TECHNOLOGICAL PROGRESS, STRUCTURAL CHANGE AND EFFICIENT ENERGY USE: TRENDS WORLDWIDE AND IN AUSTRIA

INTERNATIONAL PART

Final Report

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The Austrian case study will be symmetrical to the structure of this report, and will be supplied separately.

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Technological Progress, Structural Change and Efficient Energy Use:

Trends Worldwide and in Austria

INTERNATIONAL PART

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Technological Progress, Structural Change and Efficient Energy Use: Trends Worldwide and in Austria

> Energy is one of the fundamental *requirements* for economic growth and social improvements, and not just a *consequence* of such growth.
>
> *W. Kenneth Davis*

1. INTRODUCTION

1.1. Background and Issues

Energy systems have changed radically since the onset of the Industrial Revolution. The traditional sources of energy and energy-use patterns in pre-industrial societies relied on natural energy flows in the environment, such as biomass, wood, wastes, water flow and some limited amounts of solar heat. In contrast, the more advanced industrialized countries rely primarily on hydrocarbon sources of energy in addition to wood, hydropower and nuclear energy. The hydrocarbons (i.e., coal, oil, natural gas), hydropower and nuclear energy, are rarely used locally. Instead, most of the primary energy sources are converted to other energy carriers (forms), such as liquid fuels or electricity, and are stored, transformed and distributed to the point of use. Thus, most of the energy requirements of industrial societies are provided by elaborate systems of energy extraction and processing, conversion, storage, transportation, distribution and end-use.

Perhaps the major advantage of an increasing sophistication of an energy system is that most of the necessary energy conversion processes, from extraction to end-use, can result in a higher quality of energy carriers (often associated with higher energy densities[1], i.e. higher energy content per unit volume, weight or area) and higher efficiencies. In fact, over the last two centuries the average energy efficiency and density have increased along with the increase in per capita energy use.

We should note here that the total increase in global primary energy consumption is the result of both population growth and the increase in per capita energy use. Primary energy use in the world has increased by a factor of 21 since 1860, population by a factor of 3.6, and per capita energy use by a factor of 5.8. Thus, per capita energy growth was a more dominant factor globally in determining total energy consumption. Since the so-called energy crisis, however, per capita energy use in most of the industrialized societies has been stagnant, or has declined due to rationalization measures, conservation and higher efficiency of new technologies. In the future, as technological, economic and social determinants evolve, the efficiency of energy use is likely to increase even further. At present, the implications and consequences of, and constraints for, this evolutionary process of change are not fully understood, and will, no doubt, contain many surprises to our present perception of the future. The pervasive consensus is that future energy consumption will be more efficient than it is today, leading to lower primary energy needs for the provision of the same energy services delivered. However, quite a lot of disagreement has arisen with regard to the speed of efficiency improvements and whether they will be large enough to offset future increases of energy demand.

1.2. Objectives of the Study

The objectives of the study are to gain a better understanding of the changes in the efficiency of energy supply and end use, and it's main constituents; to investigate possible future developments worldwide, including Austria, and to assess the potential impacts of these developments. Although the identification of likely overall characteristics of future energy systems is the primary objective of the study and this report, the possible future improvements in the performance and efficiency of new (energy) technologies also constitute important aspect of the study.

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[1] Increased concentration of population and economic activities in urban agglomerations have at the same time led to higher *spatial densities* of energy use. Today spatial energy density is in the order of 10 kW per square meter in most of the large industrialized cities throughout the world. This is more than an order of magnitude higher than the solar insulation (0.3 kW per square meter of average annual direct beam irradiance in sunny regions).

We analyze energy efficiency improvements embedded in the context of overall economic and social structural changes, and technological innovation processes in particular. Furthermore, we discuss the contribution of efficiency improvements toward reducing adverse environmental impacts of energy use. These objectives are reflected in the structure of the report as illustrated in Figure 1-1.

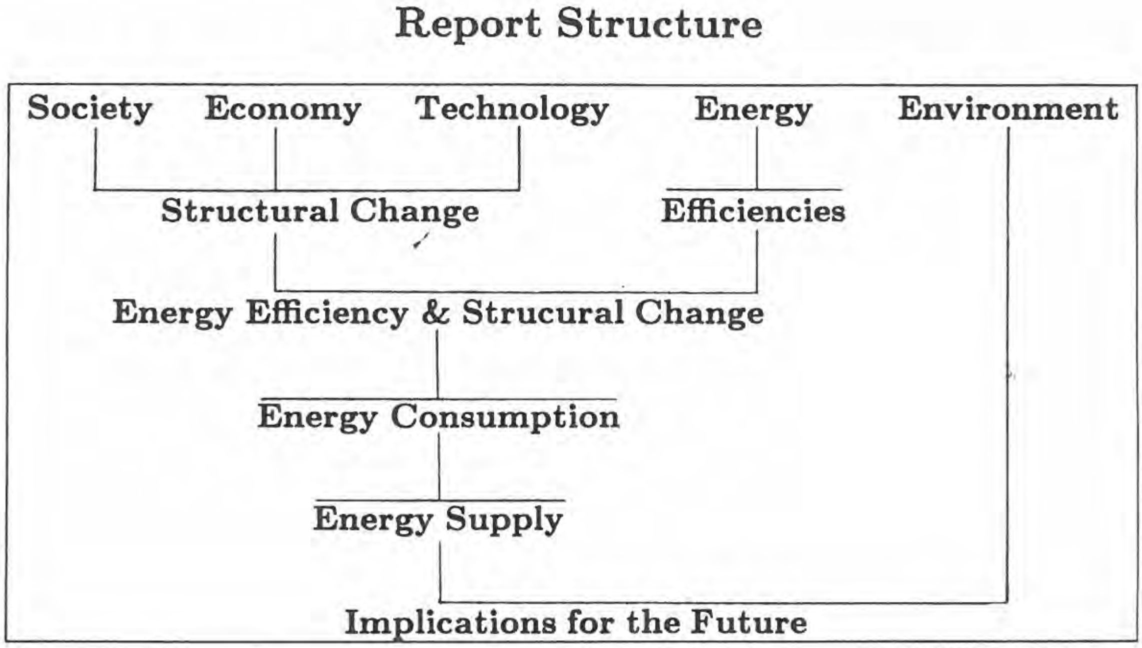

Figure 1-1 Structure of Report on Technological Progress, Structural Change and Efficient Energy Use.

After the introduction (Chapter 1), Chapter 2 focuses on transformations in the world economy that are related to technological advancement and emergence of new institutional and organizational frameworks, and which will determine the future qualitative and quantitative characteristics of the energy system. In Chapter 3 we give a brief description of the historical development of the energy system and use, and then document the recent changes in energy production, trade and consumption in the OECD countries and Austria. Chapter 4 outlines some of the more important structural changes in the economy that are related to the transformation of the energy system and how the efficiencies of energy uses have evolved in the context of overall economic and technological development. Chapter 5 analyzes in greater detail the efficiency improvements of energy conversion, distribution, end use and services in the OECD countries and in Austria. We assess current efficiencies and estimate potential improvements without changing the structure of energy end use. Chapter 6 describes the global and regional environmental impacts of energy consumption, and Chapter 7 gives a brief summary of scenarios of future energy developments and their implications for energy efficiency. Finally, Chapter 8 summarizes the main conclusions which have emerged from our discussion in the previous Chapters.

1.3. Methodology

The basic working hypothesis of the present study is that technological changes are one of the primary causes of ever increasing energy efficiencies and more effective use of energy. The dynamic changes of the energy system, energy use and technology in general are described and analyzed against the background of changing economic and social environments. The technological and economic aspects of these dynamic processes, that lead to greater efficiencies of energy use, are described in terms of quantitative indicators, while social factors, such as changes in life styles, are described mostly in qualitative terms.

The main emphasis of the study is on the systems aspects and changes in the requirements imposed on the structure and architecture of future energy systems, rather than on the technical and economic performance of individual energy technologies.

1.4. Time Horizon

The time horizon of the study encompasses the past evolution of the energy system as far back as possible, i.e. starting from the onset of the Industrial Revolution some 200 years ago.

With respect to future developments both a medium and a long term perspective are adopted. For the discussion of ongoing technological and energy efficiency trends, as well as for the discussion of energy scenarios, a medium term time scale (up to the year 2000 to 2010) is used. For the more global and long term trends in structural shifts in the economy and lifestyles, as well as for some higher aggregated technological trends and the relevant environmental boundary conditions, the time framework is extended up to the year 2030 and thereafter.

2. SOCIAL, TECHNOLOGICAL AND ECONOMIC CHANGE

2.1. International Developments

2.1.1. Time Allocation and Employment Patterns

A number of developments in industrialized countries indicate the possibility of an increasing demand for services as a consequence of changing lifestyles and a transition to a new economic and social structure. With the longer life expectancy, the population age structure will shift toward the elderly, indicating not only new challenges and potential difficulties in social security schemes, but also the need for different products and services. Demographic changes are no doubt one of the most powerful determinants of the characteristics of future markets and labor dynamics. In conjunction changes in the demand structure of products and services, time-budgets and time allocation to various activities are measures that very accurately describe the structural adjustments accompanying the process of economic and social change. These indicators prove to be rather resilient even under the conditions of a major techno-economic paradigm change. This is because they are determined by underlying social mechanisms that are not strongly affected by turbulent transitions from an old economic structure and technological base to a new phase of development.

Working on the job has a very high score on the benefit ranking of individuals emphasizing the importance of working time as a social institution. The importance of the experience of time structures is well recognized in social-psychology. For instance, studies on the unemployment effects in Marienthal (conducted in 1933 in a small Austrian textile community) Jahoda *et al.*, 1933, illustrate the impacts of unemployment on time perception and on time structure of individuals without work. A similar phenomenon can be observed today. We conjecture that time-budgets and perceptions of time structure are fundamental, slowly moving variables, and may thus provide an additional insight into the nature of possible transitions from one particular development trajectory to another.

Additional advantages do exist. For instance, human activities and time allocation are related to sectoral changes such as the gradual shift in employment from agriculture to industry and more recently to services. These changes mirror the interplay between the formal and informal (grey) economic activities, and may thus not always be reflected correctly in the system of national accounts. It can be shown, for instance, that the total employment in activities, formerly included in agriculture (production of factor inputs, direct marketing, etc.), is by far larger than suggested by the employment statistics of people working in the agricultural sector. Thus, present employment statistics overestimate the shift away from agricultural activities (in a large sense) as they mirror also the transition from complete vertical (i.e. a farmer is responsible for **all** activities related to food supply) to horizontal integration, where the industry and service sector have taken over a large part of previous agricultural activities. For these reasons, time-budgets and time allocation of different activities may prove to be more useful indicators for capturing long-term structural changes than for instance sectoral employment statistics.

Finally, we refer to the institutional aspect. The time-budget concept is probably a good measure to identify heterogeneity, i.e., heterogeneity of the working time between different countries, between different sectors, and perhaps more importantly, between majorities and minorities (i.e. sexes, races, etc.). Figure 2-1.A illustrates the gradual changes in the life hours spent at contracted or paid work in the UK over the last hundred years.

This example was chosen because it was possible to assemble this kind of quantitative information over a sufficiently long period. For other countries, this kind of data is not readily available, but the overall trends are not very different in the industrialized regions. During the 1870s the average male worked approximately 166,000 hours throughout his lifetime, which has been reduced today to some 88,000 hours. The reduction in average working time for women has not been so dramatic, primarily due to the increasing participation in the labor force over the same time period. The same picture appears relatively smooth for the average total working population, female and male. The following individual measures contributed at different degrees over time, to this long-term structural transition: hours worked per week; weeks worked per year; and years of active participation. Together they produce the final variable of life-hours spent at work. As illustration, Figure 2-1.B shows the evolution of these three main working time indicators for women in the UK over the same period.

Productivity increases, since the onset of the Industrial Revolution, have thus led to a considerable reduction in the life time hours at work. When we consider time allocation, we do not want to look at individual time-budgets in isolation, but rather at how they are embedded in a larger

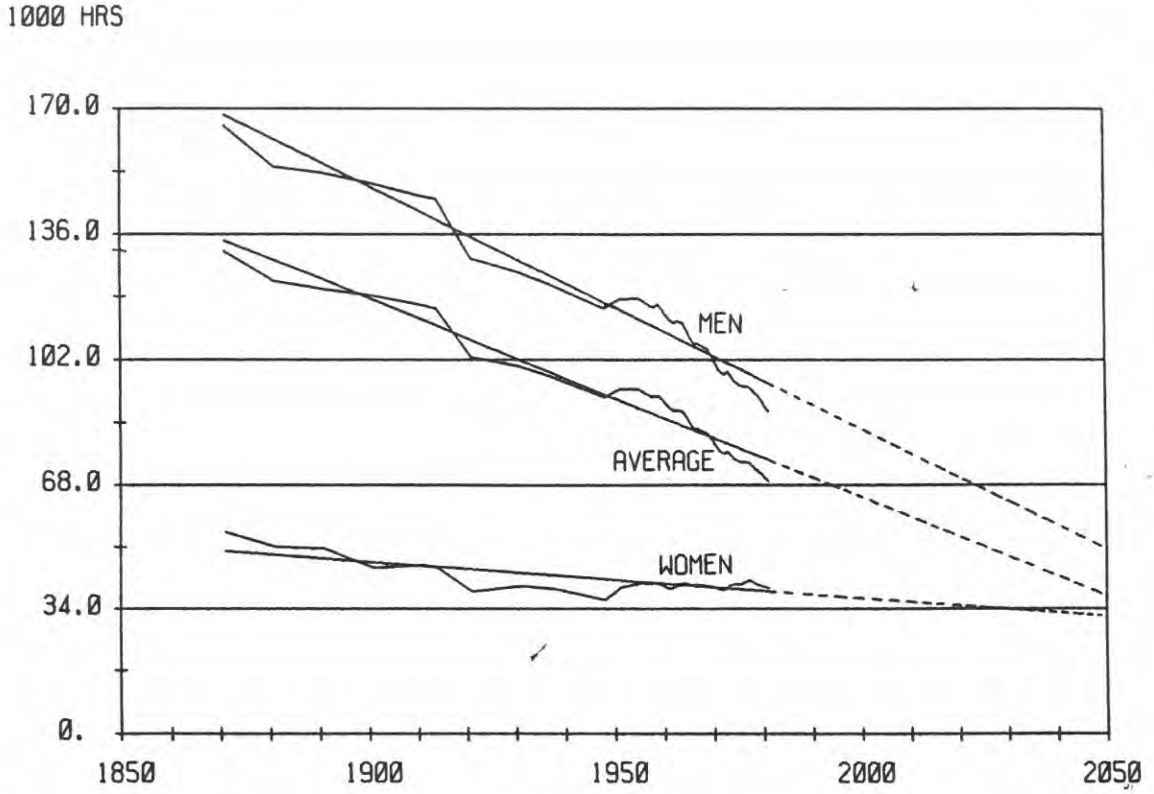

Figure 2-1.A Life Hours at Work in the UK (Ausubel and Grübler, 1989).

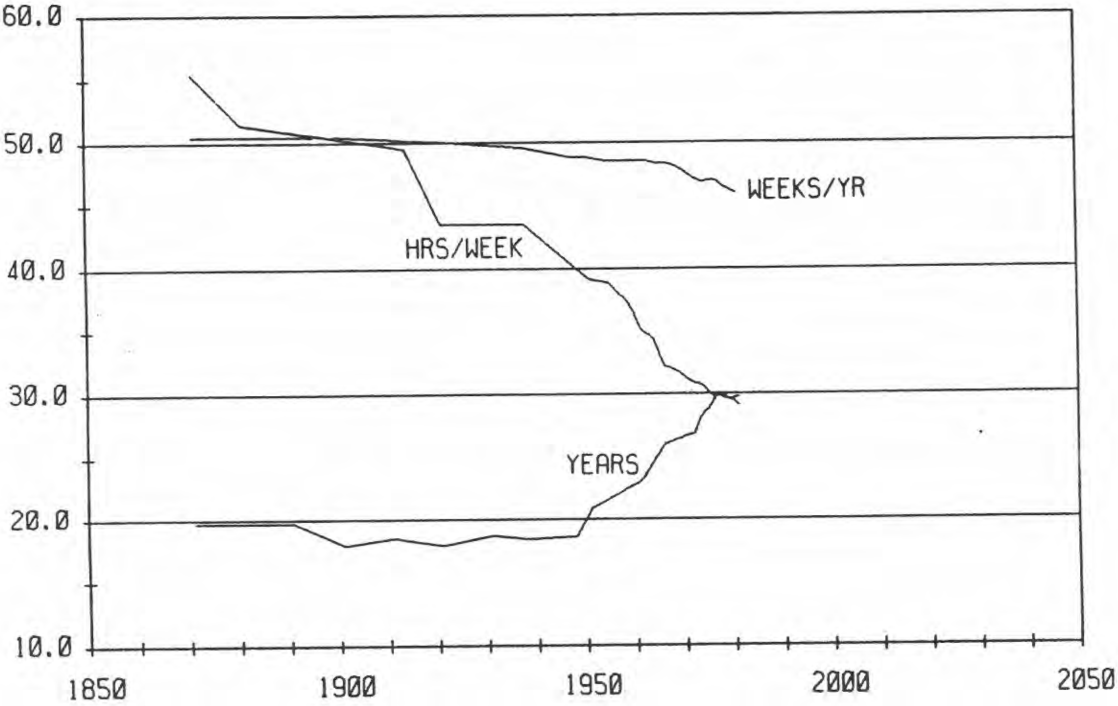

Figure 2-1.B Main Working Time Indicators for Women in the UK (Ausubel and Grübler, 1989).

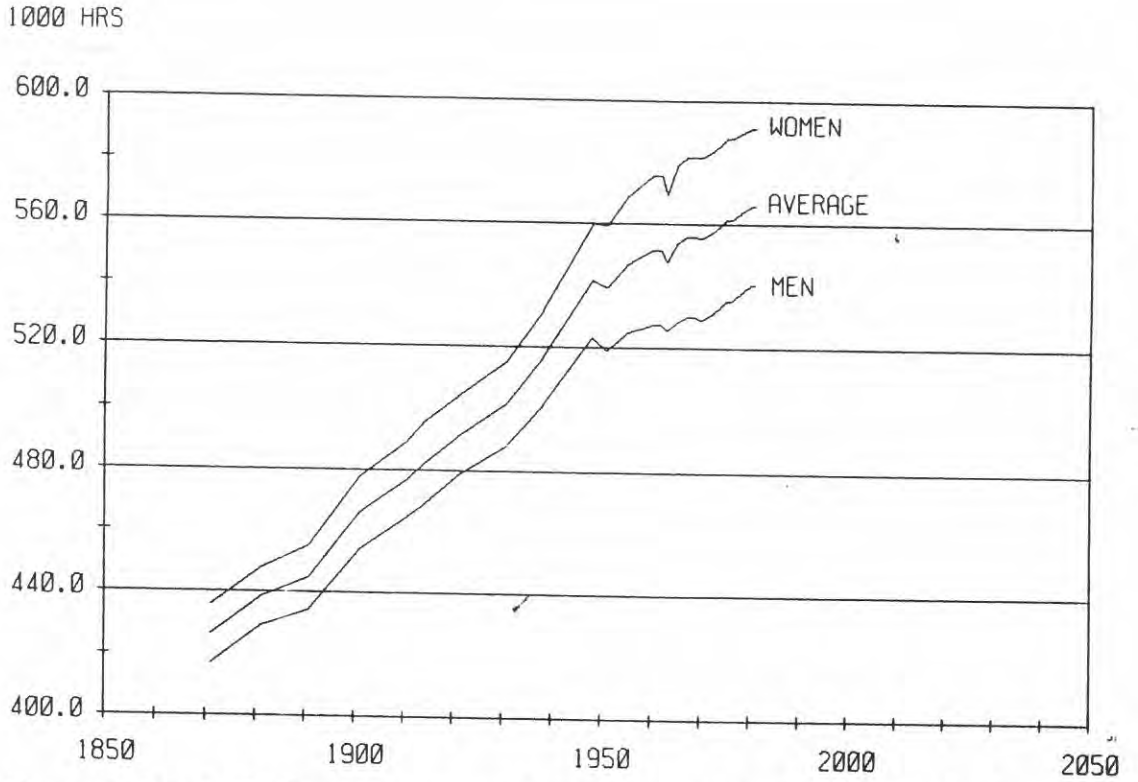

Figure 2-2.A Life Expectancy at Age Ten in the UK (Ausubel and Grübler, 1989).

