidly industrializing countries, where commercial energy intensity is still increasing, such as in Nigeria. Commercial energy is replacing traditional energy forms so that total energy intensity is diminishing while commercial energy intensity is increasing. The present energy intensity of Thailand resembles the situation in the United States in the 1940s. The energy intensity of India and its present improvement rates are similar to those of the United States about a century ago.

At the global level, the long-term reduction in carbon intensity per unit value added has been about 1.3 percent per year since the mid-1800s. Decarbonization of energy occurs at about 0.3 percent per year and the reduction of energy intensity of value added at about 1 percent per year, resulting in a reduction of overall carbon intensity of value added of about 1.3 percent per year. This falls short by about 1.7 percent of what is required to offset the effects of global economic growth, with rates of about 3 percent per year. This means that the global carbon dioxide emissions have been increasing at about 1.7 percent per year, implying a doubling before the 2030s. This is in fact quite close to emission levels projected in some of the global scenarios.

Figure 3 shows that, for the time being, the carbon intensity of primary energy is still developing in the same direction in all of these countries. However, as mentioned above, without the proposed structural changes in the energy systems towards carbon free and hydrogen rich sources of primary energy, trend reversals cannot be excluded in the future. This figure also illustrates the large impacts in achieving decarbonization by introducing zero carbon sources of energy as illustrated by the growing shares of nuclear power in France.

There is a possible way to reconcile the increasing needs for electricity and hydrogen rich forms of final energy such as natural gas with the relatively slow and often opposing changes in the structure of energy systems and primary energy supply. This can be best illustrated by the historical replacement of coal by oil and later by natural gas at the global level. Primary energy substitution (Marchetti and Nakicenovic, 1979; Ausubel, *et al.* 1988; Grübler and Nakićenović, 1988; Nakićenović, 1990) suggests the likelihood that natural gas and later carbon free energy forms will become major sources of energy globally during the next century.

Figure 4 shows the competitive struggle between the five main sources of primary energy as a dynamic and quite regular process that can be described by relatively simple rules. The substitution process clearly indicates the dominance of coal as the major energy source between the 1880s and the 1960s after a long period during which fuelwood (and other traditional energy sources) where in the lead. The massive expansion of railroads, the growth of steel, steamships and many other sectors, are associated with and based on technological opportunities offered by the mature coal economy. After the 1960s, oil assumed a dominant role simultaneously with the maturing of the automotive, petrochemical and other industries. The current reliance on coal in many developing countries illustrates the gap between the structure of primary energy supply and actual final energy needs.

Figure 4 projects natural gas as the dominant source of energy during the first decades of the next century although oil still maintains the second largest share until the 2040s. For such an explorative "look into the future", additional assumptions are required to describe the future competition of potential new energy sources, such as nuclear, solar and other renewables, that have not yet captured sufficient market shares to allow an estimation of their penetration rates. In the future, we assume that nuclear energy will diffuse at comparable rates as oil and natural gas half a century earlier. Such a scenario would require a new generation of nuclear installations; today such prospects are at best questionable. This leaves natural gas with the lion's share of primary energy during the next 50 years. In the past, new sources of energy have emerged from time to time coinciding with the saturation and subsequent decline of the dominant competitor. "Solfus" is a term employed to describe a major new energy technology, for example, solar or fusion, that could emerge during the 2040s at the time when natural gas is expected to saturate.

This analysis of primary energy substitution and market penetration suggests that natural gas would become the dominant energy source and remain so for half a century, perhaps to be replaced by carbon free energy sources, such as nuclear, solar or fusion. Thus, primary energy substitution implies a gradual continuation of energy decarbonization in the world. The methane economy could provide a bridge towards a carbon free future.

Figure 5 shows the resulting changes in the hydrogen to carbon ratio from global primary energy substitution. Fuelwood has the highest carbon content with about one hydrogen per 10 carbon atoms. If consumed unsustainably, as was the case in the past and still is in most developing countries, fuelwood has higher carbon emissions than all the fossil energy forms. From the fossil energy sources coal has the lowest hydrogen to carbon atomic ratio of roughly one to one. Oil has on average two hydrogen per one carbon atom, and natural gas or methane, four. These factors are used in Figure 5 to determine the hydrogen to carbon ratio of global energy. This ratio can be expected to increase as projected in Figure 5 to the asymptotic level of four hydrogen to one carbon atom if natural gas becomes the dominant form of energy. Further improvements would have to be achieved by the introduction of non-fossil energy sources, such as nuclear, solar, fusion and sustainable use of biomass. The methane economy offers the bridge to this non-fossil energy future consistent both with the dynamics of primary energy substitution and steadily increasing carbon intensity of final energy. As non-fossil energy sources are introduced in the primary energy mix, new energy conversion systems would be required to provide other zero carbon energy carriers in addition to growing shares of electricity. As suggested in Figure 5 an ideal candidate is hydrogen. Thus, the methane economy would lead to a greater role for energy gases and later hydrogen in conjunction with electricity. Hydrogen and electricity could provide virtually pollution free and environmentally benign energy carriers.

3 Fossil Energy Reserves and Resources

Availability of energy is an important constraint in any assessment of long-term energy and economic development. Fossil energy reserves and resources are especially important in this context. More than 80 percent of primary energy consumption in the world comes from fossil sources. It is certain that over the next few decades humanity will continue to rely on fossil energy and will perhaps even increase the consumption levels before the alternative energy sources can increase their market shares. This is not a problem of potential exhaustion of known energy resources since they are indeed plentiful, but it is rather a problem of whether sufficient quantities of cleaner fossil fuels will be available to help achieve a transition towards alternative sources. This paper argues that natural gas would be an ideal bridge to such a future. The next question we will address is whether the natural gas resource base is large enough to make such a transition feasible.

Fossil energy resources and their potential recoverability cannot be characterized by simple measures or single numbers. They comprise quantities all along a continuum in at least three dimensions: *geological knowledge, economics*, and *technology.* McKelvey (1972) proposed a diagram with a matrix structure for the classification along two dimensions: decreasing geological certainty of occurrence and decreasing economic recoverability. For example, identified occurrences have the highest geological certainty and are followed by inferred and speculative ones. *Reserves* are those occurrences that are identified, measured and at the same time known to be economically and technically recoverable. Thus, reserves are recoverable using current technologies and prices. *Resources* comprise the remainder of occurrences with less certain geological and economic characteristics. The *resource base* includes both categories.[2] Additional quantities with unknown certainty of occurrence or with unknown or no economic significance at present are referred to here simply as "*occurrences.*" For example, such occurrences include methane clathrates, known to exist in large quantities, but with unknown certainty of occurrence and unknown economics of extraction.

Improved geological knowledge, both scientific and experimental (e.g., reservoir theories and exploration), improved technology and changing prices have continuously served to increase the fossil energy resource base and have also led to numerous large discoveries. In fact, the additions to the resource base have historically outpaced consumption. Increasing prices can render previously marginal or even uneconomic resources profitable. Improved technology can help to identify and assess quantities that were previously only inferred, and sometimes also results in reclassification of resources into reserves. It can increase the technical recoverability of known and even of depleted deposits (e.g., enhanced oil recovery can double the extraction from some reservoirs). Finally, technology improvements can reduce the costs of recovery or even make quantities recoverable, which were previously classified as not recoverable.

Current global fossil energy reserves are estimated at 43,600 EJ. This quantity is so large that it could last almost 125 years at the 1990 level of global energy consumption (353 EJ). It is more than four times larger than the cumulative fossil energy consumption since the beginning of the coal era in the mid-nineteenth century. Table 1 summarizes past and current consumption levels, the estimates of global fossil energy reserves, resources and additional occurrences. Coal accounts for more than half of all fossil reserves. Consequently, its reserve to production ratio is the highest (more than 200 years at 1990 consumption levels), while this ratio is the smallest for oil (less than 50 years). Oil and natural gas reserves have increased dramatically during the last 50 years as crude oil has become the world's dominant primary energy source, as shown in Figure 4.

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[2] The resource base estimates include (ultimately) recoverable reserves, and potentially recoverable resources of coal, conventional oil and natural gas, and also of unconventional oil (oil shale, tar sands, and heavy crude) and natural gas resources (gas in Devonian shales, tight sand formations, geopressured aquifers, and coal seams).

Estimates of additional resources and occurrences of fossil energy are much larger but also more uncertain. Table 1 shows the global fossil resource base estimate to be about 163,000 EJ and additional occurrences up to 982,000 EJ. Table 2 gives estimates of the ultimately recoverable reserves of conventional and unconventional oil and gas to be discovered in the future at 95, 50 and 5 percent probability levels. They range from 1,838 to 5,455 EJ for oil and 2,709 to 10,877 EJ for gas (Masters *et al.*, 1991) and are given in Table 1 under the category of "reserves to be discovered". The estimates are given for 11 world regions and for the world total. The regions includes Western Europe but other neighboring regions such as the Former Soviet Union and Middle East and North Africa are also given in Table 2 in order to indicate how large the import potential of additional amounts of natural gas might be for the West European countries.

Methane resources are of particular interest because they have the lowest specific carbon emissions per unit energy of all fossil fuels. The figures presented in Table 1 indicate reserves of unconventional gas to be at least a similar order of magnitude as those of oil. The conventional gas resource base is almost twice as large as that of oil. Additionally, there are large gas occurrences in form of clathrates in permafrost areas and offshore continental shelf sediments (in the range of 630,000 EJ, or 130 times the identified conventional gas reserves; see MacDonald, 1990) suggesting that methane might be an abundant form of hydrocarbons in the Earth's crust. The relative abundance of hydrocarbons on Earth has led a number of researchers to reopen the question of the origin of fossil energy (Gold, 1987). According to these alternative theories natural gas would be mostly of an abiogenic origin and much more pervasively distributed around the world. It is argued that the natural gas in the earth's crust has a primordial origin stemming from the time when the earth accreted. Where this is the case, the amount of methane potentially available for energy uses would be for all practical purposes truly unlimited. Over the time horizon of interest in this study, the next 50 - 100 years, major break throughs in technologies cannot be expected that would make this practically unlimited methane resource base available for energy purposes. Over this time frame we do assume that all of the conventional and unconventional energy resource base of Western Europe and the surrounding regions would indeed be available with relative minor changes in technological and economic conditions. This would also include reserves to be discovered given in Table 1. Together the West European gas resource base would correspond to about 750 EJ, about 14 years at current total primary energy consumption levels in Europe. Therefore it is evident that the resource base is sufficiently large to last more than 30 years even with very high increases of the natural gas share in the primary energy mix. Furthermore, we also assume that some of the more speculative occurrences of natural gas given in Table 1 might also become available with advances in appropriate technologies, but of course at higher costs compared to the conventional and unconventional natural gas base. With these assumptions and the possibility of natural gas import from neighboring regions, the availability of natural gas should not be a bottle neck to wider use during the next century in Western Europe.

4 Energy Scenarios for Western Europe

The objective of this study is to investigate the future role of natural gas in Western Europe as means of achieving lower carbon intensities over the next few decades and as a possible bridge to the hydrogen economy of the more distant future. The basic approach is to determine the highest share of natural gas in the future energy system that is consistent with other assumptions of a scenario that is otherwise not biased towards natural gas. This means that the estimates of the costs, performance, environmental impact, and other characteristics of future energy technologies are based on 'best guesses', rather than on implicit ways to favor natural gas. For example, the structure of the future reference energy system, starting from energy conversion and going to end-use, includes a full portfolio of possible energy technologies. In fact, the cost estimates would favor smaller scale, modular devices due to the assumed effects of the learning curve. Primarily, this would tend to increase the use of renewable sources of energy in the later periods but to a much lesser degree also some natural gas end-use devices. This sensitivity analysis was performed with the energy systems model MESSAGE III. MESSAGE III is a dynamic linear programming model that derives optimal energy strategies under exogenously defined constraints. It is a part of the model set used in the ECS project to develop global energy and emission scenarios for the 11 world regions given in Table 2.

Figure 6 gives an overview of the model structure: After extraction, primary energy goes into domestic use, with the option for import. Conversion technologies produce secondary energy like crude oil distillation or electricity generation. Finally, after transport and distribution, all energy goes into final consumption as useful energy or energy service.

One very important feature of our analysis is the availability of advanced technologies such as combined cycles, fuel cells, and hydrogen as an advanced energy carrier. Additionally, all important technologies are treated as dynamic entities that will undergo improvements over the coming decades. Performance is assumed to improve in proportion to cumulative use of these devices. As an example, a gas-fired combined cycle could be ready for delivery with an efficiency of 50 percent in 1990, but could reach 60 percent by 2030. High temperature fuel cells could become commercially available in 2010 with an efficiency of 60 percent, but could reach 65 percent by 2040. Advanced technologies are also available for other energy sources, such as coal or biomass, but their relative economics are not assumed to be as promising as those of new gas technologies.