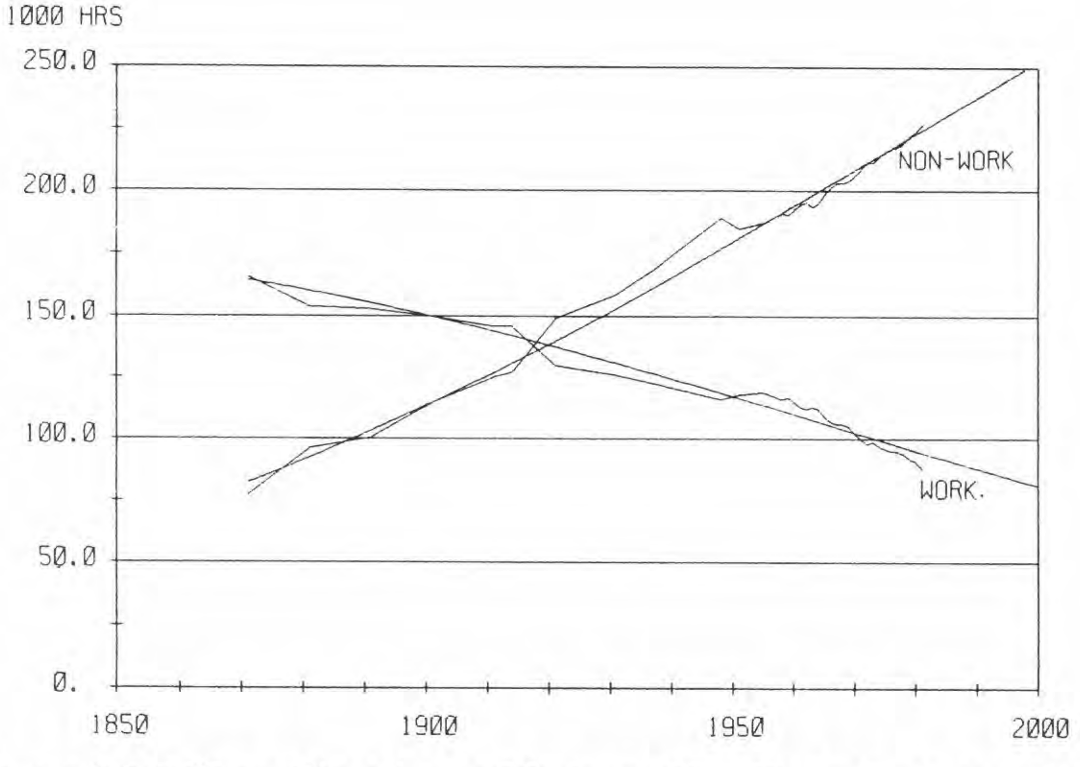

Figure 2-2.B Time Allocation to Work and Non-Work, Excluding Physiological Time, Over Life Time for Men in the UK (Ausubel and Grübler, 1989).

context. In particular, we would like to link the analysis to the evolution of longevity and the structural change in the population, in particular, aging. Here we will illustrate the effects of increasing life expectancy and decreases of contracted work. However, one could extend this approach to other activities such as communication and travel, education and training, retirement and finally leisure.

Figure 2-2.A shows the dramatic increase in longevity for the whole population, female and male over the last one hundred years; it gives the average life expectancy at the age of 10 in the UK. So while time spent at contracted or paid work hours has decreased, life expectancy has increased dramatically. During the last hundred years, there were dramatic shifts in the structural composition of the time allocation to work and non-work over the life time of an average male individual.

Figure 2-2.B shows how the disposable life time budget of an average male is allocated to different activities after subtraction of the necessary physiological rest and sleep time. Around 1870 more than 70 percent of disposable life time budget was spent at paid work; decreasing to less than 30 percent at the present time.

Thus, enormous productivity achievements, since the onset of the industrialization, have both raised the general standard of living, increased life expectancy and reduced the working time. One hundred years ago a typical working day was often in excess of 12 hours and only a few (apart from public) holidays existed. Working weeks are now being reduced to as little 35 hours in parallel to longer vacation periods. All told, the share of the life-time spent at paid work has decreased dramatically. At the same time, the participation of women in the working force has increased and is expected to grow, so that in the longer term the sexual differences in the contracted working time may be slowly converging.

Over time, as societies become more affluent, the population spends less and less time for regular, salaried work at the workplace, and more time at home (housework and raising children), and for leisure proper. Ausubel and Grübler (1989) have shown that this trend to more leisure time with increasing affluence is consistent over a large number of industrial countries, including centrally planned economies.

The changing pattern of time allocation away from formal, contracted work and other "socially obligatory activities" (housework and child care) to "free" or leisure time may be summarized, in economic terms, that consumption has become predominant over production. This highlights the growing importance of consumption patterns, lifestyles and changing social habits in shaping future energy demand in societies becoming more affluent.

Increased leisure time and higher incomes, for instance, will certainly result in additional long distance transport needs, while the change in work time and occupational structure will place new demands on short-distance commuter infrastructures. Flexible working time and higher participation in the labor force in general, imply the need for more efficient, flexible and fast means of commuter transport, especially if car ownership should saturate in the near future.

All of these three developments, older age structure, increasing wealth with decreasing time at work and increasing leisure time, will place new demands on the types of products consumed, services rendered and, as a consequence, also on the quantity, type and quality of energy needed in the future. This poses a number of critical research questions relating to new technologies and work forms, ways of developing new infrastructures adequate for the emerging needs, public policy and funding. Together with the transformation of social attitudes and the emergence of new paradigms there will no doubt be new constraints and new driving forces shaping the energy systems of the future. This will most likely go beyond the current requirements of flexible, safe, clean and, in general, environmentally compatible systems.

Changing population structure, social attitudes and lifestyles will result in different consumption patterns and economic structures. Already today the so-called service economy is becoming one of the most important sectors in the industrialized countries. We have shown that the longer-term changes in time allocation indicate an increasing need for services in the likely transition to more leisure and educational needs in comparison to the emphasis on improving industrial output and production of tangible goods in the past. Thus, the transformation of time budgets tends to suggest a trend toward disintensification of the overall economic activities from physical production to consumption of services. This restructuring process is also reflected in employment patterns.

As an illustration we will show the changes in the employment of the whole work force in the four major OECD countries: France, Japan, the US and the UK. Figure 2-3 shows the share of labor force directly engaged in agriculture. It is intuitively clear that the UK, as the first country to industrialize, already had only slightly more than 20 percent of its labor force in agriculture already at the beginning of the last century. In contrast, Japan, as one of the leading world countries to industrialize rather recently, portrays a much higher share of labor in agriculture, approximately 80 percent around the turn of the century. Taken together, the process is convergent in time, as most of the industrialized countries are converging towards only

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1 Data source: Mitchell (1980 and 1982), Flora (1987) and ILO, 1988.

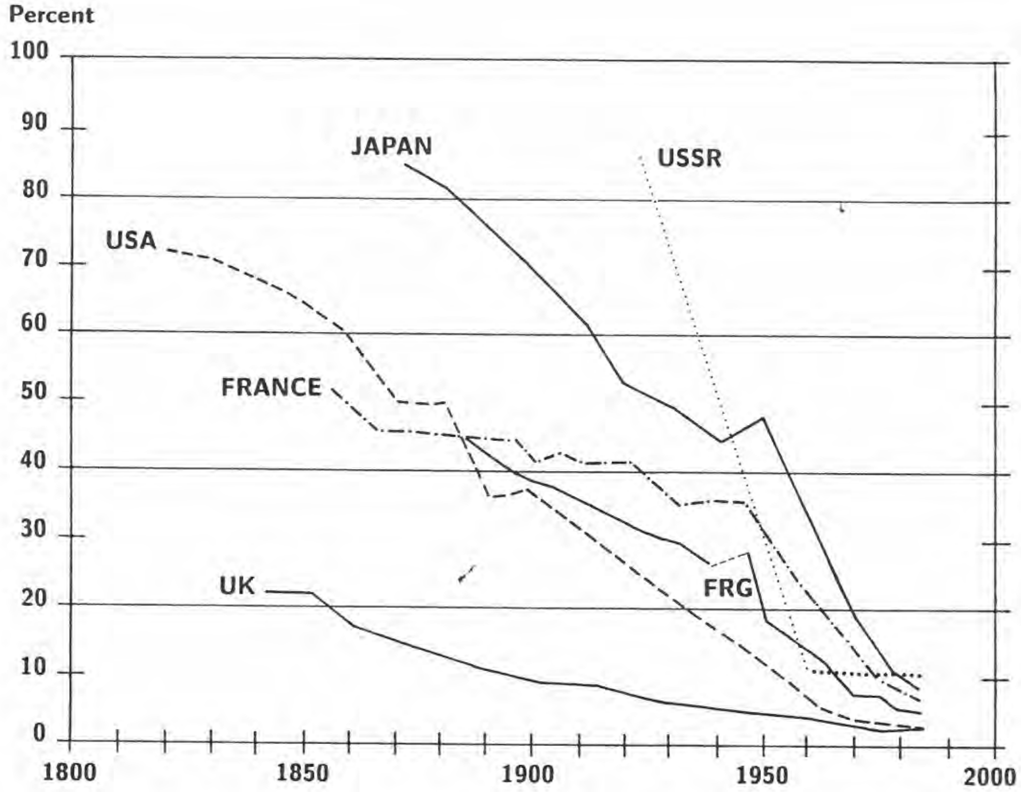

Figure 2-3 Share of the Work Force Employed in Agriculture.

a few percent share of labor force engaged in agriculture. Thus, the employment patterns reflect very clearly the flow of labor from agricultural to industrial activities during the last two hundred years. They are an indicator of the overall restructuring of the whole economy and the associated social and institutional changes.

Figure 2-4 shows the historical changes in the share of the labor force engaged in industry. The development is analogous to the previous figure in that the increase of employment in industry is almost a mirror image of the declining employment in agriculture. The UK, due to their early industrialization, is an exception with an almost constant share of people working in industry. Japan has the highest increases in industrial employment as a consequence of her catching-up in industrialization. This figure clearly illustrates the relative industrialization pace of these four countries. Thus, during the last century the percentages of the labor force engaged in industry is relatively large among the four country sample; the UK industrializing first and Japan last. Nevertheless, there is convergence during the last decade and what is more interesting is the first signs of a decline in industrial employment in all four countries.

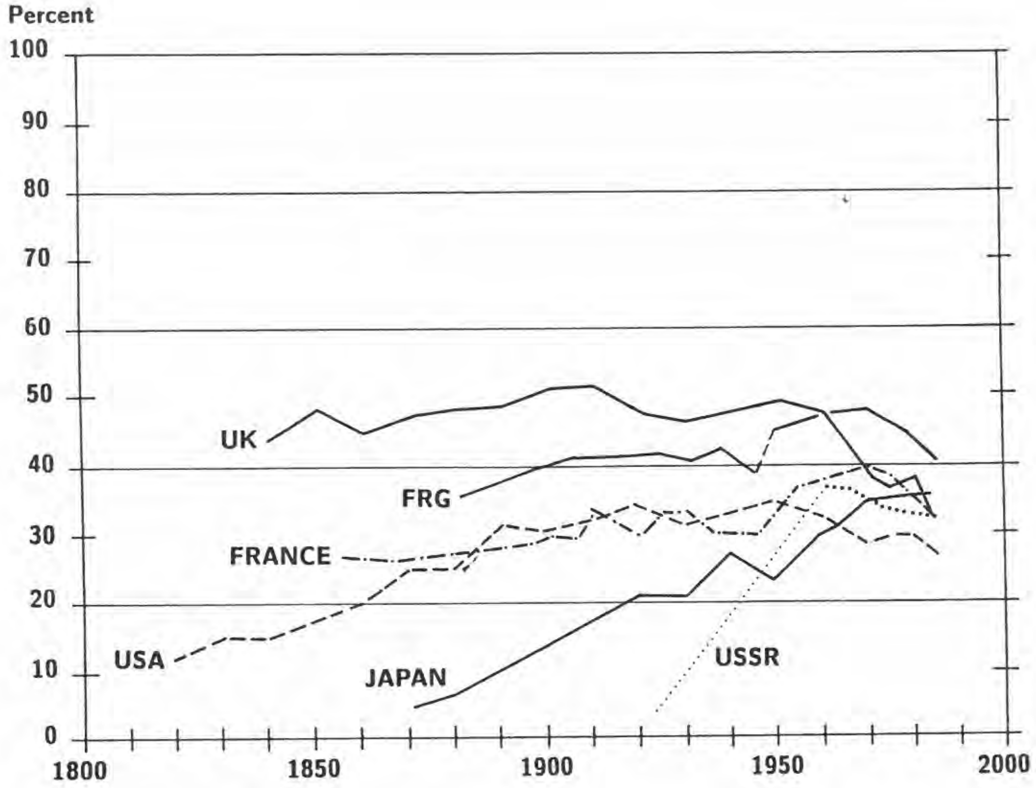

Figure 2-4 Share of the Work Force Employed in Industry.

Figure 2-5 shows that the services sector is becoming a major area of employment in the four industrialized economies, exceeding 60 percent in the US and UK, and about 50 percent in Japan and FRG. However, while those trends are obvious and well known, they are masking the fundamental nature of the structural change. Today, agriculture has 5 percent of the total labor employment, but many of the activities that used to be in agriculture are now in services and industry. For example, the whole food sector is now distributed between industry and services, while traditionally all of the food was provided by agricultural activities. Today agriculture is a horizontally integrated operation related to both up and down-stream service and manufacturing sectors. So, in terms of actual activities, the importance of what used to be the traditional agriculture is certainly higher. This is why it is important to keep track of the overall development, and not just to concentrate on a few chosen sectors and indicators.

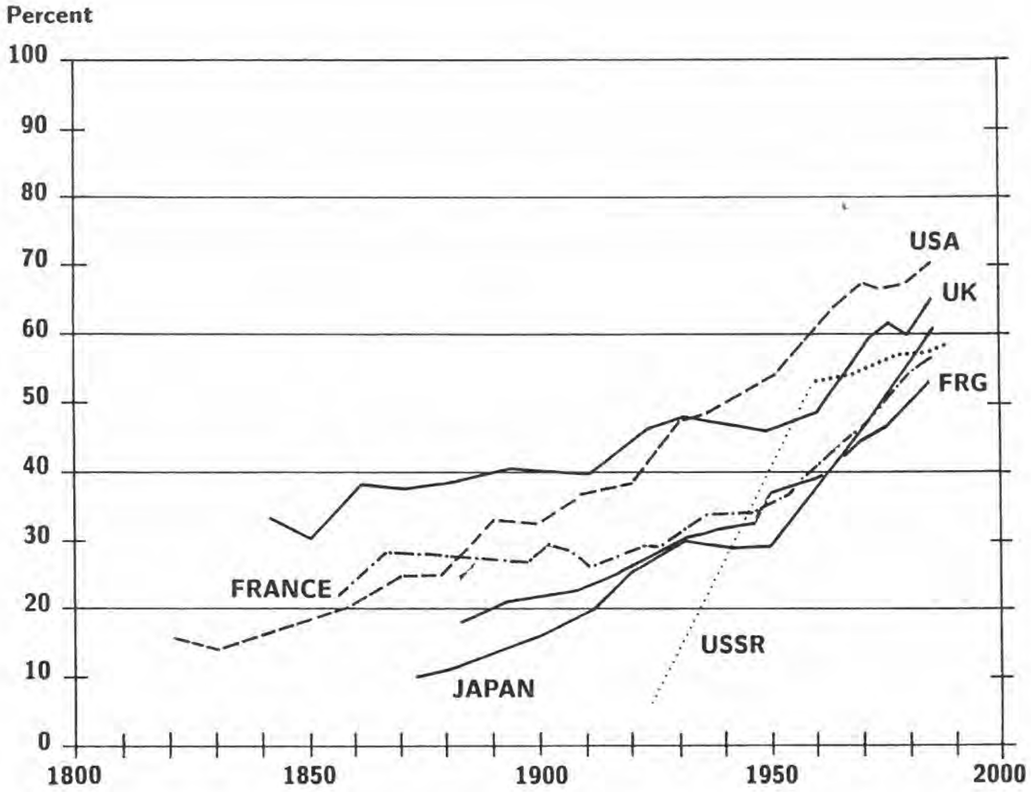

Figure 2-5 Share of the Work Force Employed in Services.

2.1.2. Social Changes and Institutions

The evidence of fundamental transformations in developed countries is quite transparent. Material intensive activities are decreasing, while services are becoming not only the most important generator of employment and value added in the economy, but also a sector with a large application of new technologies and institutional forms. This denotes the importance of the on-going structural change; it includes creation of completely new economic activities, new work and employment relations, application of new chnologies, increase in value and information of provided goods and services and also different patterns of energy services and requirements.

The changes in social relations and institutions that are reflected in the transformation of time budgets and employment patterns, which we have attempted to describe, are often discontinuous and sometimes even disruptive. Indeed, we can observe development phases where we have more rapid economic growth and expansion of industries and new sectors; but they are interlaced with periods of adjustment and restructuring. Thus, the process of change is frequently of a discontinuous nature, creating mismatches and frictions throughout the society, and it is usually during these periods that new technologies and social institutions emerge. If the conflicts resulting from these mismatches are resolved, these adjustment periods can lead to the creation of new growth sectors, new employment opportunities and subsequent economic growth. Thus, the adoption of new techno-economic systems, especially those that are pervasive in the sense that they affect almost all activities across all sectors of economy, is a social process.

The institutional aspects are of fundamental importance to the success or failure of restructuring processes. Innovations themselves are not enough; it is the *diffusion* of the innovations, whether of an institutional nature, or of a technical or product nature, that is fundamental. Since the diffusion of innovations is mediated by society, the nature of social impacts will either promote further diffusion or block it. We have illustrated the fundamental nature of these impacts by showing how the work time and employment patterns have been transformed from long working days and agricultural activities of most of the working force, to more "free" time and employment in services.

The structural adjustment period in which we are apparently now, or have experienced over the last decade or so, is a reflection of a number of *mismatches and frictions*, not only in the processes of production but also at the institutional level and especially in the employment area. At the same time, one of the preconditions for further economic growth will be to create proper development priorities in order to allow *pervasive diffusion* or dissemination of new activities throughout the economy; not just within a few sectors.

Last, but certainly not least, the question of sustainability of such developments should also be included as a research topic in our present considerations. In a wider sense sustainability should not only be considered from an environmental point of view alone, but also in the sense of having opportunities for employment and general economic and social development. However, the environmental sustainability will also have an effect on the structure of labor markets and changes in competitiveness. Environmental legislation and constraints could fundamentally change some economic activities and will certainly have heterogeneous effects, since they will be more strenuous in some parts of the world than in others (see Chapter 6). Thus, the regulation policy in general is a very important factor in determining the future development paths.

The socio-institutional framework always influences, and may sometimes facilitate and occasionally retard processes of technical and structural change, coordination, and dynamic adjustment. Such acceleration and retardation effects relate not simply to market "imperfections", but to the nature of the markets themselves, and to the behavior of economic agents (Dosi *et al.*, 1988). In other words, institutions are an inseparable part of the way markets work, and perhaps even more importantly, they are an inseparable part of technological change and economic development.

2.1.3. Diffusion and Evolution of Technologies

Technological change in all areas of economic and social activities has been a major determinant of development. In essence, advances in technology make it possible to achieve more with less. This implies that in time productivity increases will be accompanied by improvements in the efficient use of energy, basic materials, capital and other inputs, and improving also generally the environmental compatibility.

Technological improvements are achieved both through the introduction of fundamentally new solutions (basic innovations) and through incremental improvements of existing techniques and systems (product and process innovations). It is important to distinguish the two classes (although an overlap exists), because the basic innovations, as originally formulated by Schumpeter (1935 and 1939), are those which lead to the creation of new industries and growth sectors and thus to the emergence of whole new "socio-technical paradigms", (Freeman and Perez, 1988), characteristic for the form and direction of economic development during particular historical time periods.

In addition, there is a gradual transition in the diffusion process, from basic innovations that initially lead to the creation of new industries to incremental improvements, and product innovations as the diffusion process matures. Diffusion of some innovations become pervasive in the sense that they lead to a host of interrelated new activities across many sectors. Electricity, automobiles or computers are examples of such systems that have changed many facets of our everyday life, thereby creating whole new industries and economic activities and fundamentally contributing to the dramatic pace of economic development. During the early development phases of this process the new industry is fluid with a high degree of diversity and experimentation. The major emphasis is on improving technical performance without much regard for cost. In the Schumpeterian sense there are often monopoly opportunities arising for the innovative entrepreneur.

As competition begins to set in with the entrance of more producers, one particular technological variant becomes dominant and standardization emerges in the new industry. This is usually a disruptive phase of development with a characteristic "shake-out": only a few competitors survive this competitive phase as a downturn in prices becomes significant with the increasing cost reductions due to the effects of standardization and learning curve effects. The emphasis shifts then to incremental improvements and small cumulative innovations. Economies of scale and further reductions of costs along the learning curve lead to advantages only for a few competitors who can internalize the benefits. This is also the development phase where the pervasive nature of some technologies becomes apparent. Pervasiveness in diffusion tends to block alternatives and is thus reinforcing further widespread implementation of particular technological systems, until increasing disbenefits to further growth and expansion become widely apparent (Brooks, 1988). Some innovations diffuse in many sectors, such as manufacturing, services and marketing. Computers and information processing systems are good examples.

Thus, diffusion of pervasive socio-technical systems can fundamentally change many commercial activities and even the everyday life. Nevertheless, as the technology and its applications mature, the awareness of many disbenefits can emerge. Cumulative and incremental improvements increasingly covers a smaller domain of technical and managerial possibilities. The saturation starts and the problems associated with the widespread and large scale applications become important. The social and institutional response is rather nonlinear and disruptive. The awareness of social disbenefits and risks often increase rapidly making further applications unacceptable.

It is precisely during such periods that new techno-economic paradigms can emerge and the old development trajectory associated with the previous generation of pervasive technologies and institutional forms is not only challenged, but in time also replaced with new solutions. This illustrates that there are strong links between social development, economic growth, innovation process and the subsequent diffusion of new technologies. Dosi *et al.* (1988) characterize the main features of technological, economic and institutional change in the following words:

1. Technical change is a fundamental force in shaping the pattern of transformation of the economy.
2. There are some mechanisms of dynamic adjustment which are radically different in nature from those allocation mechanisms postulated by traditional (equilibrium type) theory.
3. These mechanisms have to do both with technical change and institutional change or the lack of it. As regards the former it is both disruptive during the transition period (marked by fluctuations, frictions and sometimes crises) and it is a source of order for the directions of change and the dynamic adjustment process, as new technologies diffuse through the national and international economies.

Some of the most important changes in socio-institutional frameworks and economic structure are indeed related to pervasive adoption of new systems. They include for instance the development of infrastructures. Today, the emergence of new systems such as the information and communication technologies is often mentioned in this context because there are reasons to believe they may become pervasive throughout the economy, and they will not diffuse in just a few selected sectors. Another way to formulate this phenomenon is to consider the interrelationships among different diffusion processes and their clustering in space and time.

One can almost talk about hierarchies or about a taxonomy of systems. For example, the diffusion of motor vehicles was contingent on the development of numerous other systems, such as paved roads, the internal combustion engine, oil refining and motor fuels, new sheet metals and high quality steels, electrical equipment and a whole host of other new technologies and products. Table 2-1 illustrates this clustering cross-enhancing effect of a number of interrelated technological systems, which were main driving forces of particular economic expansion and growth periods since the onset of the Industrial Revolution.

Table 2-1 Clusters of Pervasive Technologies.

1770-1830	1820-1880	1870-1940	1930-1990	1980-2040
Water Power, Sails, Canals Turnpikes, Iron Castings, Textiles	Coal, Iron, Steam Power, Mechanical Equipment	Railways, Steam Ships, Heavy Industry, Steel, Dyestuff, Telegraph	Electric Power, Oil, Cars, Radio, TV, Durables, Petrochemicals	Gas, Nuclear, Aircraft, Telecomm., Information, Photo-Electron.
Mechanical Equipment, Coal, Stationary Steam Power	Steel, City Gas, Indigo, Telegraph,	Electricity, Cars, Trucks, Radio, Phone, Oil, Roads, Petrochemicals	Nuclear, Computers, Gas, Telecommunication, Aircraft	Biotechnology, Artificial Intelligence, Space Industry & Transport
Manufacture	Ind. Prod.	Standardization	Fordism-Taylorism	Quality Control

Adapted from Pry (1988).

The list of technology clusters as presented in Table 2-1 is illustrative rather than exhaustive and also the timing of the various development periods is only approximative. Still it represents a general overview of the main technology clusters, which were responsible (frequently, as in the case of railways, studied under the leading sector hypothesis by economic historians) for much of the extent and the general direction of economic growth during particular historical periods. The top of Table 2-1 gives the principal technology clusters dominating a particular epoch of development. The lower part indicates technologies which are introduced and emerge during the same phase, in order to become pervasive in the next phase of development. For example, the dominant cluster of the 1930s to the present time includes: great growth in electric power, oil and petroleum, petrochemicals, radio and TV, instruments and controls etc. During the same period we had innovations and emergence of new industries which may become important in the future: Nuclear energy, computers, natural gas, telecommunication and information systems.

On the bottom of Table 2-1 we have attempted to summarize the general "trajectory" or principle driving force and direction of economic growth during the various epochs: economies of scale based on Fordist production and scientific management principles (Taylorism) in the period from the 1930's to the present for instance, and economies of scope and quality control and management most likely in the next phase of development. The transition from one phase of development to another one is triggered primarily by the fact that the technological cluster, responsible for much of the economic growth, approaches a number of limits: saturating markets, diminishing returns to further incremental improvements and productivity gains, increasing awareness of social and environmental disbenefits associated with a continuation and further intensification of the traditional mode of development. This "crises" in predominant techno-economic paradigms are generally manifested in increased turbulence and volatility in markets, prices, even in social relations. At the same time, it is exactly during these transitional adjustment phases that clusters of new technologies emerge and the characteristics and direction of the next phase of development are being shaped by a social process. These changes in the techno-economic paradigms illustrated by the emergence and diffusion of interrelated clusters of pervasive technologies also gives, at the same time, the history of energy use, employment and skills, as the structure of the economy changed.

Brooks (1988) gives a list of possible new technologies and activities that could emerge during the coming decades. Some of them could have a profound influence and may lead to revolutionary consequences on the next phase of economic development:

1. The potential application of genetic engineering to food productions and the detoxification of organic wastes.
2. Developments in medium-scale, combined-cycle gas turbines for electricity generation fueled by natural gas or clean low calorific gas produced in coal gasifiers.
3. Sophisticated application of microelectronics to the control and monitoring of energy consumption, with a potential for providing energy

services using less primary energy.

4. Development in ceramics, composites, and fiber-reinforced plastics with the possibility of substitution for metals and alloys used currently.
5. Low-polluting, closed-cycle food production and industrial processes.
6. Development of cost-competitive photovoltaic solar energy systems and fusion reactors.
7. Discovery of abundant resources of deep natural gas in addition to the large quantities of conventional and unconventional gas resources identified to date.
8. Wider application of superconductivity for efficient energy transmission and storage, or for cost-competitive rapid transport systems based on magnetic levitation (Maglevs).
9. Introduction of hydrogen as a clean energy carrier for a number of applications including automobiles and advanced supersonic and hypersonic passenger aircraft.
10. Further increases of recycling of manufactured products by new applications of flexible and computer integrated systems for assembly and disassembly eventually closing the flow of materials through the economy and thus dramatically reducing the wastes and material needs.

Those new techno-economic systems and innovations made over the last decades have not diffused sufficiently to make an impact at the aggregate level, while the older systems, based on the old paradigms are approaching or have already reached saturation. Depending on whether and how our societies will adopt the systems, we may witness new clusters of diffusion in the future which would have fundamental impacts both on employment, location of economic activities and competitiveness, structure of the economy and consequently also on the patterns of energy use. Since their adoption and mediation by the society will not be homogeneous and will affect different countries and regions differentially, the process can be expected to be disruptive.

2.1.4. Structural Change in the Global Economy

Technological and institutional changes are thus creating immense transformations of the global economic structure. They are affecting how enterprises and nations organize production, trade goods, invest capital and develop new products and processes (Muroyama and Stever *ed.*, 1988). Sophisticated information technologies permit instantaneous communication among the far-reaching operations of global enterprises, coordination of production, marketing and sourcing activities. Application of new materials is revolutionizing sectors as diverse as construction, aerospace and electronic industries. Advanced manufacturing technologies have altered long-standing patterns of productivity, employment and organization of work. Transportation systems and communication technologies have greatly increased the worldwide flow of people and exchange of goods and services. Thus, there is no doubt that the global economic interdependence has increased. This means that innovation and technology dynamics are a worldwide phenomenon so that any marginal competitive advantages are likely to be short-lived and that the diffusion is a global phenomenon albeit with some lags between the leaders and the followers. With the greater interdependence between firms, regions and nations there is also a trend towards increasing harmonization of institutions, legal frameworks and organizational structures. Today any industrialized economy must operate in the context of a truly global market not only for goods and services but also for technology and money. Thus, in the longer-term the only alternative for any nation is to innovate and try to improve its competitiveness on international markets despite the fact that this will certainly create disruptions, structural unemployment and many institutional frictions in the short-term. Appropriate national polices must reflect this transformation of the global economy to one interrelated entity; they should stimulate innovative activities, to improve the level of skills, quality of capital and infrastructures. In the following subchapter we will try to illustrate how appropriate structural changes in the energy system and provision of energy services could enhance economic productivity and environmental quality of energy use while simultaneously achieving better overall efficiencies of energy consumption.

2.1.5. Process Technologies (Primary Commodities and Materials)

With the achievement of relatively a high level of per capita income there appears to be a phase transition in the requirements for basic materials. While the initial process of industrialization is associated with a large increase in the consumption of basic materials, the so-called postindustrial societies of the northern hemisphere have experienced during the last decades a decrease in materials consumption both in per capita terms and per unit of value added (measured by GDP or GNP). Figures 2-6.A and B illustrate the decrease in materials intensity in the US in terms of per capita consumption and in terms of GNP, respectively. The development has been similar in other industrialized countries. Since the production of basic materials is energy intensive, these developments indicate that the industrial energy intensity is also declining. As the materials intensity decreases, more materials can be recycled which further reduces both the wastes and need for processing of basic materials. For example, energy needs for steel production are almost ten times lower if scrap iron and steel is used instead of iron ore.

One of the major driving forces for decrease of materials intensity is the increasing value density of manufactured products. Less materials are used both in the production process and the products have lower specific materials content due to the increasing use of new materials such as light weight alloys, composites and plastics. This is almost a universal trend ranging from vehicles to electronics. Consequently, the production of basic materials is stagnant today. However, it may increase in the future due to the additional demand stemming from developing countries.

The enormous increase in the absolute amount of materials consumed world wide during the last two centuries could only be achieved through the improvement of prospection, extraction and processing technologies. For example, Figure 2-7.A shows that the global steel production increased from about 300,000 tons in 1860 to about 700 million tons today, which is a factor of three orders of magnitude in about 100 years. Figure 2-7.B shows that this increase was made possible by the development of new steel production technologies, each representing a large improvement in quality, diversity and output with the same time lower energy requirements per unit of output. It gives the relative shares in total steel output of different production methods worldwide. In many countries, the share of electric arc furnaces are even higher from the world average of Figure 2-7.B, for example in Italy and Japan. The increase in electric steel production is accompanied by a larger share of recycled steel and much lower specific energy and iron ore requirements. At the same time, the real costs of steel production have decreased. Each of the new steel production technologies was dependent on advances in the energy system and has in turn resulted in a reduction in the specific energy requirements.

Equivalent developments can be documented for most of the traditional basic materials such as metals, cement, glass and also for some of the newer commodities such as plastics or fertilizers. The main exception to this overall trend toward decreasing materials intensity is the consumption of paper. The consumption of paper and paper products has increased dramatically in most of the industrial countries with the widespread application of information and data processing technologies. It is almost paradoxical that the flow of information increases so does the consumption of paper (Herman, *et al.,* 1989). Other increases of paper (and plastics) consumptions are also due to the packaging industry and increasing globalization of the world economy. Transport and packaging requirements have increased both for finished products as well as for the intermediate goods and are likely to increase even further with increasing international division of production

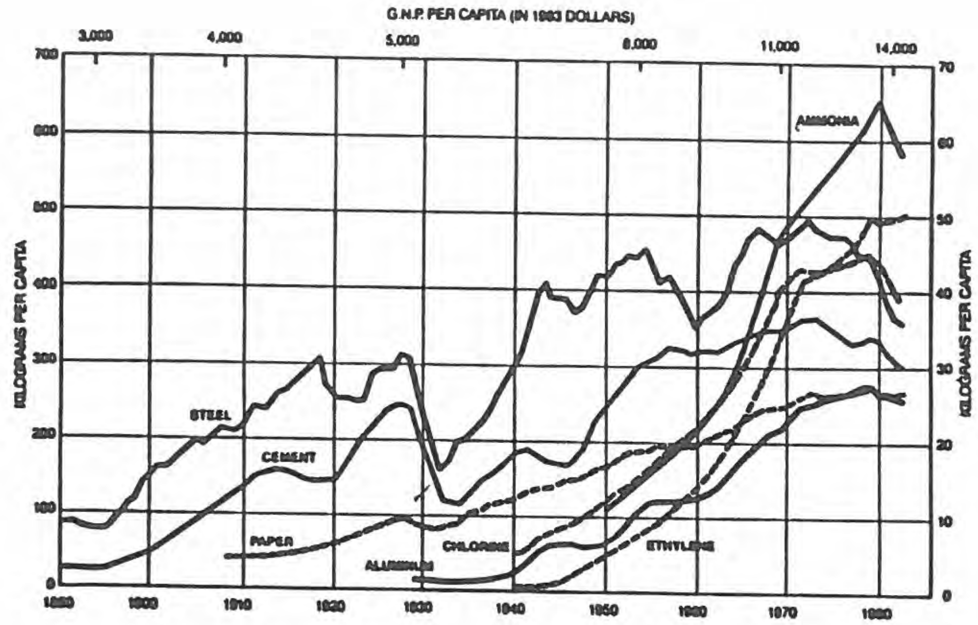

Figure 2-6.A Materials Consumption per Capita, US (Larson *et al.*, 1986).

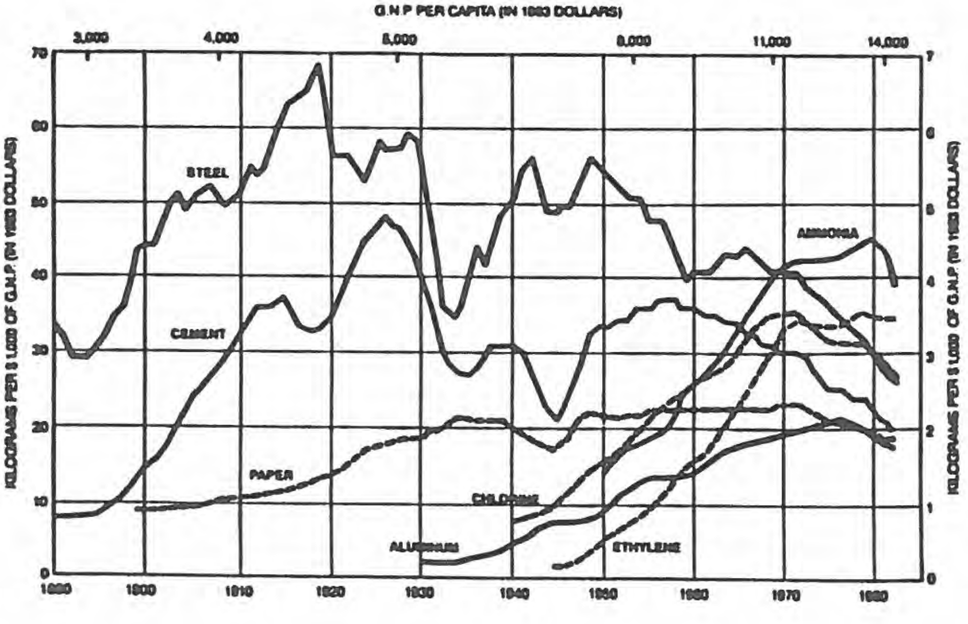

Figure 2-6.B Materials Consumption over GNP, US (Larson *et al.*, 1986).

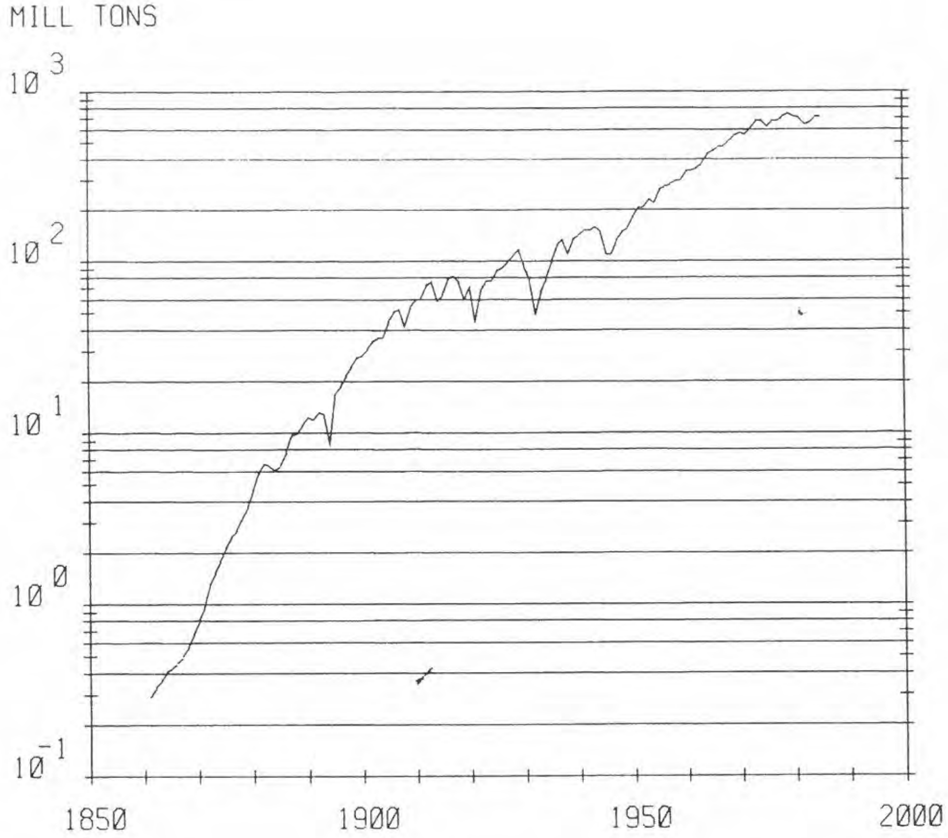

Figure 2-7.A Steel Production, World.

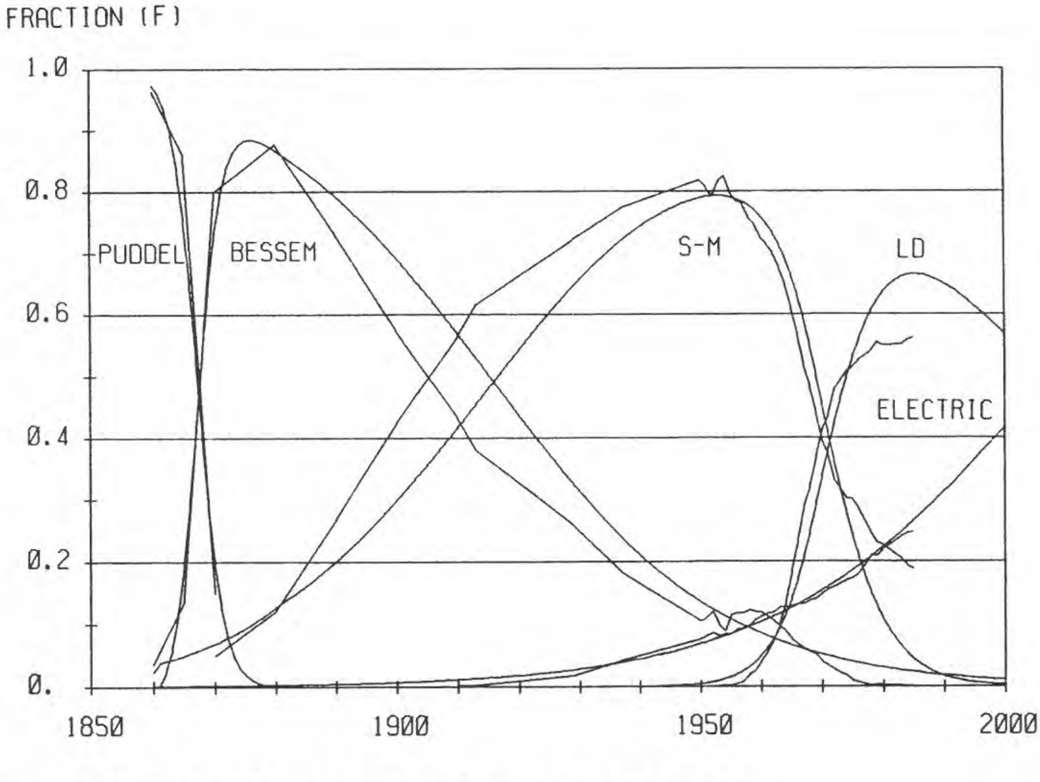

Figure 2-7.B Steel Production by Method, World.

and trade.

Whilst material disintensification appears to be a newly emerging characteristic of the future growth pattern of industrialized countries, it is frequently argued that significant growth in basic materials output will result from 3rd World development. Without denying the importance of the basic materials sector for economic development, it becomes increasingly clear also that developing countries may not repeat in a similar quantitative way the material intensive development trajectory of the post WWII era, as illustrated by the increase of the global crude steel output by over a factor 7 since 1950 alone (see Figure 2-7.A.)

We conjecture, that successful development in the 3rd World will depend more on restructuring along the direction of the emerging information intensive, but material (and energy) extensive growth trajectory of industrialized economies, than a mere repetition of an old, by now progressively vanishing, material intensive development pattern based on shipbuilding, automobile industry, etc. As a result, growth in basic materials output in developing countries may thus be more modest than frequently assumed.