The model covers Western Europe as an integrated area with a rather crude representation of end-uses. This was chosen in accordance with the rather long time horizon (presently up to 2050, to be extended to 2100). Further disaggregation of the model would require extensive evaluations of technological potentials for all demand categories, which is beyond the scope of this integrated analysis.

However, subregional specifics, like different attitudes towards nuclear power in countries like France and Sweden, resulting in different safety and commissioning procedures and finally different costs of installing a new reactor, are represented. A political constraint concerns import dependence: since domestic energy sources in Western Europe are rather expensive compared to world market prices, a limit was imposed on energy imports to 50 percent of overall energy use.

The model analysis is embedded in an approach developed at IIASA to link the energy systems model (MESSAGE III) to the known long-term energy-economy model Global 2100 (Manne and Richels, 1992). Energy demands were derived from a scenario of 0.2 percent/yr population growth and 3.4 percent/yr growth of GDP. Resulting growth in final energy use is 1.5 percent/yr, decoupling of final energy demand from GDP growth is 1.3 percent/yr.

World market prices of fossil energy carriers are based on the assumption that the oil price will stay stable around 15$/boe until 2000, then start to grow again and reach a maximum of 25$/boe by 2030. After 2040 it would decline again and reach 21$/boe by 2050. Import prices of natural gas are linked to the oil price, but will assume higher value shares over time (from presently 75 percent to 85 percent in 2050).

Overall primary energy consumption would grow at an average rate of 0.54 percent per year and reach 80 EJ by the year 2050. The contribution of the various energy carriers can be seen in figure 7. The share of coal would decline from presently 23 percent to 6 percent, oil's share would be relatively stable around 37 percent (slightly less than in 1990), while natural gas would take the lion's share of growth. The use of natural gas would increase from 14.4 percent in 1990 to 30 percent in 2050. Under our price assumptions nuclear energy is only viable in countries with positive attitudes towards this energy source and consequently faces declining contributions, while renewable sources of energy are expanded at an average rate of 1 percent per year, from 10 percent in 1990 to 14 percent in 2050.

Figure 7 shows clearly that natural gas assumes the strongest growth over the coming decades. However, oil remains the dominant energy carrier over the whole model horizon. Figure 8 further investigates the uses of gas for 1990 and 2050, respectively. In 1990 13 percent of primary gas went into electricity generation and 7 percent to own uses in transport and distribution. The major share (45 percent) went into residential and commercial applications, mainly heating. Industry used 31 percent and 4 percent were consumed as chemical feedstocks. Preliminary analyses show a considerable growth potential in the electricity generation market, where gas takes up all fossil-based electricity generation or 50 percent of the market. Growth rates of all other existing applications of natural gas are underproportional, while the transport sector, which presently consumes hardly any gas, would take 12 percent of gas in 2050. In absolute terms, only industrial uses of natural gas decline in our analysis. Industrial furnaces increase their use of coal given relatively stable low coal prices, and fueloil, a residue of refineries producing growing quantities of motor fuels, but also growing amounts of biomass are used in industrial boilers.

Figure 9 investigates gas' shares per sector. While industrial use of gas declines from 23 percent in 1990 to 15 percent in 2050, the residential share of gas increases from 25 percent in 1990 to more than 35 percent in 2050. By 2050 also more than 30 percent of chemical feedstocks come from gas and 16 percent of energy use for transport is natural gas. These results indicate that the relative economics of the different energy carriers in the various sectors play a vital role in determining the market shares of the fuels. Since gas is very competitive in electricity generation, coal and residual oil, which are both available, are used more in alternative applications, mainly in the industry.

Domestic natural gas supply (see table 3) increases from 4.3 EJ to nearly 12 EJ by 2050, an overall quantity of 500 EJ is extracted over that time period. Setting this in relation to the gas resource base of Western Europe of 750 EJ, our scenario would imply the use of two-thirds of these resources in half a century.

Gas imports increase by a factor of 4 (from 4 EJ to 16 EJ), overall gas imports over these 60 years would be 630 EJ. According to our preliminary analysis Former Soviet Union (FSU) could use 2250 EJ of natural gas and export 180 EJ to Eastern Europe over the same period. If all imports of Western Europe (630 EJ) are imported from FSU with the assumption of continuing high losses of 14 percent in gas transport, this would yield a cumulative natural gas extraction of 3173 EJ. Since the natural gas resource base of the FSU (see table 2) is estimated at 5000 EJ, our results would imply extracting 63 percent of this quantity by 2050.

Considering the required transport infrastructure, imports in 2050 of 16 EJ could be supplied by 16 pipelines of the size of the Urengoy–Uzhgorod pipeline completed in 1984 which, with a diameter of 56 inches, has an inlet capacity of 3.1 bcfd (Korchemkin 1993). With a length of 2766 miles this pipeline constituted 7.8 percent of overall gas transport capacity in 56 inch pipes and 2 percent of capacity in all transport pipelines in the Former Soviet Union in 1992. Capital requirements of 16 pipelines with a speculative length of 3000 miles would be in the range of 100 billion US$. Distributed over 50 years this would represent an annual investment requirement of 2 billion US$, which is rather small compared to other sectors of the energy system. All nuclear reactors available in 2050, which are of the relatively cheap French type, represent a capital infrastructure of US$ 280 billion. At stable output levels and a technical life of 30 years, 9.3 billion US$ would have to be invested annually.

Carbon dioxide emissions grow underproportionally to primary energy consumption: while total primary energy grows at 0.54 percent per annum, carbon dioxide emissions grow at a rate of 0.33 percent/yr, yielding a decarbonization of 0.2 percent per year. This falls short of the historically observed 0.3 percent per year and could indicate that the resulting coal and/or oil shares are still too high.

Concluding, we use the Kaya identity to investigate the components driving carbon dioxide emissions according to our results: Population grows at 0.2 percent/yr, GDP per capita at 1.86 percent/yr, primary energy use per unit of GDP declines at 1.5 percent/yr, and carbon dioxide emissions per unit of primary energy decline at 0.2 percent/yr. Over the model horizon of 60 years this results in a 22 percent increase of annual carbon dioxide emissions.