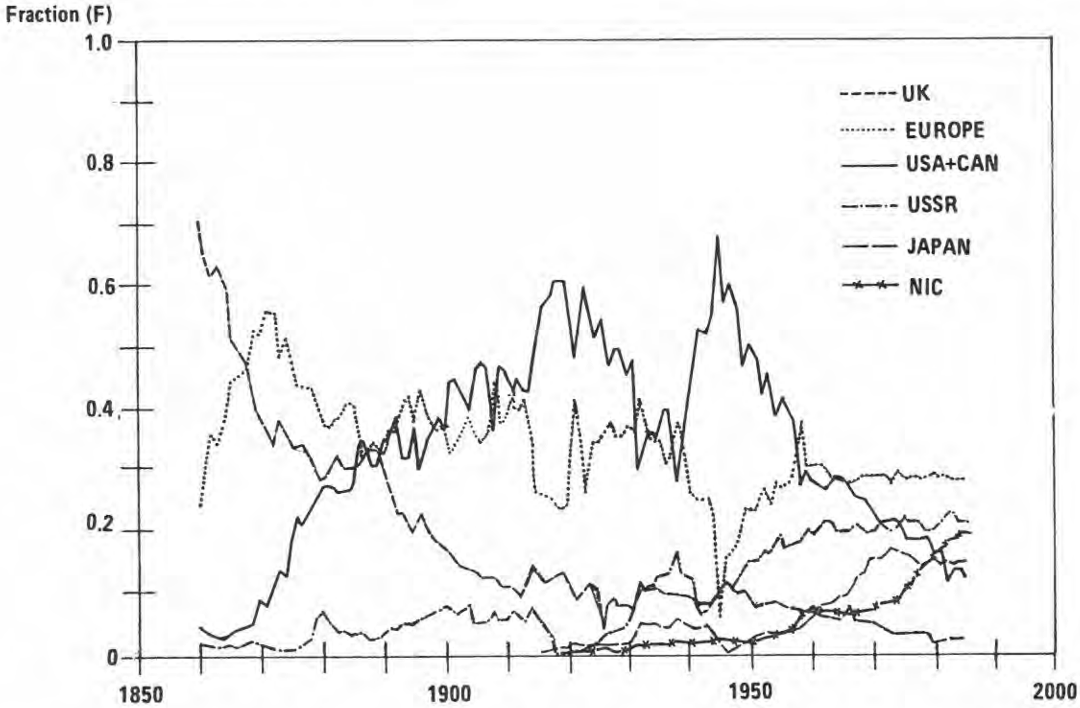

Figure 2-8. Share of Different Regions in World Crude Steel Production (Grübler, 1987)

However, material disintensification will be more pronounced in industrialized countries leading to further relocation of relative market shares and most likely also of absolute production capacities to developing countries. This, however, is far from being historically an unique event, as illustrated in Figure 2-8 for the regional breakdown of raw steel production (Grübler 1987).

Another aspect related to "dematerialization" in industrialized countries is recycling that goes along with the increasing quest to improve environmental compatibility by a closed industrial metabolism. Recycling of scrap metal, paper, glass, even some kinds of plastics as well as the recycling of organic matter (composting) will increase without doubt in future in all industrialized countries as alternatives, such as simple waste disposal and incineration are facing increasing environmental regulation aiming at reducing negative externalities associated with the disposal of wastes of "throw away" societies.

Even in the case of the US, which due to its high per capita waste generation, estimated to exceed 1.5 tons per year per capita, is frequently considered as the worst case of a throw away society, recycling has become already significant. For instance, about 40% of copper consumed in 1987 in the US was produced from recycled scrap. The percentage of recycling for other materials such as iron and steel (46%), nickel (45%) and lead (55%) is already of a similar magnitude. Lower recovery rates are achieved for textiles (17%) and zinc (14%) in the US (Herman *et al.*, 1989). Although paper makes up the greatest fraction of solid waste (30-35 per cent) in the US, it has still a rather low recycling rate. In 1987 approximately 26 percent of paper consumption in the US came from recycled paper, a percentage which has increased however from as low as 15%, typically for the 1960s and early 1970s.

The situation with respect to waste generation and recycling in other OECD countries is generally much more favorable than in the US. Lower per capita waste production, between 250 to 400 kg per capita per year (Tchobanoglons *et al.*, 1977) and higher recycling rates, especially for paper and glass (close to 40% in the FRG; UBA, 1989), put these countries in a more favorable position to restructure further in direction of material disintensification and to progressively close the materials flow cycles of their economies.

The consequences of increasing material disintensification and recycling on energy demand are obvious. Absolute reduction in demand or at best stagnation of basic materials consumption (with the exception of paper demand, which is likely to increase in the future), along with increasing recycling rates will lower both the specific energy consumption per kg produced as well as absolute demand by industry. For instance, the German

Umweltbundesamt (UBA, 1989), estimates that with the current glass recycling rate of about 40% in the FRG about 2.3 MJ/kg on glass production are saved. Technically, the recycling rate could go up to 70 per cent, which would result in further significant reductions in specific energy requirements. Energy savings of up to 20–70 MJ/kg for recycled aluminum as compared to primary production (UBA, 1989) are a further example for the potential for lowering the energy requirements of the primary materials sector that goes along with recycling.

2.1.6. Industry

Major transformations in the manufacturing sector were always accompanied by changing requirements in the supply of energy. The transition from centralized mechanical power based on steam engines, and even earlier from mechanical hydropower (that had to be distributed to individual machines by cables and pulleys) to decentralized electrically powered prime movers, provides a good example. This decentralization of end use was made possible through appropriate transport and distribution grid systems that link centralized power generation with the consumer. This transition resulted in a significant improvement of energy efficiencies and led to a subsequent decline in specific energy demand. Recently similar decentralization of manufacturing processes has resulted in further reductions of specific energy, materials and other factor inputs. The emphasis in manufacturing has shifted from quantity to quality. Furthermore, the intensified competition worldwide caused a number of measures and organizational changes for increasing the efficiency of manufacturing process. Many of them are not revolutionary, but are based on incremental and cumulative improvements of traditional methods through better design, logistics, quality and more flexible and innovative management and organizational structures. Some of the energy savings in manufacturing were also achieved during the last decades through relocation of energy-intensive production to low-wage and some other developing countries. This was due to wage and production cost differentials and partly also more stringent environmental controls in industrialized countries, and to a lesser degree in order to reduce domestic energy requirements.

Many of the new manufacturing processes such as FMS (flexible manufacturing systems) and CIM (computer integrated manufacturing), combined with just-in-time inventories, demand new and high performance transport services, while the environmental compatibility will require low waste resulting in lower energy requirements and more stringent demands on the quality of the energy carriers. Perhaps the most important aspect of these innovations and improvements is the increasing emphasis on quality and economies of scope[2] rather than economies of scale. This has led to stronger up-stream and down-stream linkages in most of the industrial organizations. Competitive sourcing of intermediate products is no longer the best way to assure quality; instead suppliers are now more often partners who work together with the manufacturer. After market (post-production) quality control is also becoming more important in order to enhance reliability and compatibility with other related products, and improve service and maintenance. All of these changes are transforming the nature of the production process. New technologies are increasingly needed for design, production and logistics. This is reflected in the composition of manufacturing investment, which is declining, for traditional equipment such as machinery and vehicles, but is increasing for communication equipment, electronics and office machinery. In the US the share of industrial investment in traditional equipment has declined from about 74 percent twenty years ago to about 55 percent, while the high-technology investment in information and communication technologies and software has increased accordingly (Brooks, 1988). Similar changes have occurred even more rapidly in other industrialized countries (e.g. in the UK, see Soete and Freeman, 1987). This is just one aspect of the overall transformation to more flexibility and economies of scope.

Figure 2-9 illustrates the rapid growth of FMS systems worldwide. Flexible and integrated manufacturing systems allow rapid introduction of new and better products according to market conditions as well as the introduction of new processes that come with growing knowledge and experience (Landau, 1988). Such improvements in both products and processes, that are facilitated by the extensive introduction of flexible systems, are made at an increasingly rapid rate to maintain competitiveness. Thus, industries that rely heavily on computers, flexible automation, effective telecommunication and logistic operations are in a particularly favorable competitive position. During the last decade it has become increasingly clear that the character of the world economy is changing and one of the most pronounced signs is reflected in the industrial restructuring towards higher quality and economies of scope in manufacturing.

With regard to new robotics technologies, in addition to FMS, there is a new potential for disassembly and reassembly with the aim of recovering and recycling valuable waste materials and components. The question here is to explore more fully the economic niche of flexible robotics technologies in the light of changing societal values and new concepts such as "no-waste" manufacturing and "no-waste" societies. This, in turn, could open the

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[2] Economies of scope refer to the increasing economic returns from higher flexibility, variety and quality of production as opposed to increasing economic returns from the production in larger units of one single type of product or commodity (economies of scale).

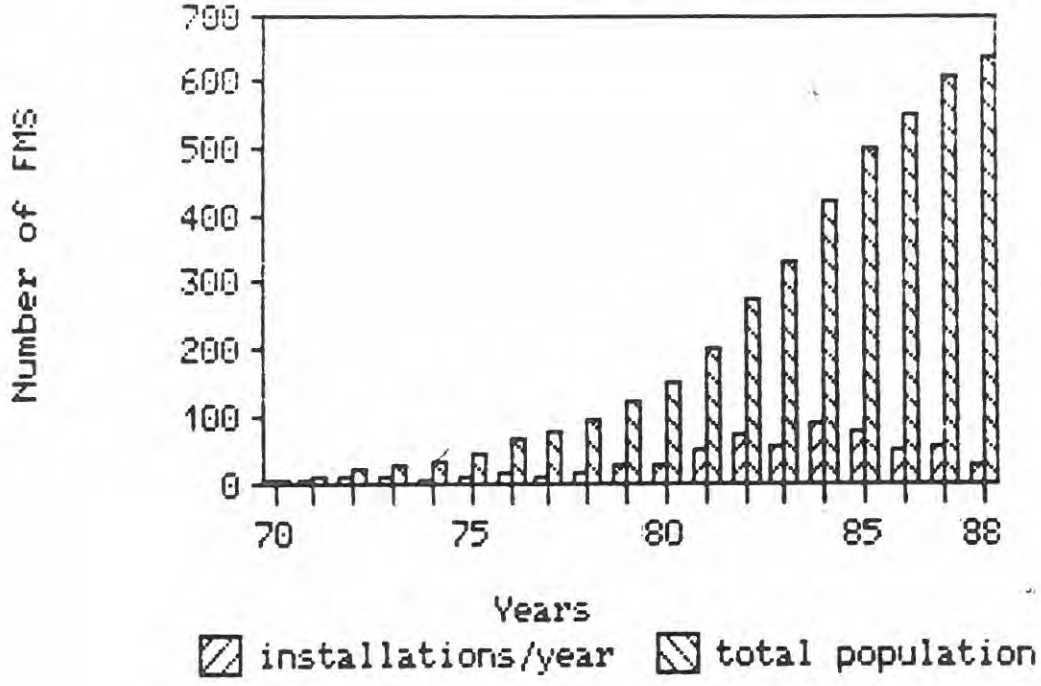

Figure 2-9 Diffusion of FMS Systems, World. (Tchjiov, 1989)

possibility of moving back basic materials industries from the fringe to the industrialized core countries. Such developments, depending on which factor will predominate, will have significant impacts on the level and location of energy demand associated with industrial production.

A large unknown in these developments are the prospects of newly industrialized and developing countries. Similar diffusion of consumer durables and energy intensive services in developing countries, as they have been observed in the industrialized world, may indeed result in a new and large additional demand for products and services, which even with most energy efficient technologies, would still result in increasing energy demand for manufacturing in these countries.

2.1.7. Agriculture

A large portion of the increase in agricultural output, both in terms of person-hours and yield, were achieved through the replacement of work animals and of human labor by machines and large increase in use of

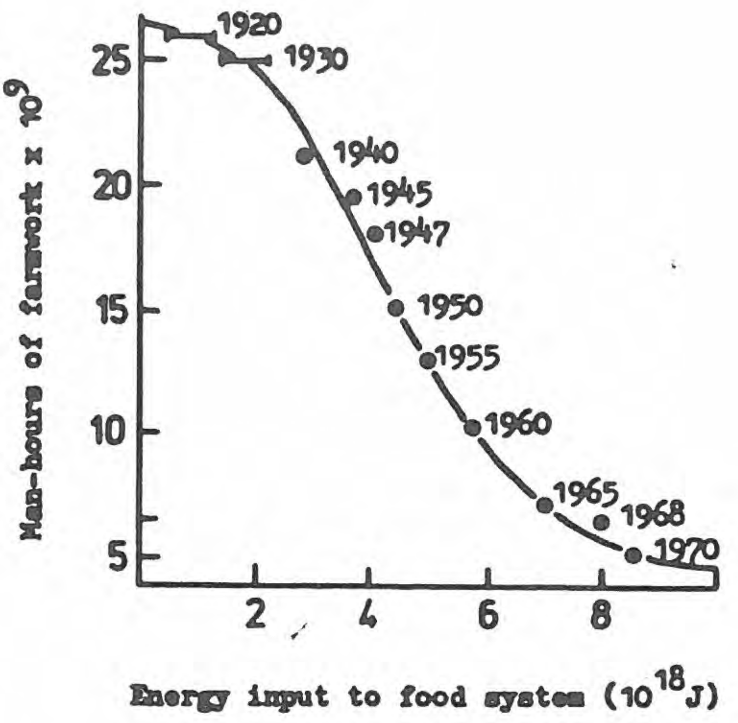

Figure 2-10 Replacement of Man Hours Farmwork by Increasing Energy Intensity in the US 1920–1970.

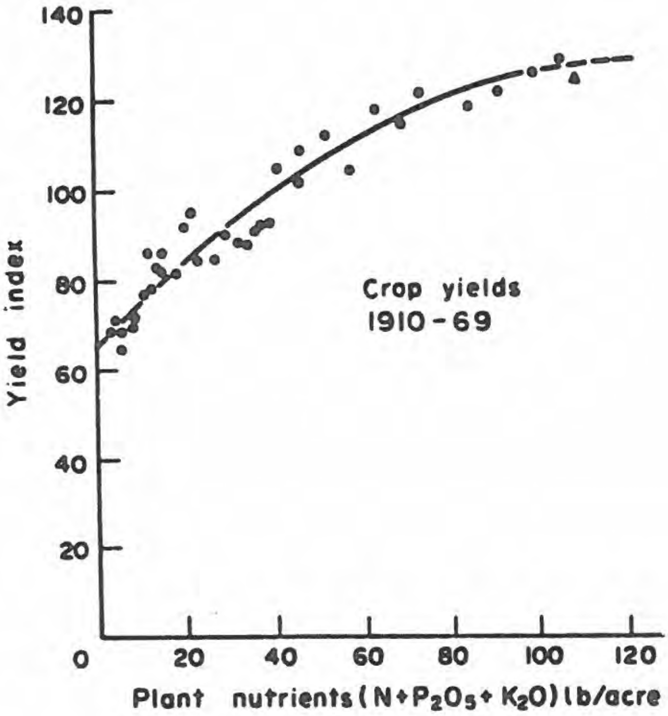

Figure 2-11 Relationship of Plant Yield Increases with Increases of Plant Nutrients (Fertilizers) US 1910–1969.

fertilizers. This replacement process is shown in Figure 2-10. These two developments have led to a high degree of energy intensity of modern agriculture but at the same time to unprecedented levels of agricultural surplus output. The relationship between fertilizer (and also other energy inputs) to increases in crop yields is, however, not linear. With increasing fertilizer inputs, crop yield increases show diminishing returns, in order to finally become insensitive to further increases in fertilizer input. This relationship is illustrated in Figure 2-11 for the evolution of fertilizer input and resulting increases in the crop yield index for the US over the period 1910 to 1970 (Allen, 1977).

A number of studies indicate, as a consequence, that the specific fertilizer and fuel use per hectare has already reached a maximum in most of the industrialized countries and since the agricultural surplus must be reduced, the energy use in agriculture is likely to decrease in the future. This will be enhanced by an increased emphasis on the quality of agricultural products and decreased use of fertilizers, pesticides and large-scale, heavy mechanization. Despite these tendencies, yields are not likely to decrease substantially, due to the development of new bio-engineered crops and pest control.

Thus, some energy disintensification can be expected in the agricultural activities, both due to less emphasis on heavy machinery and overfertilization. The major counter-trend will be the increasing need of greenhouse farming and long-distance transport of high quality and specialty foods. Already today food transport is gaining an important share in the worldwide air cargo volume. Increase of food production in the developing countries may also be based progressively on low energy intensity methods, such as may be possible through further advances in genetics and bioengineering, e.g. direct nitrogen fixation from air. In view of these developments, it appears today rather unlikely that developing countries will experience significant increases in the energy intensity of their agricultural production, notwithstanding increases in energy demand with rising food production and in particular some additional liquid fuel use for agricultural machinery.

2.1.8. Transport

History shows that transport and communication activities enhance each other and have been non-substitutable goods in the past (Nakićenović, 1989). The emergence of the "information society" of tomorrow is in our opinion unlikely to affect the complementarity of transport and communication demands. Transport energy requirements will not be reduced in the future by lowering transport demand but by increased efficiency and better end use management, e.g., traffic controls. A number of studies show (e.g. the transport model developed by Zahavi, 1979), that the modal split and allocation to different means of transportation results in the maximization of travel range, subject to constraints in individuals time budgets, and households disposable income. This basic behavior is reflected in the historical shifts to larger shares of faster means of transportation as a function of economic growth and availability of advanced forms of transportation.

At the level of transportation infrastructures this development is clearly illustrated in the replacement of canals by railroads and later on of railroads by road and air travel. In terms of market shares in both the size of transport infrastructure as well as the productivity in terms of passenger kilometers transported, as shown in Figure 2-12.A, air travel is increasing, while the older means of passenger transport are saturating (road transport) or are apparently declining (railways).

These tendencies appear not affected by differences in market structure and relative transport cost structures as illustrated in Figure 2-12.A in the comparison of the intercity passenger modal split in the US and the USSR. It is shown in Figure 2-12.B that also in the area of freight transport the highest quality products are airfreighted. This is due to the high degree of reliability, flexibility and speed of air transport. Products of high value density of say more than DM 100 per kilogram include a variety of categories ranging from manufactured goods such as electronic components or even some household appliances, foodstuffs and avionics.

All in all, the transport sector will continue to be a large energy consumer, notwithstanding further and necessary efficiency improvements. In terms of energy demand these macro-trends imply continued high energy intensity of transport and further increase the needs for new communication technologies to match this increase in travel demand. The specific energy demands of transport and communication technologies will certainly decline, but the demand for these services is very likely to increase at a higher rate than the energy-efficiency improvements. The bulk of the increase of the fast means of transportation will be in air travel and new ultra-high speed (plus 500 km/hr) Maglev intercity links. This will require electricity for Maglevs and new fuels such as methane and hydrogen for aircraft, that can alleviate some of the current and future environmental concerns. Historically we can observe that a similar environmental driving force was at the origin of the substitution of horses by automobiles. The diffusion of the automobile removed a big environmental burden in the large cities at the beginning of the century – the horse manure from the streets.

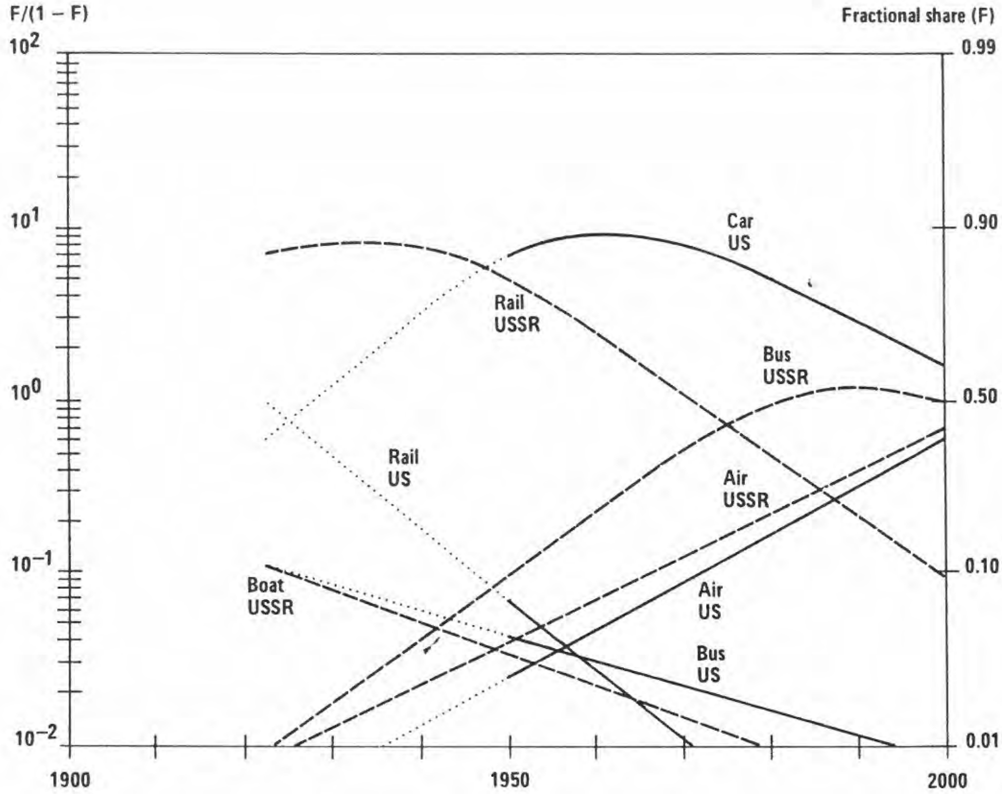

Figure 2-12.A Modal Split in Long-Distance Passenger Travel, US and USSR (Grübler, 1989).

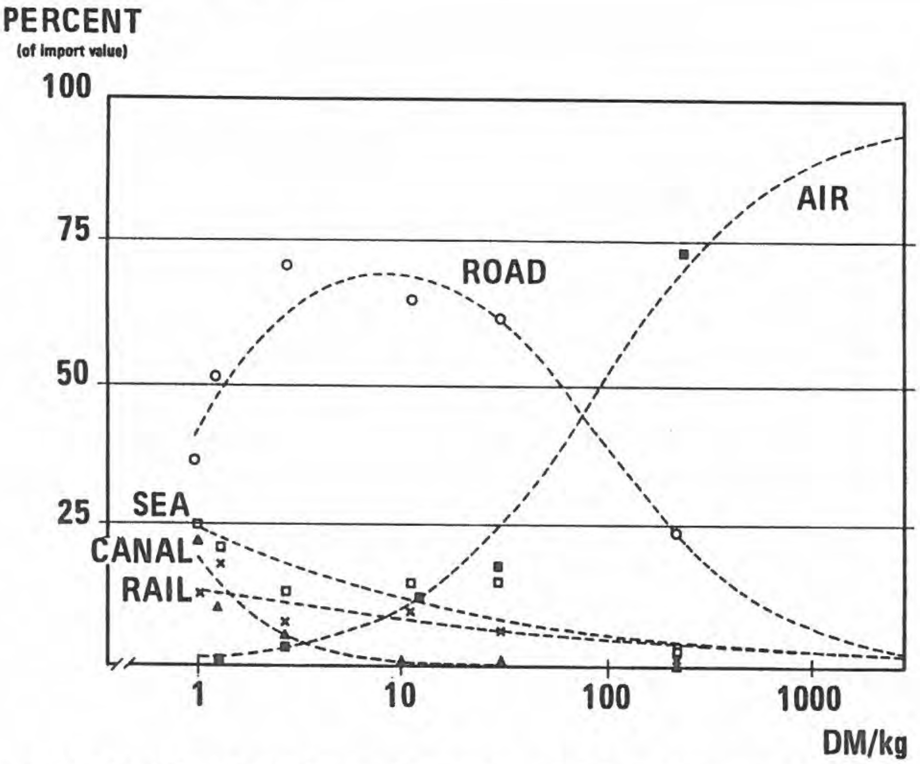

Figure 2-12.B Modal Split in Imports of Manufactured goods According to Value Density of Manufactured Goods, FRG. (Grübler,1989).

2.1.9. End Use and Appliances

Wide dissemination of end-use devices and appliances in industrialized countries was as a result of increasing incomes and higher living standards. The inhomogeneous spatial distribution of the widespread end-use appliance diffusion indicates the potential for further growth in consumer demand for these products in industrialized countries. At the same time higher incomes have resulted in increases in the available floor space per person, a trend which is likely to continue in the future. Technological change and improvements have at the same time resulted in lowering of the specific energy requirements per household appliance.

For every given energy service task there are therefore two basic driving forces that influence the overall demand. There is the replacement of older by new and more efficient technologies that reduces specific and overall energy requirements, and at the same time, there is the diffusion of new applications, or more widespread use of a particular energy service task. Thus, the color television sets are becoming more efficient and require less energy for a particular task, but at the same time, more consumers own the TVs and their performance increases (both factors off-setting to a degree the efficiency improvements). The diffusion, or the increase in ownership rates, is generally easier to assess than the improvements in technical performance in general and that of energy efficiency in particular.[2]

Figure 2-13 shows the diffusion of radio, television (both color and black and white sets) in the United States expressed as percentage of all households owning these particular appliances. It clearly shows that this process is complete in that almost all households already have at least one radio and television set. Thus, in the United States the influence of efficiency improvements on household energy demand could be very large, due to almost complete diffusion; in the future more efficient new generation of radios and TVs will be replacing the older ones. In other countries, however, the diffusion is quite low, so that there will be two simultaneous effects, the replacement of old sets (increasing efficiency) and increases in ownership (expansion in service task) that will lead to higher energy demand.

Figure 2-14 shows that the increase in color television ownership was rather rapid in the FRG, France and Austria since 1973, while the diffusion process was almost complete by the late 1970s in the United States. All of the other three industrialized countries still had lower ownership per household in 1984 than the United States in 1973. Thus, during the next decade we can expect that the diffusion will become also completed, leading to

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[2] Much of the material presented in this section is based on the data given in Euromonitor (1978 and 1988).

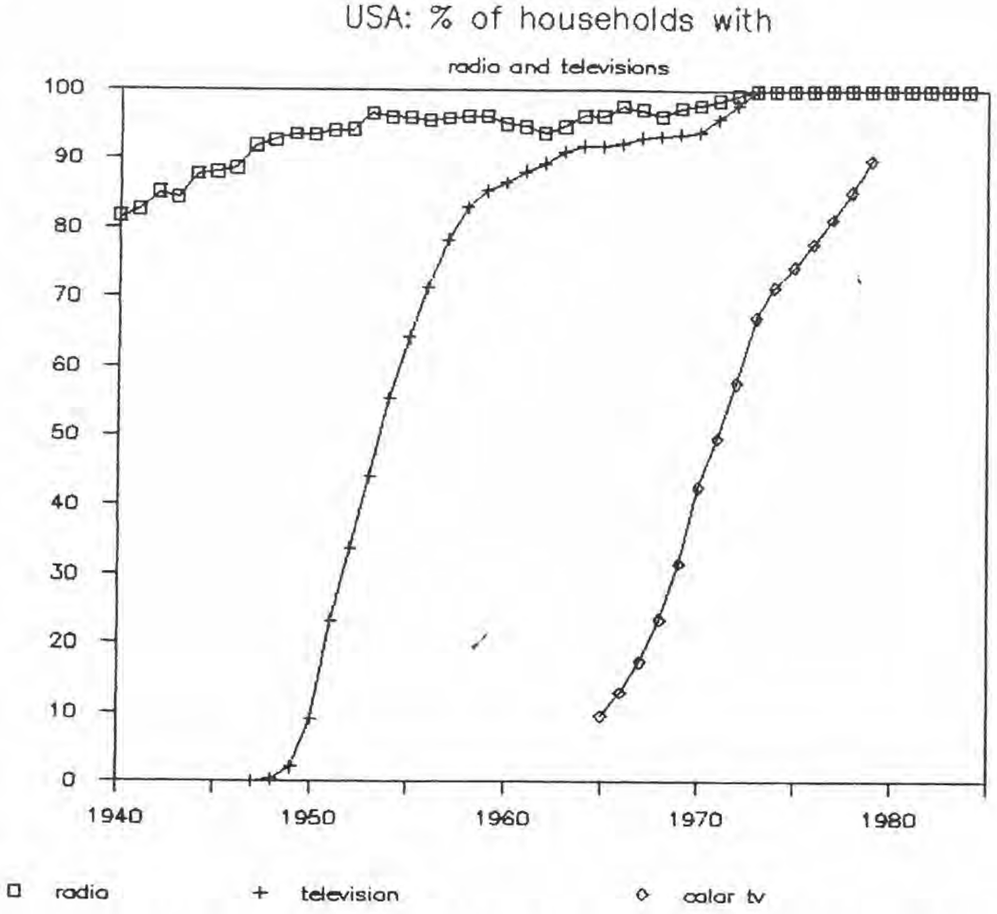

Figure 2-13 Household Ownership of Radio and Television, US.

increases in electricity requirements. We have a similar situation with most of the household appliances. Most of the households in the United States have a dish washer, washing machine, deep freezer and refrigerator, while in many European countries the ownership is still growing. The next four figures show the diffusion of these household devices in FRG, France, Austria and Finland and the following two figures give a more widespread comparison of household ownership of appliances and of TVs in the United States, Japan, the above four European countries and three developing countries: Taiwan, Brazil and India.

Figure 2-15.A shows that the diffusion of the refrigerators is now almost complete in all four European countries. Diffusion of household ownership of refrigerators in Europe has thus followed with a time lag the diffusion patterns in the US. Almost 99 percent of all households own a refrigerator. The situation is different with deep freezers as is shown in Figure 2-15.B. Slightly more than half of the households own a freezer in FRG, Austria and Finland, while in France the numbers are lower with about 30 percent. However, the two diffusion processes are dependent: New refrigerators usually include a freezer compartment, so that the ultimate

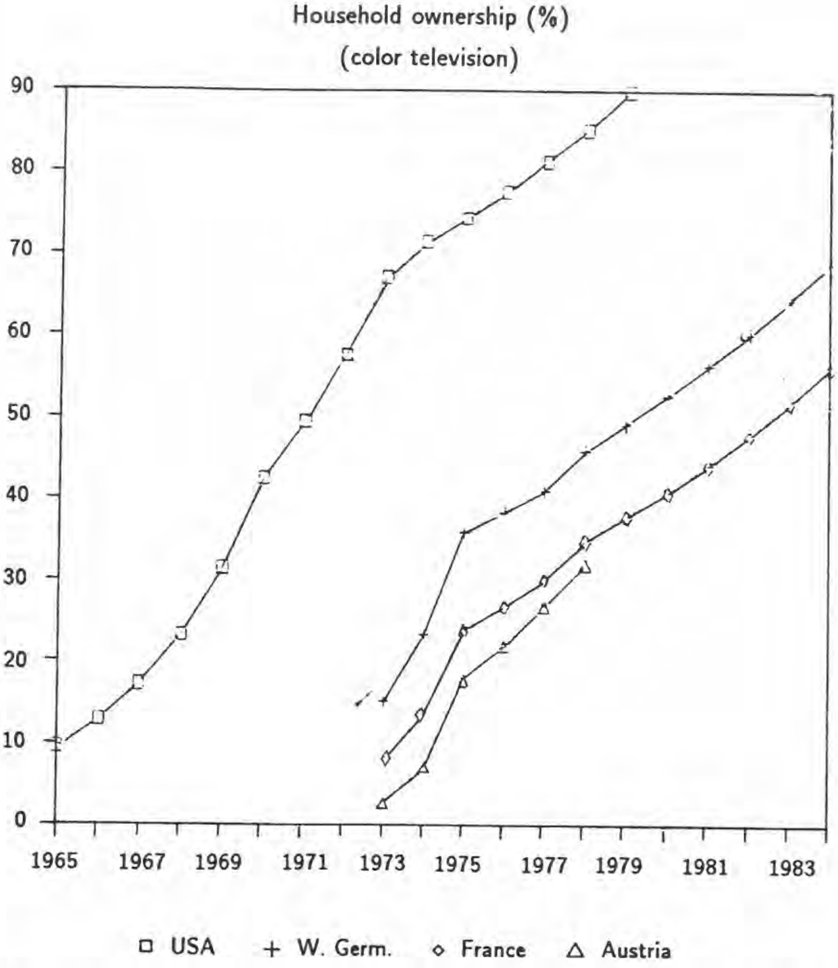

Figure 2-14 Household Ownership of Color Television, Selected Countries.

saturation level for the stand-alone freezers might not be much higher than half of the households. Better knowledge of the ultimate saturation level is important for determining the electricity demand since cooling appliances are one of the largest consumers of electricity. Their specific electricity needs may not be very high, but they are switched-on most of the time. Rosenfeld and Hafemeister (1988) have estimated that 125 million household refrigerators and freezers in operation today in the United States require the electricity from 30 standard (1 GW) power plants. If they were as inefficient as the average 1975 model, they would require 50 power plants. Thus, the refrigerator efficiency improvements achieved since 1975 are equivalent to the output of 20 standard power plants! By the same token the doubling of the number of efficient refrigerators would require as much as 30 new power plants.

Figure 2-15.C shows that almost 90 percent of all households in the four European countries already own a washing machine. This means that efficiency improvements will in any case lead to the reductions of electricity demand since the diffusion process is almost complete, just as in the case of the refrigerators. The situation is quite different with the ownership of dish

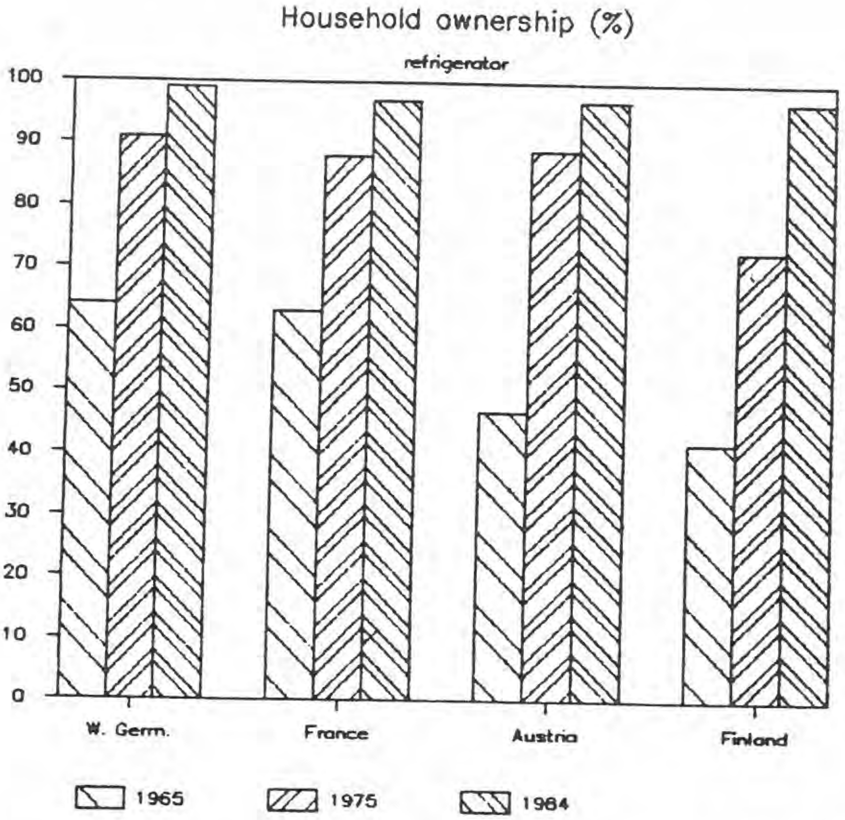

Figure 2-15.A Household Ownership of Refrigerators, Selected Countries.

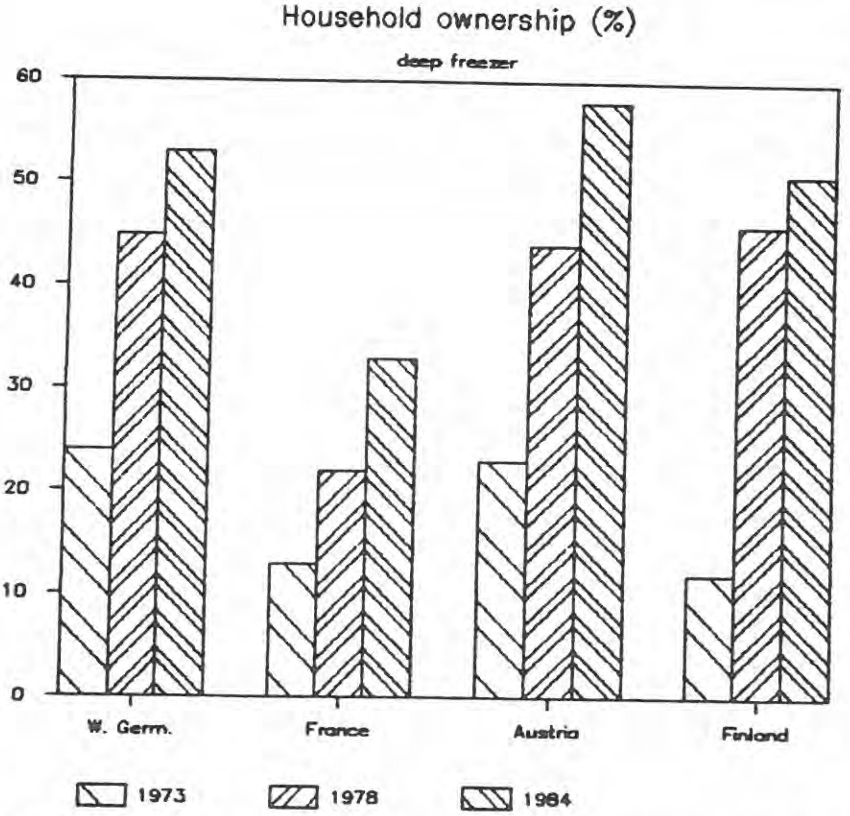

Figure 2-15.B Household Ownership of Deep Freezers, Selected Countries.

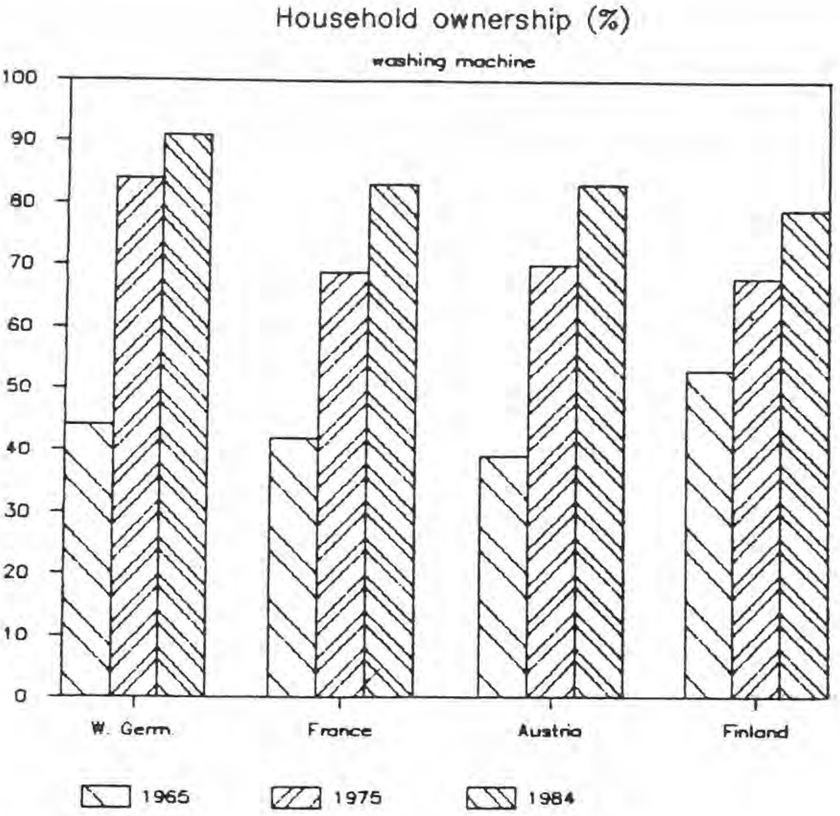

Figure 2-15.C Household Ownership of Washing Machines, Selected Countries.

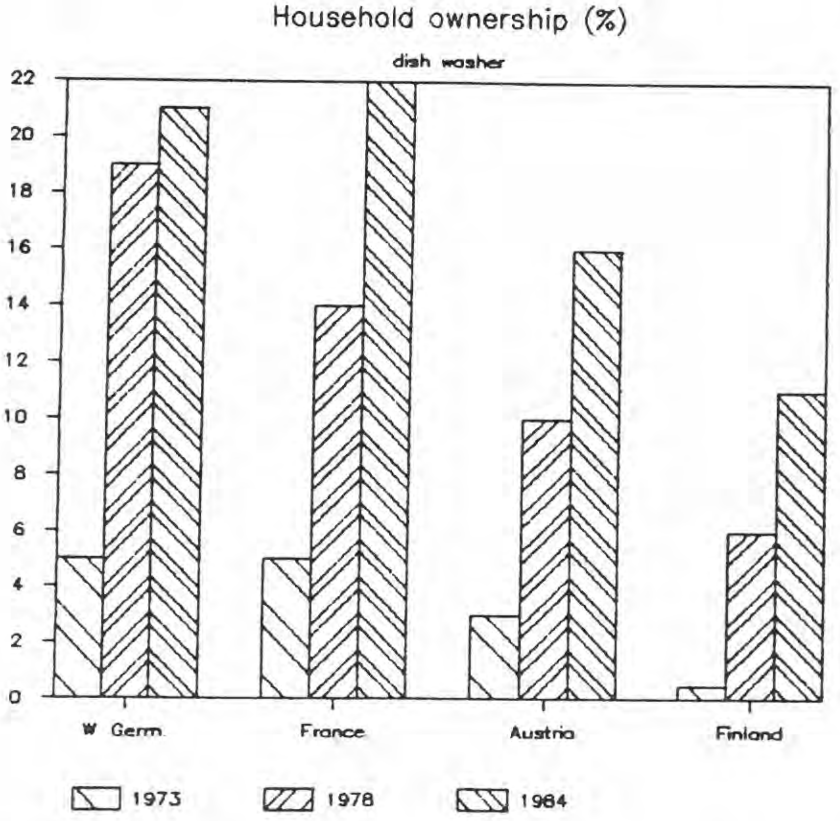

Figure 2-15.D Household Ownership of Dish Washers, Selected Countries.