5 Conclusion

The objective of the study was to determine the highest share of natural gas in the future energy system of Western Europe that is consistent with the estimated endogenous resource base and potentially available imports from the surrounding regions. The larger role of natural gas could be a means of achieving lower carbon emissions in the future. The findings indicate that such a strategy is indeed feasible. One half of the cumulative consumption of natural gas could be supplied from the estimated endogenous resource base and the other half was assumed to be imported, primarily from Russia, North Africa, and the Middle East. At face value, this does not appear unreasonable since the current import dependency of Europe is much higher for natural gas. Thus, natural gas resources do not appear to be a major bottle neck in achieving a transition towards a methane economy. At the same time, the analysis of long-term patterns in substitution of primary energy sources (Figure 4) has shown that natural gas would need to become the dominant primary energy source in the next century if the historical rate of energy decarbonization were to continue during the next decades. In fact, reduction of carbon dioxide emissions would require much higher rates of decarbonization. Unfortunately, some first signs of a possible trend reversal to lower rates of decarbonization compared to the historical average did occur during the last decade. This is also mirrored in the energy substitution paths of Figure 4. The results of the analysis of a larger role of natural gas with the energy systems model MESSAGE III reveal a similar tendency. Natural gas increases in the total energy mix, but it is not possible to replace oil as the dominant energy source in Western Europe. To do so would require more drastic changes in the model assumptions, for example, concerning relative costs of natural gas to the consumer compared with other alternatives. As a consequence, the resulting rate of decarbonization was also somewhat lower than the historical rate. Nevertheless, the average rate of carbon dioxide emissions per unit energy consumed would be lower than today and that in itself is encouraging. The analysis also shows that even an evolutionary strategy towards a larger role of natural gas would be very difficult to achieve. This means that other measures would be required for successful mitigation of carbon dioxide emissions. Apparently, no single measure is sufficient if the goal is to drastically reduce the emissions. The analysis of this paper indicates that the larger role of natural gas is one of the more promising alternatives.

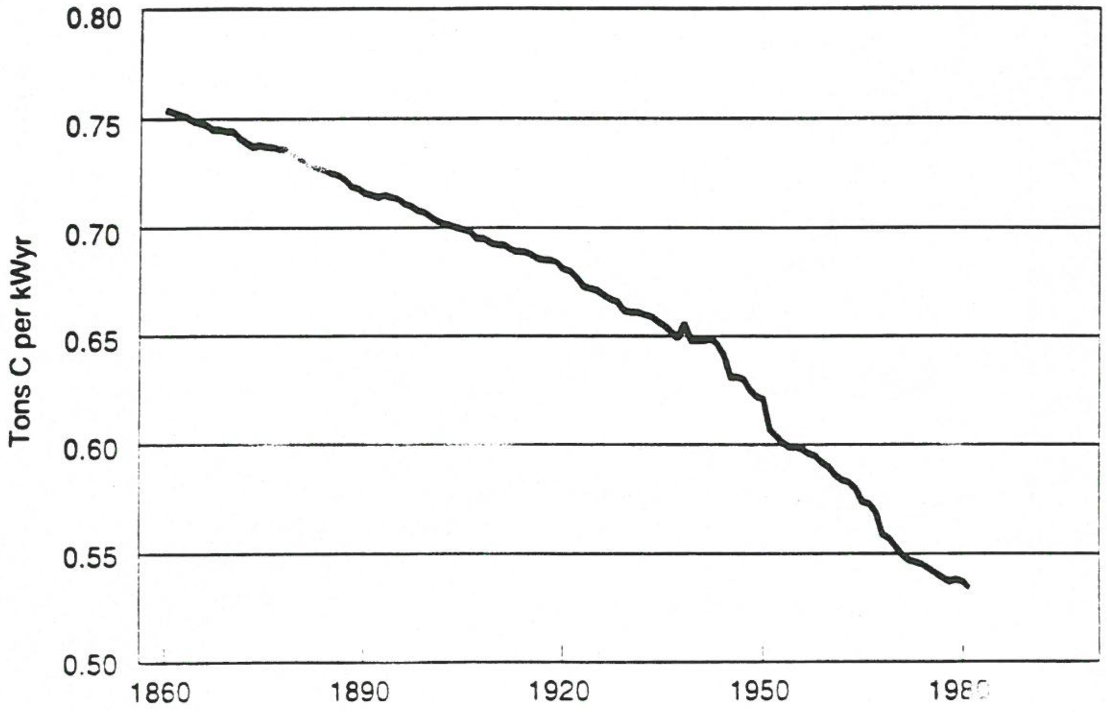


Figure 1: Global decarbonization of energy from 1860 to 1980, expressed in tons of carbon per kilowatt year (tonsC/kWyr).