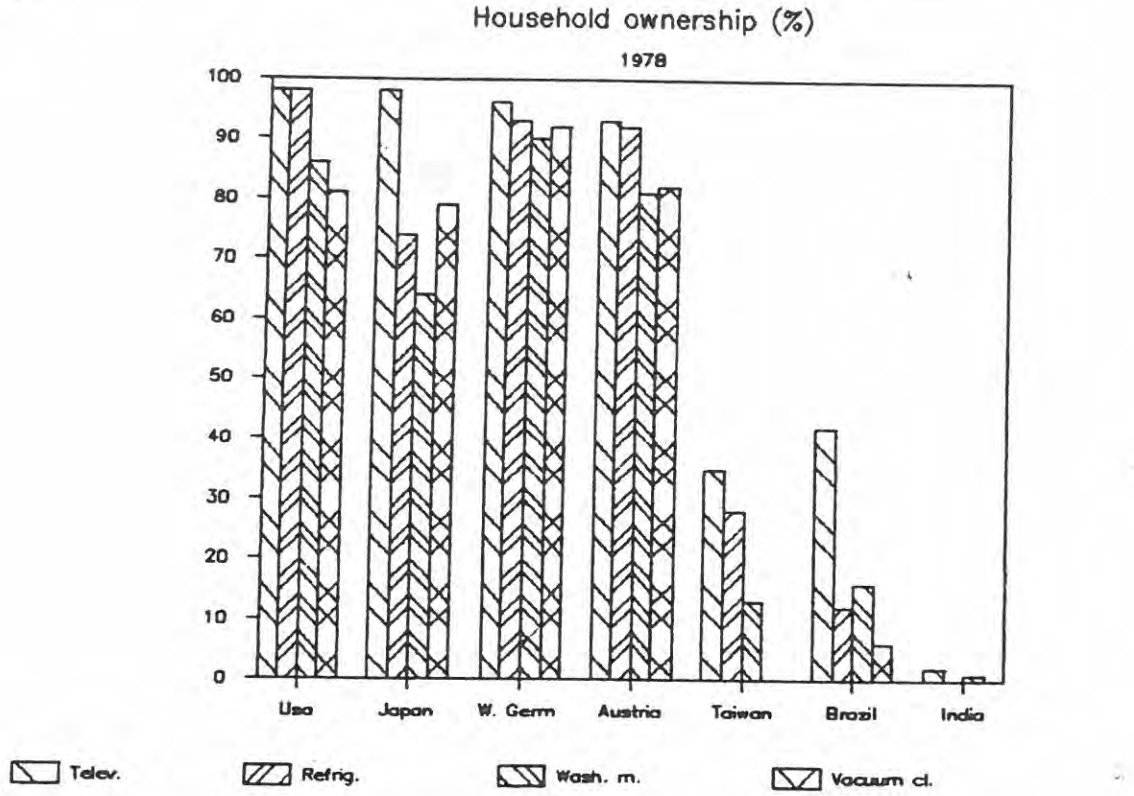

Figure 2-16.A Ownership of Household Appliances in 1978, Selected Countries.

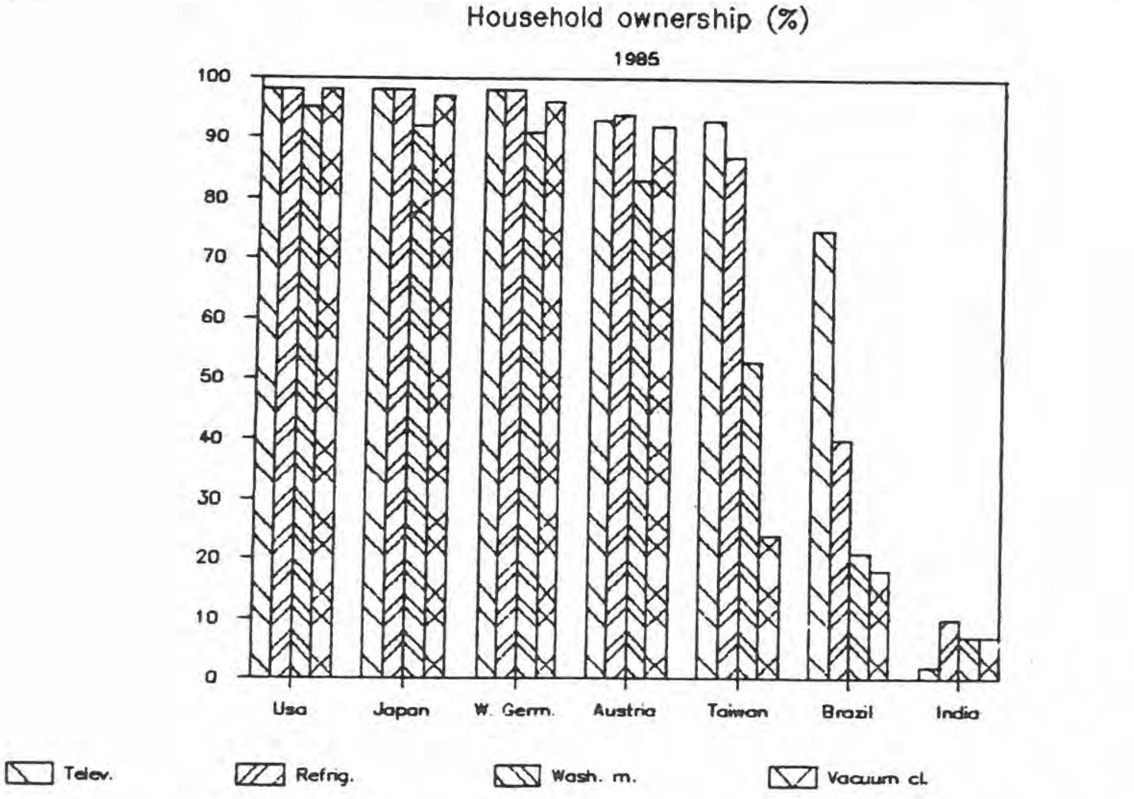

Figure 2-16.B Ownership of Household Appliances in 1985, Selected Countries.

washers as shown in Figure 2-15.D. Less than a quarter of households own a dish washer in FRG and France, while the numbers are even lower in Austria and Finland. Here, efficiency improvements may not necessarily lead to reduction of electricity demand depending on the rate of further diffusion. It is a question of whether the improvement rate of the whole population of dish washers will be quicker than the increase in ownership rates.[3]

The picture changes dramatically if we expand our view beyond the OECD countries as is shown in Figures 2-16.A and B. In 1987 most of the households in the US, Japan, FRG and Austria already possessed television and refrigerator. In the US and Japan less households had a washing machine and a vacuum cleaner than in FRG and Austria. In the three developing countries presented, however, the ownership of all these appliances was very low, with the exception of television in Taiwan and Brazil where about 40 percent of the households had one. By 1985 the diffusion process was complete in all four industrialized countries, almost all households had all four appliances. In Taiwan most of the households owned television and refrigerators, while in Brazil only television ownership increased. This illustrates that electricity demand may increase substantially in the developing countries as the standard of living increases and more households can afford modern appliances. It is very likely that in all of these countries the increases in ownership will be much higher than the efficiency improvements.

2.1.10. Summary

At the end of the chapter describing international developments in the areas of social, technological and economic change let us briefly summarize the main macro trends and their relevance to efficiency improvements.

Energy efficiency will improve in all areas of basic materials production, agriculture, industry, transport and household end-uses. Improvements in energy efficiency will be enhanced by increasing tendencies for dematerialization, recycling and increasing value and information density of production.

At the same time the scale of many activities will increase counterbalancing the demand lowering effects of efficiency improvements. For instance, large advances in house construction and conservation will continue to lower specific space conditioning energy demand. At the same time the available floor space per person will continue to grow, both as a result of increasing incomes, as well as of changing lifestyles, kinship and family

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[3] Main data sources used for this subchapter are: Euromonitor (1978 and 1988).

patterns. Similar increases in ownership rates of household appliances and in comfort and leisure travel will go along with increasing incomes.

Production will shift to more high value and information density and especially more diverse and high quality (custom made) products. This will on one hand reinforce tendencies for dematerialization and lowering energy requirements. At the same time scale and quality requirements (speed, flexibility and security) of the transport requirements of "just-in-time" production regimes will be high, resulting in increases in ton-km transported and shift to higher quality transport modes (e.g. air freight). An additional factor to be taken into account is the fact, that energy costs (and thus efficiency considerations) will represent ever smaller, even negligible, portions of the value added of high value density products. This implies, that rationalizing effects from economic incentives, for instance stemming from higher energy prices, will be less pronounced in future high value density products manufacturing, than was the case for the basic materials dominated industry sector in the post 1973 period.

The biggest unknown in this context is the future evolution in developing countries. Increases in energy demand due to industrialization and raising per capita energy consumption with increasing incomes are likely. At the same time it also becomes apparent, that the energy intensity of development trajectories could be much lower than generally anticipated. Future growth in developing countries may well be more consistent with current restructuring efforts in developed countries to value and information intensive and material and energy extensive production, than on a repetition of a traditional resource intensive, smoke stack industrialization paradigm. Perhaps the most important characteristic of future development in these countries will be the persistence of distinct heterogeneity in development patterns, lifestyles and resulting resource consumption levels. Heterogeneity within developing countries is as large, even larger, than between these countries and the industrialized world. This heterogeneity has become an inherent structural characteristic of developing countries themselves (Nowotny, 1988) and excludes therefore the development of scenarios of strong homogenization of lifestyles and resource consumption levels between an extreme diversity of countries with differing initial conditions, social structures and industrialization paths.

3. CHANGING ENERGY SYSTEMS

3.1. Energy in Historical Perspective

Provision of energy was always an important human activity. Energy played an important role in enhancing human capabilities to control and adapt to the environment. One of the first major achievements was the use of fire to crack the chemical compounds in animal and vegetable foods that were not digestible in their raw state. This increased the food availability enormously. In time also the embodied energy increased in almost all human activities, products and commodities usually enhancing their quality and availability. Traditionally all of the required energy inputs were harnessed from the energy flows in the environment. Although some of the techniques deployed required a high degree of ingenuity, traditional methods for providing energy needs were generally simple, compared with the complexity of contemporary energy systems. For instance, the transformation of hydraulic power into mechanical drives of early energy systems often involved elaborate systems of dams, water wheels and transmission devices.

One of the major discontinuities in the evolution of energy systems occurred with the replacement of energy inputs derived from natural energy flows by fossil energy. The advent of coal and steam revolutionized the patterns of energy use and the technological and institutional structure of the energy system. The harvesting of natural energy flows was mostly user oriented and generated close to the point of use. The fossil energy production, transport and conversion evolved as a commercial activity along with manufacturing.

In this chapter we will briefly discuss this evolutionary development of the energy system and then document the current global patterns of energy production, consumption and trade; together with an overview of the structure of energy systems on the international level. In the next chapter, we will then deal, in greater detail, with changes in the efficiency of energy supply and consumption.

3.1.1. Energy Flows in the Environment

There are three main flows of energy in the environment: solar radiation captured by the earth, geothermal energy from nuclear fission, frictional and gravitational thermal heating deep within the earth, and planetary motion of the earth in the solar system.

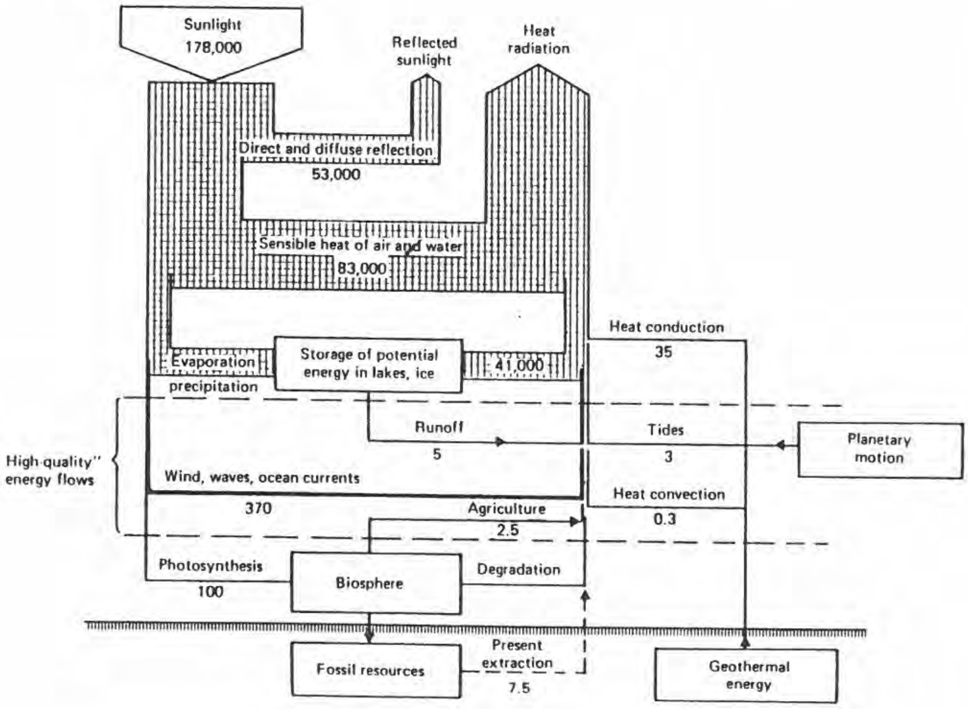

Figure 3-1 Natural Flows of Energy in the Environment, in TWyr/yr (Häfele *et al.*, 1981).

Figure 3-1 shows the flow of energy to and from the earth. The width of the bands and lines suggests the relative importance of each item to the earth's energy budget, but the numerical quantities and widths shown are only representative estimates. Therefore, only the orders of magnitude should be observed and not the significance of individual numbers.

The dominating inflow of power is the sunlight intercepted by the upper layers of the atmosphere. It contributes more than 99 percent of all natural energy flows on earth. The extraterrestrial power density of the sun in the vicinity of the earth is 1.35 kW/m^2 on a plane perpendicular to the direction of the sun. This results in the total energy flow of solar radiation intersected by the earth of 178,000 TWyr/yr.[1] About 30 percent of the solar

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[1] The energy flows are given in TWyr/yr (or 10^{12} Watt-years per year), equivalent to average power over one year in contrast to peak power usually given without the time units (i.e. in Watts, a typical example would be the

radiation is scattered on its way through the atmosphere and leaves the earth directly (short-wave radiation), and the other 70 percent are absorbed, but eventually the absorbed energy is re-radiated in the form of infrared (long-wave or heat) radiation back into the space (Häfele, *et al.*, 1981). By comparison the current global commercial energy consumption is in the order of about 10 TWyr/yr.

The geothermal energy results in a comparatively small power flow in upper layers of the earth's crust of about 35 TWyr/yr. Most of this energy is transferred to the atmosphere and the oceans through conduction, and only about one percent is released through volcanos, hot springs, deep ocean vents and other convection mechanisms. The planetary motion is the third and the smallest source of energy flows abounding to about 3 TWyr/yr which are primarily dissipated through the tidal mechanisms in the oceans. Thus, the sunlight is overwhelmingly the largest source of terrestrial energy flows.

The natural energy flows generated by these three sources at the surface of the earth are much smaller. The continental water runoff dissipates potential energy into heat through friction at the rate of about 5 TWyr/yr. Winds, waves and the kinetic energy of ocean currents dissipate about 370 TWyr/yr; the major share is due to high altitude winds in the upper layers of the atmosphere.

Only a relatively small fraction of these natural energy flows are used to support the biosphere and life on earth. For example, the net conversion rate of solar radiation to biomass is in the order of 100 TWyr/yr. By comparison only a small percent of this energy flow is taken by sylviculture and agriculture and other human activities (Bolin, 1979). This indicates that only a few natural power flows within the human traditional environment (i.e. the boundary between the atmosphere, land and the oceans in more temperate zones) are suitable for exploitation at a more significant level compared to the current global energy consumption from commercial sources of about 10 TWyr/yr.

During millenia, dating back to the dawn of human civilization, the main sources of power and heat were derived from the natural energy flows in the environment, but the energy available was not abundant and required techniques to harness it from indirect sources such as various forms of biomass, including wood and dung, and human and animal muscle power. Other natural energy flows were also exploited although at much lower rates. Typical uses included sailing vessels, river flotation, water and wind mills. In a wider sense, solar energy was also used, although not directly,

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power rating of an automobile engine or a power plant). One TWyr/yr is approximately equivalent to the energy content of one billion (10^9) tons hard coal.

but in transformed forms such as dried food, animal and plant products and other artifacts. When compared with contemporary energy consumption all of these traditional energy forms were used at low absolute levels of exploitation and low densities of generation and end-use with small need for transportation or transformation. This practice did not only prevail over thousands of years, but it was also basically similar even in different cultural settings. Major variations in energy use depended on geographical, climatic and spatial conditions. These variations were essentially related to differential abundances of natural energy flows and to a lesser degree on the techniques developed to harness them. Different geographic and climatic environments imposed different energy use patterns.

Geographical and climatic conditions were thus crucial in determining the extent to which natural energy flows could be harnessed. In fact, the early exploitation of other natural resources such as ores, and most of the manufacturing processes that required inanimate power sources, depended on the availability of mechanical water and in some locations also wind power. The basic constraint to energy supply from natural flows was the relatively low density of energy and relatively low levels of power that could be derived from these sources.

Figure 3-2 contrasts the energy densities of natural power flows with those of a few contemporary energy sources. These figures are rough estimates which are given in order to compare the relative orders of magnitudes. The energy densities are expressed in Watts (W) per m^2 and are given on a logarithmic scale. Figure 3-2 shows that a typical value of solar insolation is about 100 W per m^2. However, only a fraction of this value can be exploited even with modern solar conversion facilities. More traditional uses of solar insulation were based on much lower conversion efficiencies. Typical figures relate to the use of biomass as a source of energy. Figure 3-2 shows that the representative density of net carbon fixation in forests (e.g. firewood) is less than one Watt per m^2. Most of the contemporary energy conversion technologies based on energy flows in nature, such as direct solar heating in Austria, already achieve energy densities which are an order of magnitude larger than what could be achieved by harvesting firewood. In comparison, typical energy consumption densities in urban and industrial centers today range in the order of a few to 10 kWyr/yr per m^2, i.e. up to two orders of magnitude larger than the typical solar insolation in mid latitudes. It should be mentioned here that these consumption densities refer to primary energy inputs per unit area. At current efficiencies in providing energy services, it would be difficult to provide such energy use densities from renewable sources. Major efficiency improvements would be required to make natural energy flows into suitable sources of energy for the spatial density of energy consumption in industrialized countries.

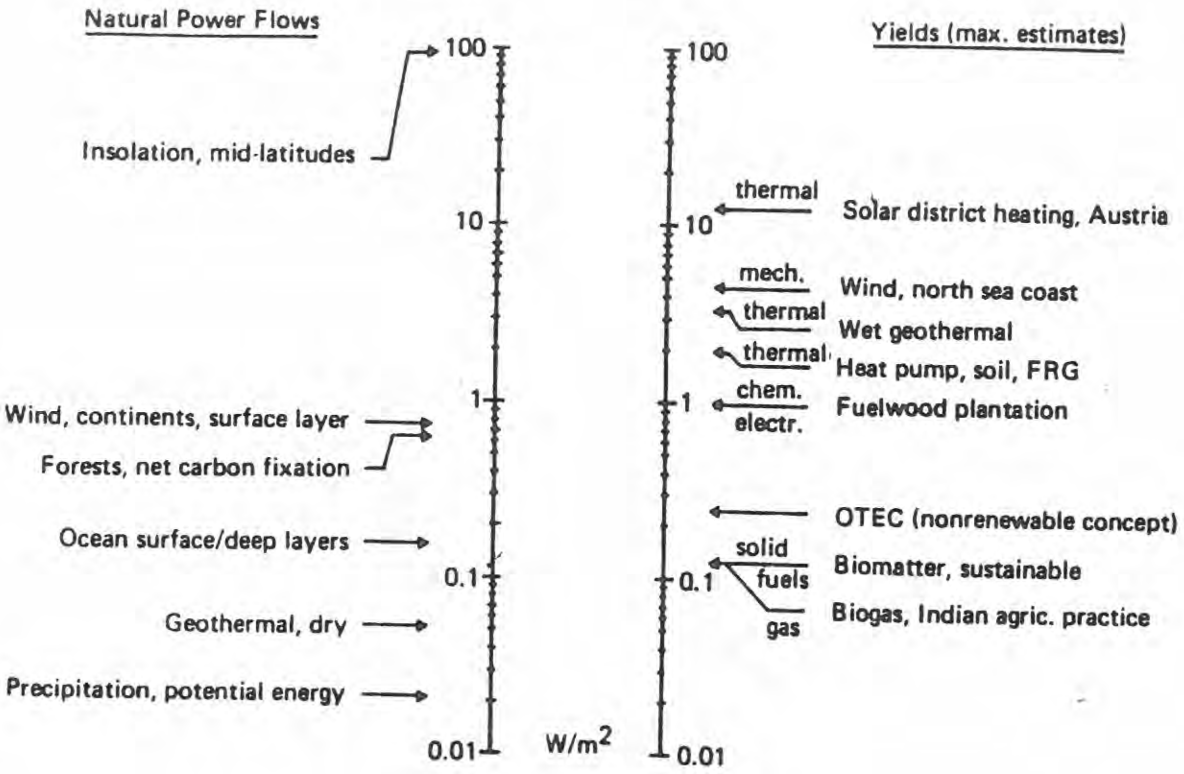

Figure 3-2 Energy Densities (Häfele, *et al.*, 1981).

This indicates how low the traditional possibilities were in converting natural energy flows into useful energy forms such as fuels, mechanical power, heat and lighting. It is the advent of exploitable high density fossil energy sources along with the development of new energy production, conversion, transport and end-use technologies that not only made large increases in energy consumption and end-use efficiencies possible, but also increased the power densities and quality of useful energy carriers.

3.1.2. Evolution of Global Energy System

With the emergence of manufacturing, industrial production, and the rapid social and technological changes over the past two centuries, the energy use patterns have changed along with improvements in energy generation technologies and energy consumption densities. At the same time total energy consumption and energy availability for an individual has increased dramatically. In contrast to the pre-industrial uses of energy that were derived from natural energy flows and animate power, the advent of commercial energy activities, initially related to coal mining and transport to consumption centers, enabled large increases in energy availability and consumption. However, the reliance on traditional sources of energy prevailed until the middle of the last century and continues even at present in many developing countries. During the last hundred years the global primary energy use increased at exponential rates.