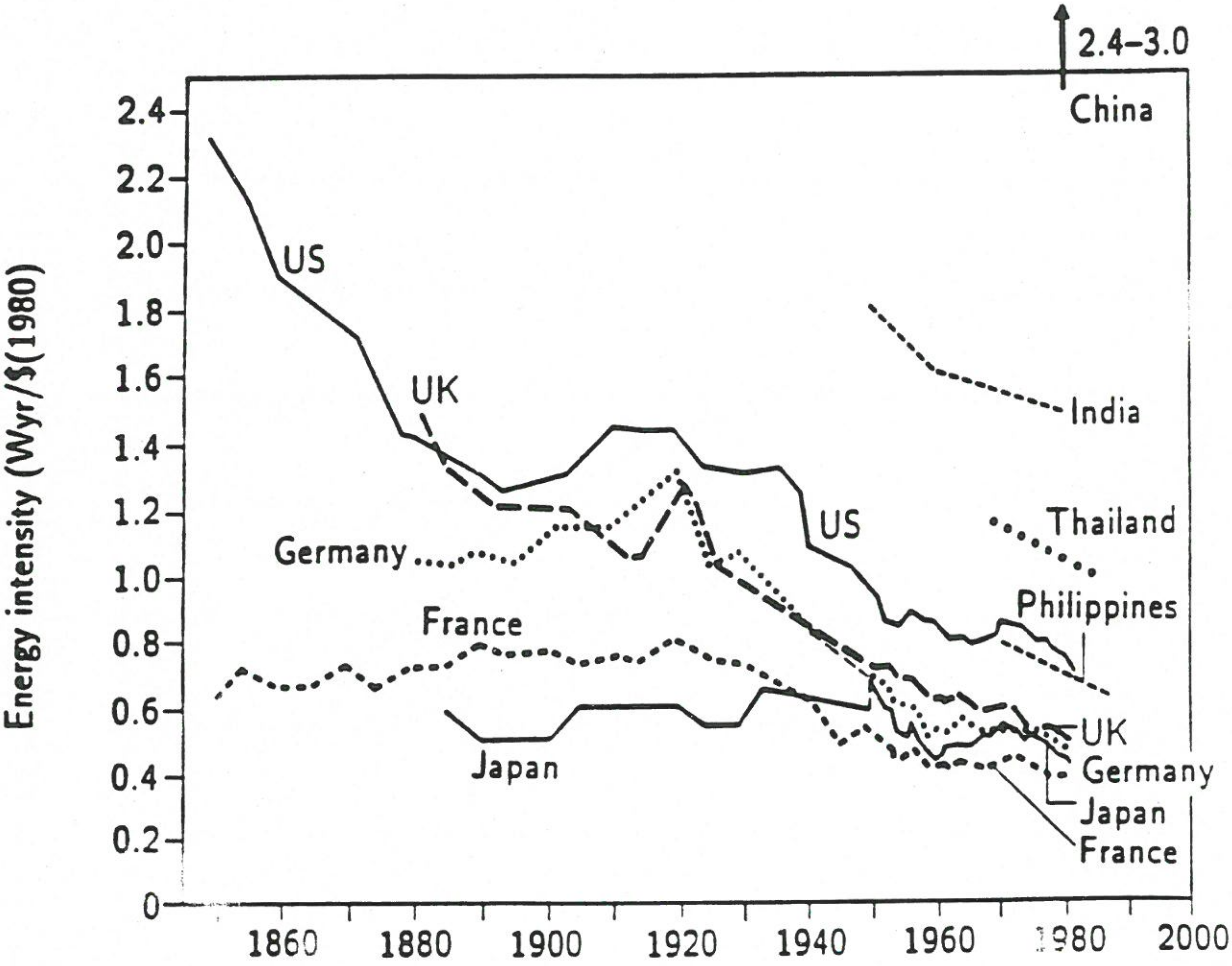


Figure 2: Primary energy intensity of value added from 1855 to 1990, expressed in watt years per constant GDP in 1980 U.S. dollars. (Including biomass, primary electricity is accounted for by equivalence method.)

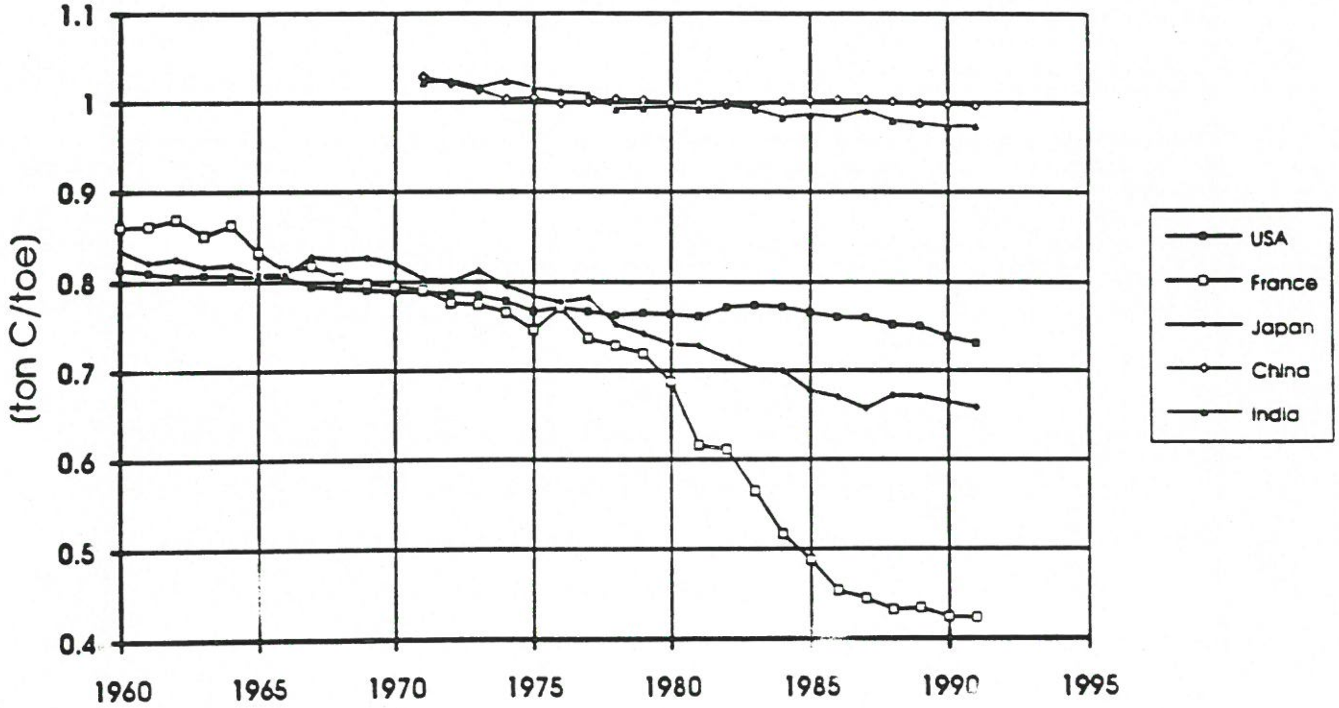


Figure 3: Carbon intensity of primary energy for China, France, India, Japan and the United States from 1960 to 1991, expressed in tons of carbon per ton of oil equivalent primary energy (tonC/toe).

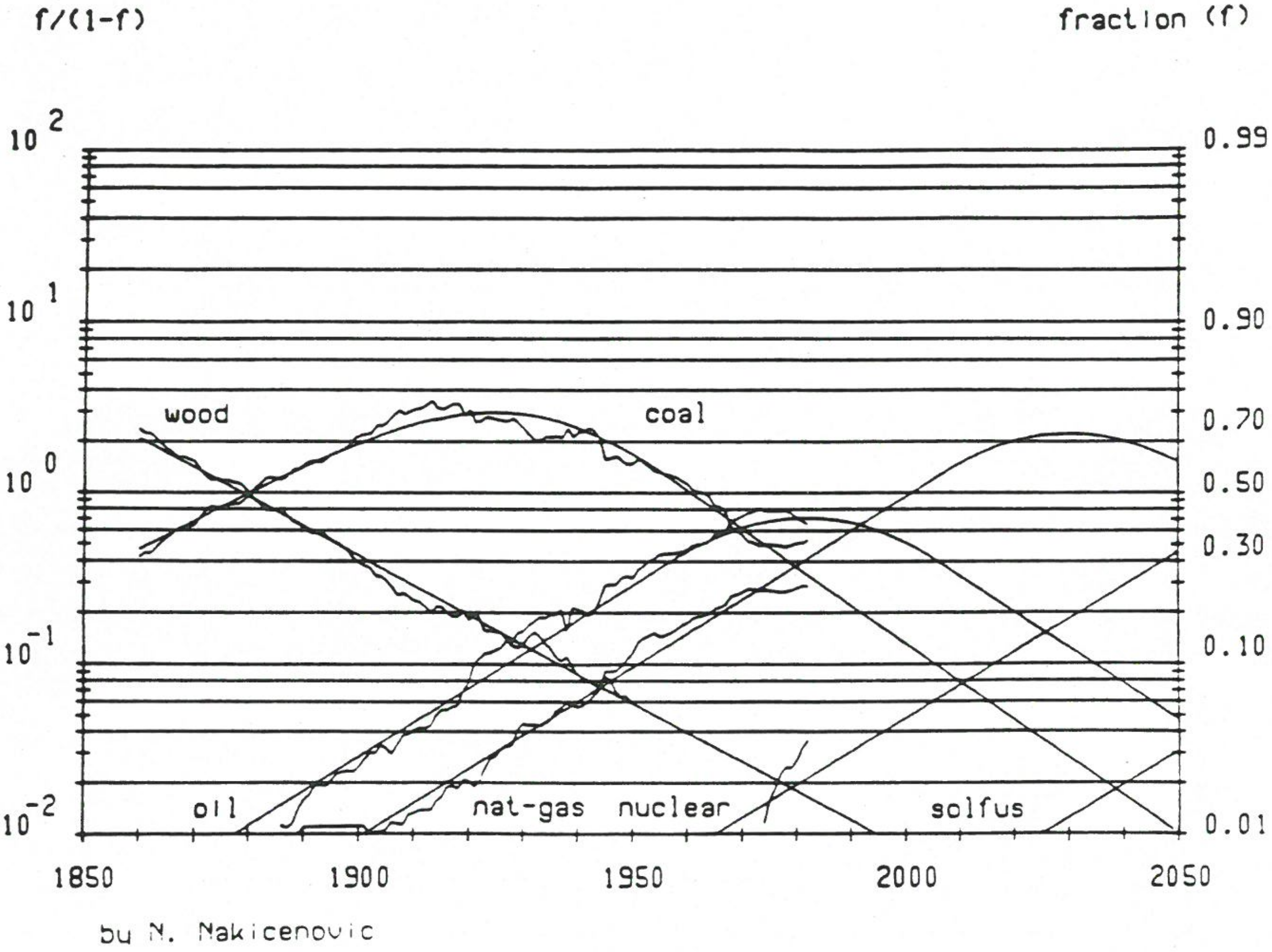


Figure 4: Global primary energy substitution from 1960 to 1982 and projections for the future, expressed in fractional market shares (F). Smooth lines represent model calculations and jagged lines are historical data. "Solfus" is a term employed to describe a major new energy technology, for example, solar or fusion. Source: Grübler and Nakićenović, 1988; Nakićenović, 1990.

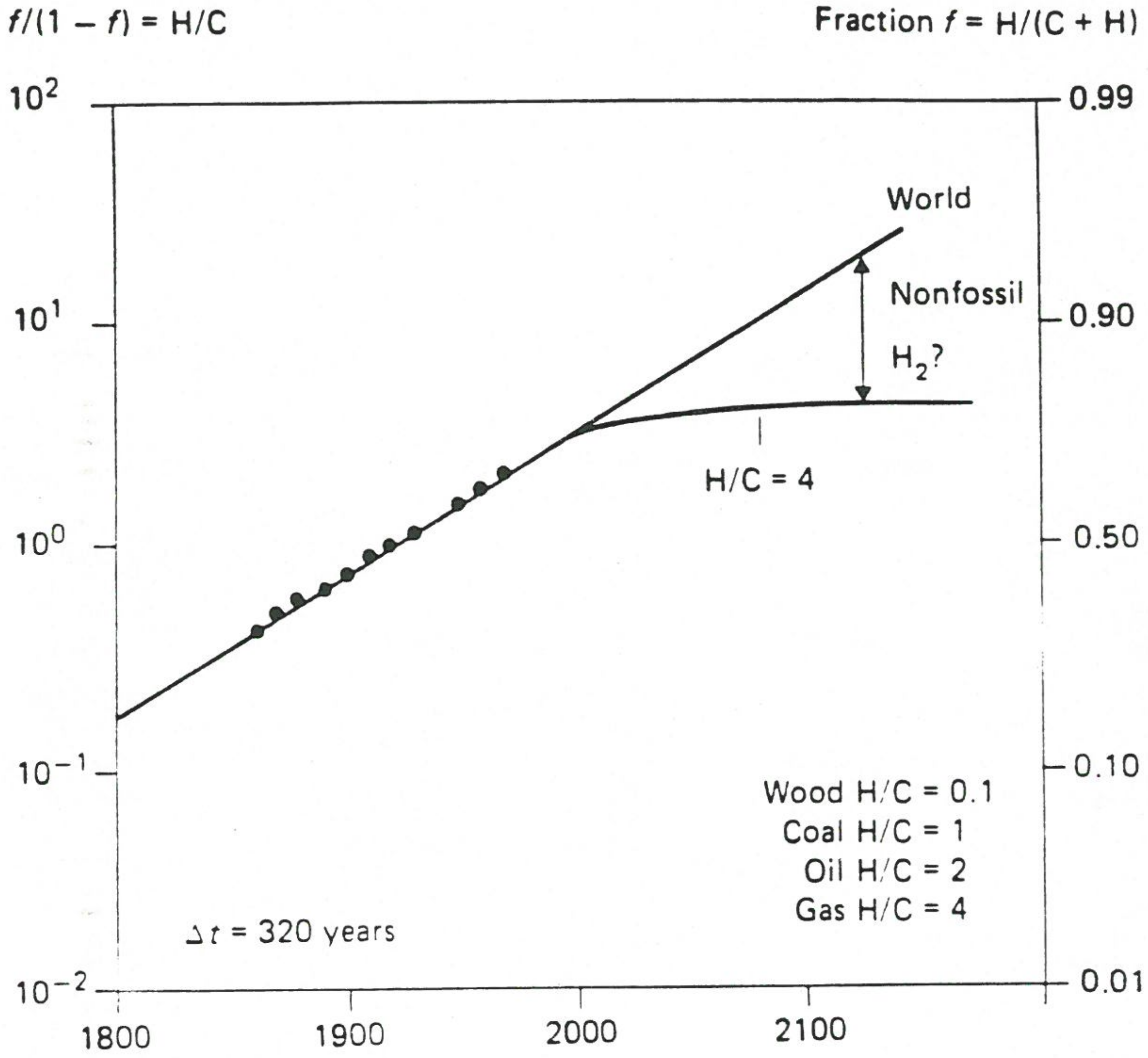
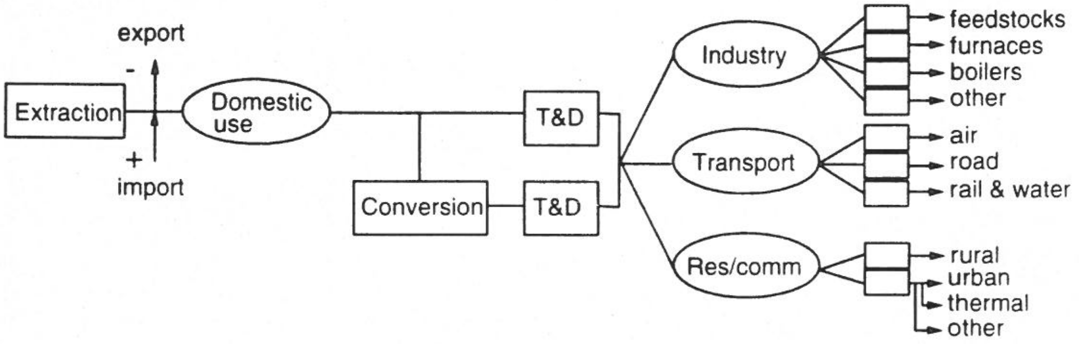