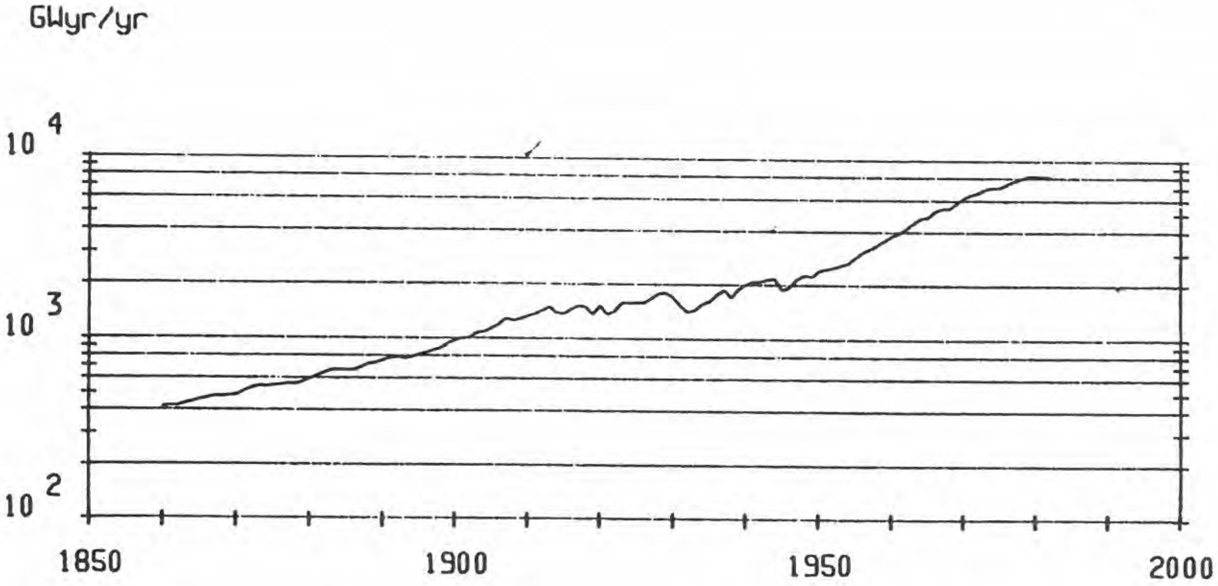

Figure 3-3 Primary Energy Consumption, World.

Figure 3-3 shows the global primary energy consumption including fuelwood (but excluding other non-commercial energy forms), fossil energy sources, and during the last decades also nuclear energy in the world since 1860. Data is plotted on a semilogarithmic scale and shows the exponential growth phases in consumption by piecewise linear trends with an average growth rate of 2.5 percent per year. The total energy consumption increased from about 400 GWyr/yr in 1860 to about 10,000 GWyr/yr today.[2] Yet during this period energy consumption did not draw equally from all sources, nor did the use of all energy sources increase proportionally.

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[2] 1000 GWyr/yr equal one TWyr/yr or 10^9 Watt-years per year and correspond to about 10^9 tons hard coal equivalent (tce).

At the beginning of the nineteenth century, fuelwood, agricultural wastes, dung, mechanical wind and water power supplied most of the inanimate energy in addition to animal and human muscle power and some uses of animal products as sources of energy (e.g. whale oil for lighting). Fuelwood represented most of the commercial primary energy inputs during the last century.

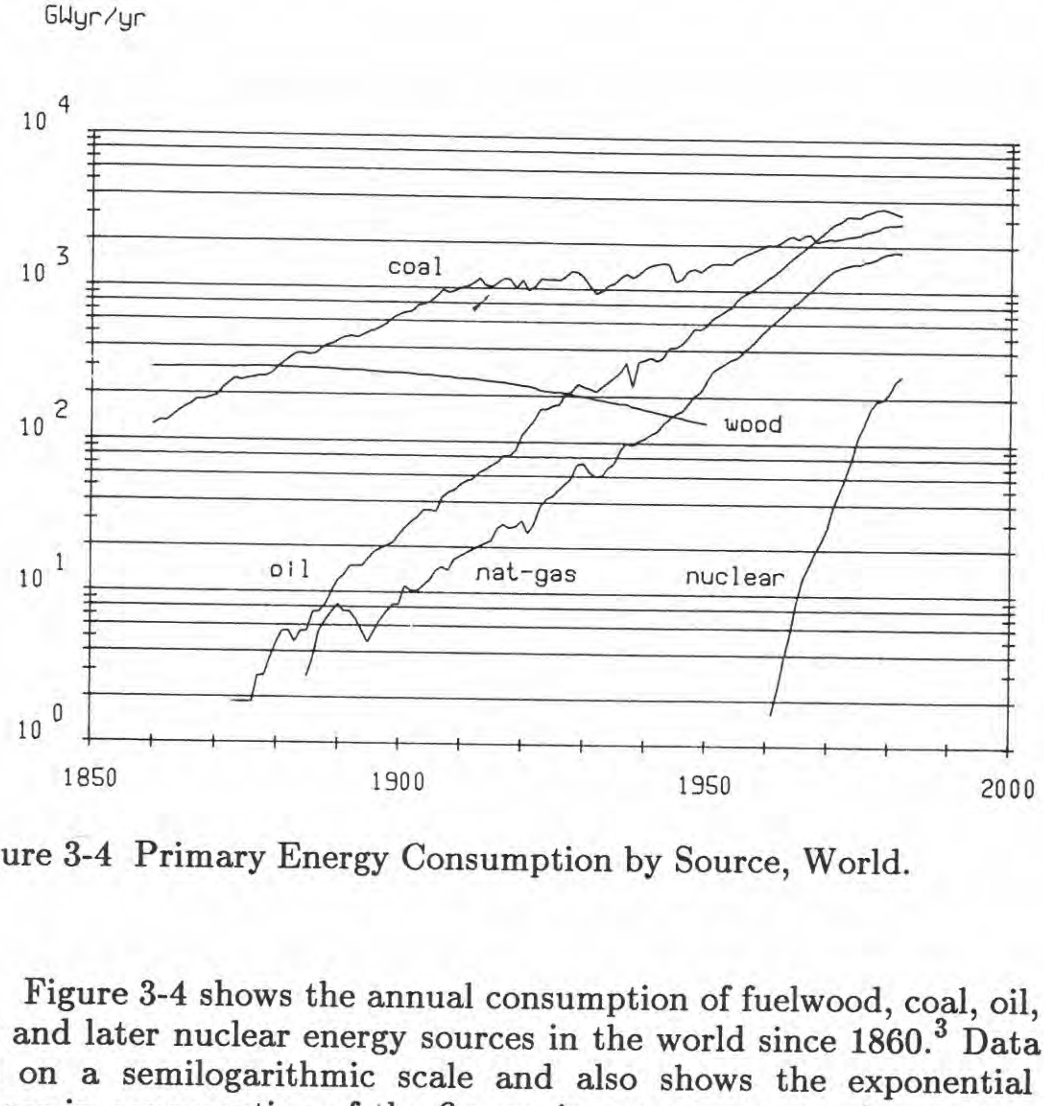

Figure 3-4 Primary Energy Consumption by Source, World.

Figure 3-4 shows the annual consumption of fuelwood, coal, oil, natural gas and later nuclear energy sources in the world since 1860.[3] Data is plotted on a semilogarithmic scale and also shows the exponential growth phases in consumption of the five major energy sources by piecewise linear trends. It is evident, from the curves, that the initial growth in the use of every energy source, except fuelwood, is exponential (i.e., the secular trend is linear on the logarithmic scale).

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[3] Unfortunately, it is not possible to reconstruct the historical consumption levels of natural energy flows at the global level. Instead, we will briefly document the evolution of energy consumption and economic development in the next chapter where we will illustrate, in greater depth, especially the British and American experience in the historical perspective and in the case of the US will also present estimates of non-commercial energy consumption back to the year 1800.

The global consumption of fuelwood, once the most important commercial source of energy, has decreased since the beginning of the century, although it is still used extensively in the developing world. Along with the decreasing importance of fuelwood, the exploitation of other natural energy flows also declined (except for the increases in hydropower) and was replaced by commercial energy production. The traditional energy sources are now contributing a small fraction of total energy consumption. Their contribution is estimated at present to amount for little more than 1 TWyr/yr. First, fuelwood was converted to charcoal in order to achieve higher energy densities and quality of fuels and later coal was mined and used directly to replace charcoal. This, however, required the development of new energy conversion and end-use devices. In the next chapter we will deal, in greater detail, with the structural changes in energy consumption and improvements of energy system. Here, we will only briefly describe the developments on the global level and then discuss international trends and changes in the energy system.

With the expansion of railroads, development of city gas infrastructure and the steel industry, as well as the application of steam in general, the use of coal increased exponentially until the 1910s when a new, less rapid growth phase started. During the time when coal held the largest share of the market, its consumption was subject to great fluctuations that coincided with the two world wars and the intervening period of worldwide economic depression. Since their introduction in the 1870s, oil and natural gas have been consumed at even more rapid rates. In 1965, oil surpassed coal, and natural gas may close the gap in a few years. In fact, oil and natural gas in Figure 3-4 have the same slope and thus almost identical growth rates; they are shifted in time by about 15 years. The increased use of oil and natural gas paralleled the growth of the petrochemical industries and the expanded use of internal combustion prime movers. Because nuclear energy is still in its early phase of development, the steep growth of the last decades may not indicate the possibility of a continuation of its rapid expansion in the future. During the last few years, the growth of nuclear energy has declined worldwide to more moderate rates, still growing in some countries, and stagnating in others.

Figure 3-5 gives the fractional shares of each primary energy source in the total consumption and indicates that the changes in the structure of the primary energy consumption are rather inhomogeneous. It is evident that the older forms of energy have been replaced by the newer ones. In terms of fractional market shares, fuelwood was already substituted by coal during the last half of the nineteenth century. In 1860, fuelwood supplied about 70 percent of consumed energy, but by the 1900s its share had dwindled to little more than 20 percent. Due to the insignificant use of crude oil and natural gas during the last century, most of the market losses incurred by

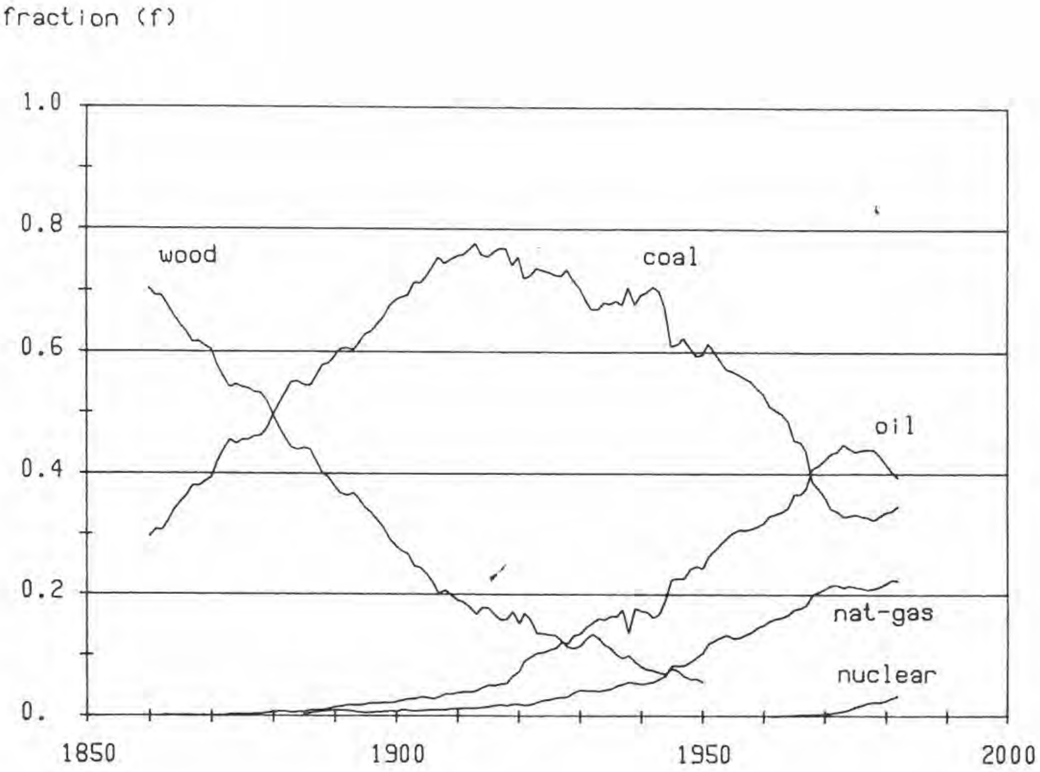


Figure 3-5 Shares of Primary Energy Sources in Consumption, World.

fuelwood were taken by coal. Consequently, the share of coal in total energy supply increased from 30 percent in 1860 to almost 80 percent by the 1900s. By 1910 the rapid increase in coal use ceased, and during the 1920s a phase of decline set in. This decline in the relative share of coal use resembles the market losses of fuelwood fifty years earlier. The replication of this pattern is almost symmetrical because after the 1920s both fuelwood and coal are substituted by still newer sources of energy - crude oil and natural gas. The market share of coal saturated during the 1920s, and oil could have reached its historically highest shares in primary energy during the 1980s. The growth phase up until the 1920s is characterized by the expansion of *coal use*, railroads, and the iron and steel industries, while the next growth pulse corresponds to the expansion of *oil*, the petrochemical industry, the internal combustion engine and road transport.

These two growth pulses can be seen more explicitly at the aggregate level of per capita energy consumption. Figure 3-6 shows the per capita global primary energy consumption divided into two growth pulses. The first one was initiated with the rapid expansion in coal consumption after the 1860s and ends during the Two World Wars, by which time coal's market

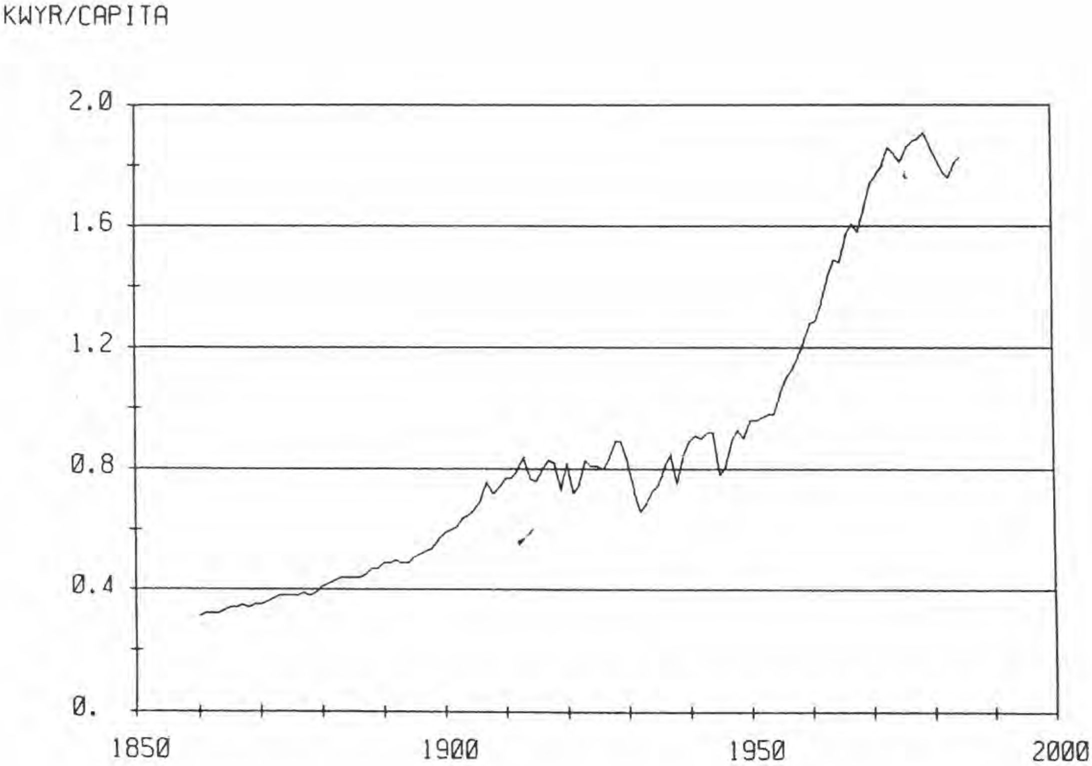


Figure 3-6 Per Capita Energy Consumption, World.

share curved into a phase of decline (see the shares of primary energy sources in global consumption in Figure 3-5 above). The second pulse is initiated with the onset of coal saturation and the beginning of the oil expansion phase (oil surpassed fuelwood in 1925) and accelerated after both fuelwood and coal were in decline. This second growth pulse is apparently nearing completion as the share of the oil market in primary energy reaches saturation. Fluctuations are strong toward the saturation of the previous pulse and at the beginning of the new one. Using this analogy, the current slow-down in the increase of per capita energy consumption worldwide, and the associated fluctuations could be indicative of a possible beginning of a new growth phase. Should it take place it would most certainly be characterized by increased energy consumption in the developing countries. It is very unlikely that the industrialized parts of the world would require higher per capita energy consumption, given their relatively high current levels.

Table 3-1 summarizes the pertinent trends in the growth of population and energy use. It gives the indices of increase and absolute levels of global population, per capita energy use and total energy consumption. It shows that the per capita energy consumption increased faster than the population

Table 3-1 Population and Energy Growth, World.

	Population		Energy per capita		Energy total	
	Index[1]	Billion	Index[1]	kWyr/yr	Index[1]	TWyr/yr
1800	73	1.0				
1860	100	1.3	100	0.3	100	0.4
1900	123	1.6	189	0.6	234	1.0
1960	225	3.0	406	1.3	915	3.8
1970	270	3.6	552	1.7	1492	6.2
1985	363	4.8	579	1.8	2170	8.8
1800-1985 %/yr	0.9	0.9	–	–	–	–
1860-1985 %/yr	1.0	1.0	1.4	1.4	2.5	2.5
1970-1985 %/yr	2.0	2.0	0.3	0.3	2.3	2.3

[1] Index is 100 percent in 1860.

during the last hundred years, demonstrating that the total energy consumption increased more due to the growth of average individual energy use rather than due to the population growth. Population increased by a factor of 3.6 since 1860 while per capita energy use increased almost twice as much with a factor of 5.8. This is also illustrated by the average annual growth rates; population increase at about one percent per year while the individual energy use increased at about 1.4 percent per year. This resulted in an average global (commercial) energy consumption increase of about 2.5 percent per year. During the last ten years, however, there has been a slight trend reversal. Average per capita energy consumption growth rates decreased to about 0.3 percent/year compared to 1.4 percent over the whole period 1860-1985, while the population growth rate increased from an average of one percent per year between 1860 and 1970 to about two percent per year since 1970.

These developments refer to commercial energy supply including fuelwood. The general development trend during the greater part of this century would not change much with the inclusion of non-commercial use of natural energy flows in the environment. However, in earlier periods, especially before the Industrial Revolution, these energy sources together with fuelwood provided essentially all energy needs.

The natural energy flows contribute only marginal shares to total energy consumption today. Even hydropower never exceeded the two percent share in global primary energy consumption it reached in 1955. The importance of hydropower would slightly increase to about a six-percent share provided that its contribution is converted to primary energy equivalent, i.e., in terms of the fossil energy needed to generate the same amount of electricity. The consumption of other renewable and non-commercial sources of energy is generally not included in historical energy statistics, due to the lack of reliable data. They constitute however, even today, a large share in energy consumption of the developing countries. For instance, dung is not included in the statistics presented so far, because of the lack of reliable consumption estimates, although its share in primary energy consumption was considerable in the past. Putnam (1953) suggested that dung, as a fuel source, has had a fairly constant 16 percent share since the 1860s in the global primary energy balance. This is only a rough estimate, the actual consumption of dung and other agricultural wastes was probably much higher during the last century and may be even higher than ten percent of all commercial energy today. Even the fuelwood consumption time series cast some doubt on their accuracy due to the lack of any fluctuations present in the use of all other primary energy sources. In fact, some sources indicate that the fuelwood consumption increased worldwide during the last decades. It has to be noted however, that much of this alleged increase is unlikely to be based on sustainable exploitation.

Table 3-2 Primary Energy Consumption in 1987, World.

	TWyr/yr	Percent
Crude oil	4.2	37
Coal	3.4	30
Natural gas	2.2	20
Hydro[1]	0.3	2
Nuclear[1]	0.2	2
Commercial energy, total	10.3	90
Non-commercial energy, approx.	1.1	10
Total energy supply	11.4	100

[1] Considering the equivalent to thermal primary energy for conventional power plants, hydro and nuclear would account for 0.7 and 0.6 TWyr/yr respectively.

Table 3-2 shows the world primary energy consumption by energy source in 1987. It also gives a rough estimate of global energy from natural energy flows or so-called non-commercial sources that include fuelwood, dung and agricultural wastes. All figures are rounded and are only indicative of the relative importance of each energy source toward fulfilling the current global energy needs. It shows an almost complete reversal in the patterns of energy supply worldwide compared to pre-industrial times. Over a hundred years ago, about 90 percent of all energy needs were supplied by natural energy flows, while today these non-commercial energy sources provide only approximately 10 percent of global energy. The other 90 percent are mostly derived from fossil energy sources. Oil, coal and natural gas give a sum total of 86.7 percent of all energy supplies. The share of hydro and nuclear, by calculating it's contribution on the basis of thermal efficiency of conventional power plants, namely by calculating how much fossil energy would have been needed to generate the same amount of electricity (i.e., the so-called substitution method) would be higher than presented in Table 3-2. Total commercial energy consumption would increase to 11.1 TWyr/yr and hydro and nuclear account for 6.1 and 4.7 percent share in the total primary energy supply respectively.