Figure 5: Hydrogen-to-carbon ratio of global primary energy from 1860 to 1982 and projections for the future, expressed in fractional shares of hydrogen and carbon in average primary energy consumed (H/C). Source: Marchetti, 1982.



Energy level:		PRIMARY	SECONDARY		FINAL	USEFUL
Energy currencies:		coal crude oil gas nuclear hydro renewables-carbon renewables-O-carbon	Primary plus: HFO light oils electricity heat hydrogen		coal HFO light oils gas electricity heat hydrogen renewables-carbon renewables-O-carbon	feedstocks HT heat LT heat kinetic/mobility electricity
Typical technologies:	coal mines oil wells		refineries power plants CHPs	pipelines grids		boiler furnaces cars res. applicances

Figure 6: Flow Chart of Model

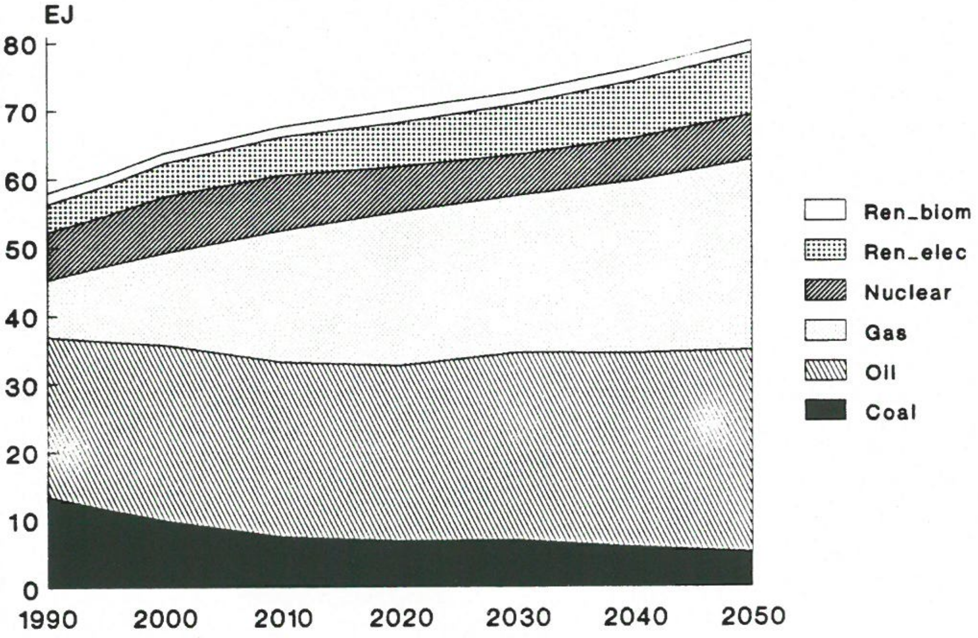


Figure 7: Primary energy use in Western Europe, 1990 to 2050, EJ

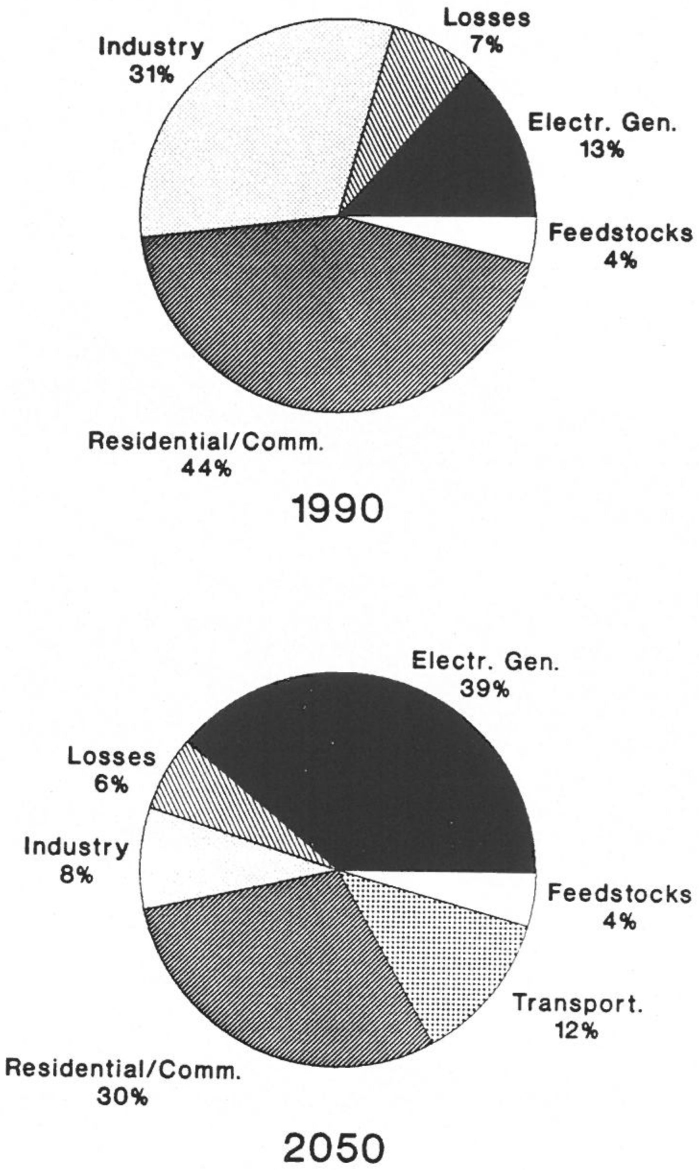


Figure 8: Shares of natural gas use in 1990 and 2050

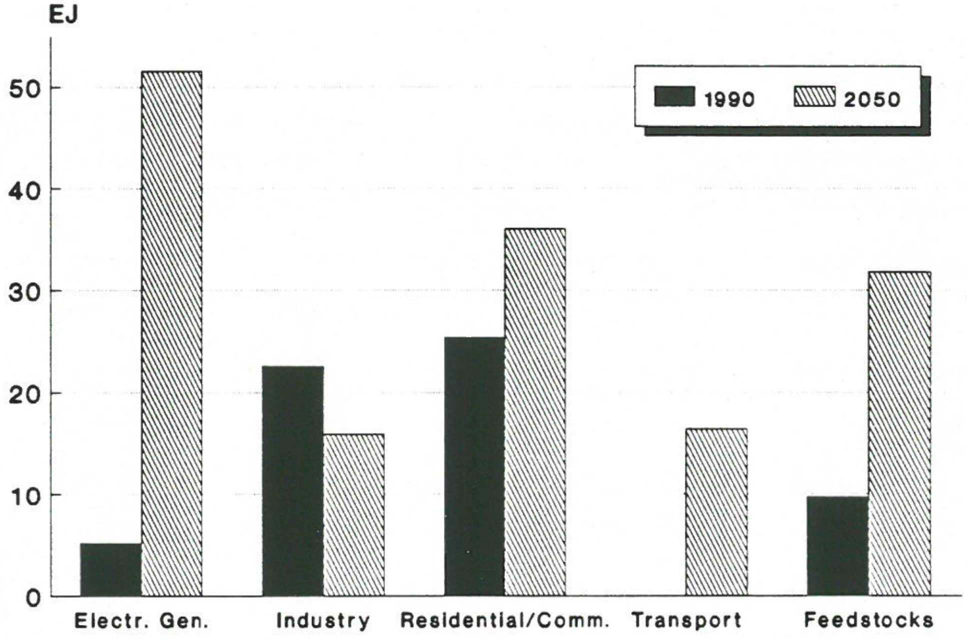


Figure 9: Shares of natural gas per sector, 1990 to 2050

Table 1. Global fossil energy reserves, resources, and occurrences, in EJ.

	Consumption		Reserves		Recoverable resources with technol. progr.	Resource base (reserves & resources)	Add. occurr.
	1860–1990	1990	Ident.	To be discovered[a]			
Oil							
Conventional	3349	125.6	6028	∼2430		∼8459	>10090
Unconventional	–	–	7117		∼14276	∼21394	>14486
Gas							
Conventional	1716	71.2	4814	∼4396		∼9210	>10090
Unconventional	–	–	6866		∼20012	∼26879	>22064
Clathrates	–	–					>630867
Coal	5191	92.1	18756[c]	∼23278[d]	∼54930	∼96966	>164038
Total[b]	10257	288.9	43584	∼30104	∼89220	∼162910	>982265

[a] Masters *et al.*, 1991, 50% probability estimates.

[b] All totals have been rounded.

[c] Identified recoverable reserves.

[d] Currently identified submarginal reserves.

– negligible amounts; blanks, data not available.

Table 2. Estimates of conventional and unconventional oil and gas reserves and probabilistic estimates of undiscovered conventional oil and gas, in EJ.

Region	Identified reserves of conven-tional oil	Identified reserves of unconven-tional oil[a]	Undiscovered conventional oil at probability			Identified reserves of conven-tional gas	Identified reserves of unconven-tional gas[a]	Undiscovered conventional gas at probability		
			95%	50%	5%			95%	50%	5%
North America	334.9	381.0	268.0	343.3	686.6	418.7	669.9	494.0	615.5	1394.2
Latin American & The Caribbean	669.9	1758.5	280.5	468.9	1180.7	263.8	535.9	159.1	385.2	1050.9
Western Europe	205.2	288.9	58.6	100.5	263.8	217.7	301.4	146.5	230.3	535.9
Central & Eastern Europe	0.125	0.125	0.83	0.83	0.334	0.167	41.9	0.209	0.334	87.9
Former Soviet Union	477.3	108.9	477.3	309.8	527.5	1653.8	2051.5	787.1	1310.5	3475.0
Middle East & North Africa	3575.5	649.0	431.2	678.3	1360.7	1578.4	1473.8	632.2	979.7	2064.1
Sub-Saharan Africa	406.1	326.6	117.2	196.8	523.4	280.5	523.4	171.7	334.9	942.0
Centrally Planned Asia & China	180.0	3387.1	121.4	209.3	573.6	0.334	849.9	121.4	205.2	552.7
South Asia	0.293	0.41	0.209	46.1	92.1	67.0	142.4	50.2	104.7	293.1
Other Pacific Asia	117.2	41.9	46.1	79.5	175.8	184.2	247.0	113.0	188.4	427.1
Pacific OECD	0.167	138.2	0.83	0.125	0.376	0.0	0.334	0.125	0.209	54.4
World	6024.8	7096.6	1838.0	2453.5	5455.4	4798.1	6870.5	2708.9	4408.7	10877.3

[a] Devonian shales, aquifers, and coal-bed methane.

Table 3. Natural gas supply, EJ

Year	Domestic	Imported	Total
1990	4.29	4.02	8.31
2020	8.62	13.89	22.50
2050	11.73	16.06	27.79
90-50	500.00	628.56	1128.5

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