Figure 3-7 depicts the worldwide primary energy consumption cumulated on an annual basis since 1860. It shows that the cumulative consumption of coal to date is still larger than that of oil, despite the fact that the annual consumption of oil has been higher than that of coal for almost two decades. The history of the energy system is therefore synonymous with the history of coal for almost a century.

Table 3-3 shows the cumulative energy consumption since 1860 compared with the estimates of global energy reserves and resources. It indicates that at current consumption levels the present known reserves of oil and natural gas would last some 40 to 60 years, respectively. In the case of coal the ratio is much higher: at current consumption levels at about 160 years. The cumulative consumption since 1860 is still relatively small compared with the magnitude of resources. If recovered, they would last hundreds of years at current consumption levels.

The concept of reserves and resources is an inherently dynamic one however, i.e., the quantities of known or estimated occurrences that may become potentially (resources) and practically (reserves) recoverable within a medium-term time horizon, is both a function of (changing) prices and of (evolving) technologies redefining the technical and economic recoverability of resources. As a result, any resource quantity estimated for a particular point in time (for a prevailing price and a given set of exploration and extraction technologies) is an insufficient estimate of the potential future resource availability. The resource base will be increasing not only due to

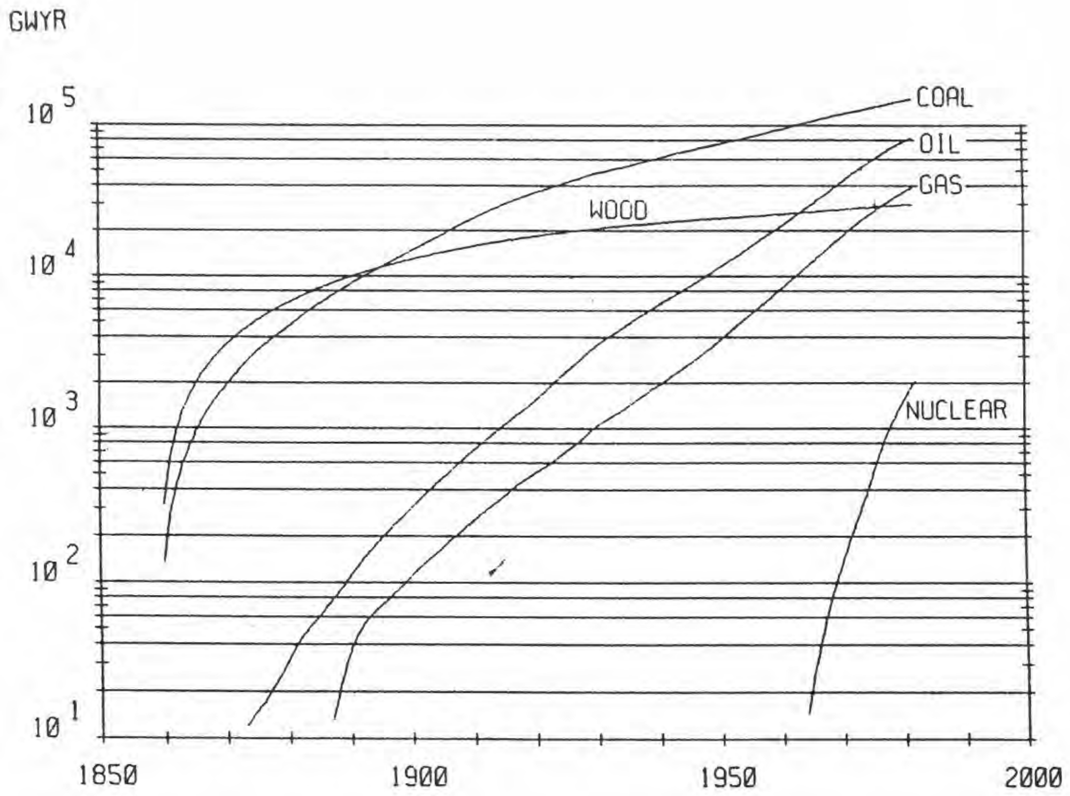


Figure 3-7 Cumulative Energy Consumption, World.

improved geological knowledge and exploration methods, but especially in case new technologies render previously "exotic" occurrences recoverable in the medium term. The use of the term occurrences indicates that from a geological viewpoint resources are not a fixed static number, but may include in the future also some amounts with no present economic potential.

A good illustration of this point is provided by offshore oil resources. Thirty years ago, deep offshore oil occurrences, the existence of which was inferred by geological analogies, were not even considered as potential resources, in the absence of technological means for their identification and eventual production. Today, exploration and production wells are drilled offshore as deep as 1,500 meters below sea level, and North Sea oil has become an important source of oil supply for Western Europe.

In view of this caveat about the problematic of defining statically an inherently dynamic resource base, we present in Table 3-4 below a range of estimates, in order to illustrate the boundaries, within which the future resource situation ought to be evaluated and which also provide the range of resource and additional occurrences estimates presented in Table 3-3.

Table 3-3 Present and Cumulative Energy Consumption and Present Reserves and Available Resource Base (including unconventional oil and gas), World, in TWyr.

	Fuelwood	Coal	Oil	Nat. Gas	Nuclear	Total[1]
1860-1987	28.8	156.2	104.0	55.4	3.9	348.3
1986-1987	1.1[2]	3.4	4.2	2.2	0.6	11.5
Reserves	n.a.	532.5	164.5	132.2	145.3[4]	974.5
Resources	30[3]	3113	1111	> 259	328[4]	> 4841
Add. Occurrences	n.a.	> 4700	> 1900	> 1560	n.a.	–

1 Hydropower is not included as it is renewable on annual basis.
2 Includes all biomass, the non-commercial wood resources might be smaller.
3 Renewable.
4 Assuming deployment in converter reactors, based on burn-up rate of 32,000 MW-day/tU 0.15% tails assay and 3% enrichment, typical for PWR reactors.

What is perhaps more important than the absolute magnitude of the estimates is that the cumulative consumption increased at a lower rate than the increase in the known resource base. This means that the potentially available energy is increasing faster than the total amount extracted up to now. In any case, the current ratios of energy reserves to consumption or resources to cumulative consumption indicate that the resource scarcities anticipated in the 1970s did not take place and are highly unlikely to occur worldwide for at least another 50 years.

This, of course, does not mean that regional and local energy shortages could not develop, but rather that at the global level energy availability could be expected to be plentiful. It is a completely different question, however, whether it would actually be possible to continue consuming energy at current or even higher rates in the future. The environmental constraints in the wake of possible global warming and other adverse effects of energy consumption might impose much lower limits on the quantities that are likely to be extracted from otherwise large global fossil energy resources.

The potential availability of fuelwood and other forms of biomass is very large even on a renewable basis. We have assumed that through appropriate management the annual potential should be in the order of about a third of the current total primary energy consumption or about as large as the energy flow taken by silviculture and agriculture in the world. Over a period of ten years, this could be a renewable source with a total cumulative energy resources of about 30 TWyr. Consumption of fuelwood on renewable basis could be even expanded. Unfortunately, most of the current fuelwood use is in the developing parts of the world and is not managed so that is it is essentially unsustainable with current practices over longer periods. It already leads to drastic deforestation in many parts of the world and virtually destroys whole ecosystems.

With the exceptions of the French Phenix and Superphenix fast breeder reactors, most of the world's commercial nuclear energy installations are based on converter reactor technologies and consume enriched natural uranium as a fuel. Plutonium and thorium fuel cycles have also been advanced for converter reactor. The current natural uranium resources are in the order of 3.6 billion tons (OECD, 1988) which translates into about 330 TWyr of thermal energy with the current technology. With the more recent slow-down in the deployment of nuclear energy worldwide, these resources are certainly sufficient to fuel the now installed nuclear capacity for a few centuries. Even a second pulse in the deployment of nuclear energy in the next decades would not lead to any resource limitations in the conceivable future. Fast breeder reactors on the other hand do not consume the fissile uranium and as such are basically not limited by fissile natural uranium resources.

The amount of coal consumed over the last century is only a small share (only 2%) of the known resources and occurrences. Thus, the limitation to future growth of coal use are certainly not resource driven, but are rather related to the difficulties of long-distance transport and many adverse environmental effects of coal consumption. Both oil and natural gas have substantially lower effluent levels and lower particulate and gaseous emissions than coal. With respect to the longer-term climatic changes, the CO_2 release associated with coal consumption is substantially higher than for other fossil energy sources (see Chapter 6).

The known resources of oil and natural gas are lower than those of coal. However, they are still sufficient to sustain the current consumption levels for about one hundred years and longer if also unconventional resources are considered. Table 3-4 presents orders of magnitude for fossil fuel reserves and resources. Due to the dynamic nature of the technical and economic availability of resources the figures should only be considered as indicative. Resources have to be understood within a matrix defined by the degree of geological assurance on one axis and the degree of technical and economic recoverability on the other. Only geologically exactly delimited, technically and economically recoverable quantities are considered as reserves. Due to the high costs involved in identifying and careful techno-economic appraisal of reserves, it should not be surprising that the economic incentive for the identification of reserves outside a medium-term planning horizon of up to 30 years is limited. Reserve to production ratios in this order of magnitude

Table 3-4 Estimated Conventional and Unconventional Fossil Reserve and Resource Base in TWyr, World.

	Conventional			Unconventional	
	Coal	Oil	Gas	Oil	Gas
Cumulative past production	156.2	104.0	55.4	n.a.	n.a.
Reserves	532.5	164.5	132.2	224.7	n.a.
Resource base[1]					
p=0.95	2580.8	39.9	82.2	682.8	45-72
p=0.50	–	73.6	136.1	2615.7	–[3]
p=0.05	–	176.6	305.2	–[3]	–[3]
Additional occurrences[2]	> 4700	> 320	> 320	> 1580	> 1240
Gas hydrates	–	–	–	–	> 20000
Presently available (reserves + p=0.95 resources)	3113	204	214	907	> 45

[1] Quantities of economic significance and principally recoverable but yet undiscovered at 95, 50 and 5% probability of recoverability. For unconventional resources: measured and identified quantities which are technically recoverable but presently sub-economic. Figures **exclude** reserves.

[2] Undiscovered, sub-economic conventional resources and identified unconventional deposits not recoverable with present day technology and prices.

[3] Included in additional occurrences.

Source: BGR, 1989; BP, 1989; Dreyfus & Ashby, 1989; Kuuskraa & Meyers, 1983; MacDonald, 1989; Masters, 1987; WEC, 1989.

(like for conventional oil reserves) are therefore no indication of the physical scarcity of resources but only one of the economic exploration horizon of companies and institutions engaged in exploration activities. The fact that reserve to production horizons of gas and coal exceed this medium-term horizon, is generally interpreted as an indicator of the wider abundance of these fossil fuel resources in the earth.

Outside the reserve figures proper, additional quantities are identified or inferred from geological studies, but with their economic or technical recoverability either not determined or presently not given (sub-economic and marginal identified conventional resources, and estimated unconventional resources, which are not recoverable with present day technology and economics); or consist of conventional resources, which would in principle be technically and economically recoverable, but have not been discovered yet. The latter category is represented in Table 3-4 by a range of values corresponding to different degrees of probability (95, 50 and 5 percent respectively), i.e., the estimated likelihood that such quantities will ultimately effectively be found.

The last category finally are quantities, whose economic potential is considered not to materialize within the foreseeable future. In order to differentiate these quantities from resources, we follow Fettweis (1976) proposal, and refer to these quantities as occurrences. These include either quantities of known, exploited deposits, which cannot be recovered technically (recall that generally below 40 percent of oil or coal reserves are recoverable by present day production technologies) or are located in such geological settings of depth, spatial concentration, etc., that their recoverability is highly infeasible with present day technology. As technologies evolve such quantities have in the past and will certainly continue in the future, to be reassessed, and moved to the resource and finally to the reserve categories as outlined in Table 3-4.

What becomes particularly visible from Table 3-4 is that large abundance of coal resources and of unconventional resources of oil (heavy crudes, tar sands and particularly oil shales) and natural gas (methane in coal seams, devonian shales, in high-pressure underground aquifers, etc). Particularly noteworthy are the huge amounts of methane, estimated to be trapped in crystalline ice structures in the sea floor (gas hydrates) and in permafrost areas (methane clathrates), estimated, for instance, by MacDonald (1989) to amount to 200 times the known gas reserves. At any rate the already presently discovered unconventional resources of oil and natural gas are so vast that the current consumption levels could be sustained in theory for centuries. However, Chapter 6 will show, that the possibility of environmental changes may become severe constraints that will make the full exploitation of these resources very unlikely without drastic changes in technologies used for the exploitation of these quantities, for energy conversion and end-use.

The cumulative energy consumption over the last hundred years, the current energy supply levels and potential resources still available show very clearly that the resource limitations and "running-on-empty" are certainly not the major energy issues today. In fact, the declining importance of fuelwood consumption, and since the 1930s that of coal, was by no means caused by absolute resource availability constraints. Many world regions have experienced relative shortages of timber, especially for those uses where it was difficult to replace, and oil after the OPEC embargo. In the long-run it was not the shortage in available resources that governed the replacement of older by new energy sources; but rather, the changing nature of economic environments and technological change that offered advantages by fuel switching. If a new energy source offers the possibilities of increasing energy efficiencies because it allows for new technological solutions and improves the economic and technical performance, then a shift to this new energy source could be beneficial even if its direct price is higher.

For example, combined cycle natural gas turbines produce electricity with very high efficiency in the Tokyo bay. The use and high efficiency of natural gas reduces negative environmental impacts. As a consequence, the liquified natural gas (LNG) that these plants consume is among the most expensive natural gas contracts in calorific terms anywhere. Considering that the liquefaction process itself increases the price and has considerable own energy consumption, the example illustrates that the high efficiency and excellent environmental performance in this case gave a preference to a very expensive solution in terms of the costs of primary energy alone, but not from the point of view of the total costs of the system given its overall performance.

In this context it is worth mentioning that although available oil and natural gas resources estimates appear to be relatively small compared to the enormous quantities of coal expected to be still recoverable, there are some new estimates indicating much higher abundance of methane and other hydrocarbons worldwide than was speculated only a decade ago, and which became particularly noticeable in the most recent estimates of unconventional gas resources and occurrences presented above. According to Linden (1986) it is now quite evident that accessible portions of the earth's crust contain a great deal more methane than liquid hydrocarbons. Natural gas has repeatedly been found in areas where such discoveries were supposed to be highly unlikely. Indeed, as Linden points out, the growing evidence of a much greater methane abundance in the earth's crust, than is consistent with traditional geological theory, has led to an increasing number of researchers to reopen the question of the origin of terrestrial hydrocarbons and fossil fuels in general.

The abiogenic theory of methane formation developed by Gold (1979, 1985, and 1988a) and others, holds that much of the carbon in the earth's crust is derived from outgassing of methane evolved from hydrocarbons trapped in the formation of the earth, (in contrast to being "fossil" remains of living organisms). Drilling in Sweden (Siljan Crater), in the Soviet Union (Cola peninsula) and elsewhere appears to provide support for the theory that a significant part of natural gas is as a result of outgassing of primordial hydrocarbons from the mantle. Such a theory implies that vast reserves of gas might be found in deep faults and rifts and other areas previously ignored in energy exploration. It has been reported (New York Times, 1986) that drilling at a depth of almost 7 km in the Siljan Crater may have tapped a large reservoir of primordial methane and some other hydrocarbons. However, prevailing opinion among geologists is certainly that recoverable resources of hydrocarbons are the result of abundant surface biology where cap rocks then sealed off large masses of organic sediments. Although the debate over the origins and amounts of "fossil" fuels in the earth is certain to continue, there are strong indications that the absolute amounts may be much larger than even the more optimistic current estimates. Thus, it is very likely that also in the future the decisions to replace older by newer energy forms will not be forced by any absolute resource limitations, but rather because of environmental, technical and economic performance limitations of old solutions, and because much larger improvement potentials are possible through the acceptance and wider diffusion of new energy sources.

3.1.3. Summary of Major Trends

The evolution of global energy systems from dependence on natural energy flow in the environment to increasing use of mineral energy sources with the onset of the Industrial Revolution and gradual replacement of the traditional directly harvested energy forms by fuels derived through energy conversion, indicates how the major energy issues have changed during the last centuries. Most of the human activities have been constrained to a large extent by energy availability in the past. Since the beginning of the oil era, energy has been very abundant by historical standards. This has allowed for the gradual substitution of physical toil by power derived from inanimate sources of energy. This is especially in the more affluent parts of the world where energy use per capita has reached levels that exceed, by a large factor, the local energy availability. The production and settlement patterns were no longer dependent on local energy availability. The industrialized world became accustomed to plentiful use of energy and more importantly to ever increasing levels of energy consumption.

With the onset of the so-called energy crisis of the 1970s, however, this paradigm of vast availability and enormous energy supplies was drastically challenged. The energy supplies were perceived as exhaustable and potentially limited. Similar periods of energy scarcities have also occurred in the last centuries, starting with often acute fuelwood shortages in many parts of the world. These were bypassed in time by the introduction of coal that slowly replaced most of the traditional uses of fuelwood. Similar, but much less severe shortage of energy was perceived during the 1930s when it appeared that the most abundant oil reserves in the United States were being slowly exhausted. This shortage was also resolved through new discoveries in the Persian Gulf, Latin America, Texas and Oklahoma. The situation in the 1970s appeared to be quite different. This time the global energy resources of oil appeared to be dwindling and looked almost irreplaceable by any conceivable alternatives. The era of cheap and plentiful oil supplies suddenly vanished. This was also illustrated in some of the trends in the changes of the global energy system. Per capita energy use stagnated and in many areas even declined since 1970, as numerous energy rationalization, savings and efficiency measures gained their effect. From the perspective of the 1970s energy appeared exhaustable and resource scarcities dominated the long-term view.

In retrospect these perceptions do not appear to have been completely correct, even though the energy rationalization and efficiency improvements that resulted, have brought many advantages. Today, the dominating energy issues do not concern any imminent bottlenecks in energy supply or availability. It was illustrated that even oil and natural gas resources could last for hundreds of years at current consumption levels. The problems concern rather the potential impacts of energy use and not the scarcity of energy availability. For the first time in history, human activities, and especially those that are related to energy use, appear to be so extensive that longer-term environmental impacts appear to be imminent.

Environmental degradation is not a new problem. Often energy related activities have caused drastic environmental degradation. For example, the excessive use of coal for domestic heating was responsible for the famous London fog. These severe problems were manageable on local and regional scales, while the changes that may be occurring now appear to be global in nature. It is the structural changes in the energy system and associated improvements in energy efficiencies that will play an instrumental role in measures to reduce the environmental impacts of human activities.

Before returning to these issues in later chapters, we will first analyze the current structure of the energy system. In the international part we will focus on the OECD countries. The reason for the emphasis on the most affluent parts of the world is that it is in these parts where the highest improvements appear to be possible and are most likely to occur. In fact, it is conceivable that the OECD countries would have to introduce more than average improvements in order to compensate for possible increase of energy needs of the developing countries.

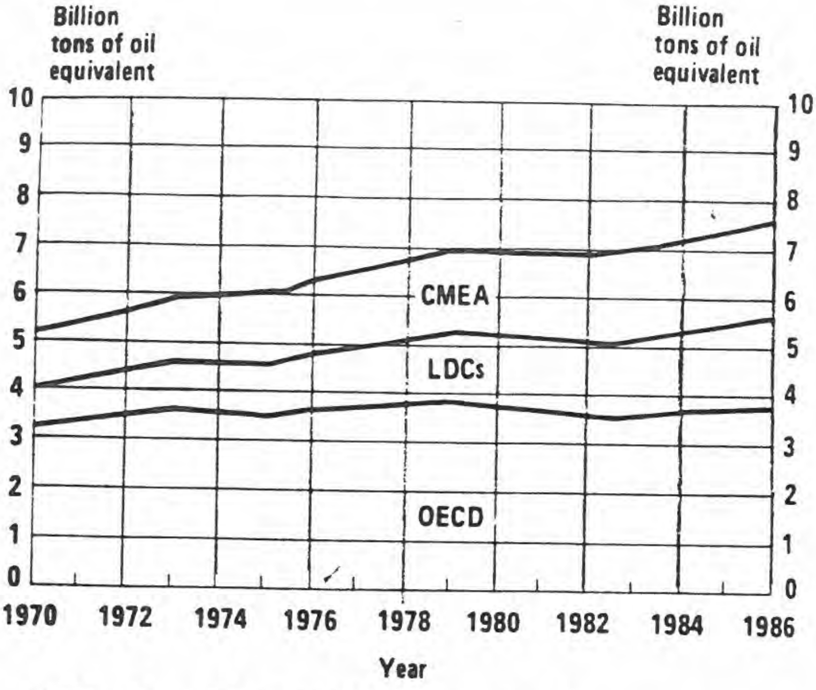
3.2. International Energy Supply and Demand

3.2.1. Consumption, Trade and Production

The dynamic changes in the mix of the primary energy supply and the overall growth rate of about 2.5 percent per year since 1860 are not exactly representative for the last two decades. The energy troubled period of 1973 to 1986 witnessed several ups and downs of regional energy consumption growth rates. Still the global energy consumption expanded by about 2.3 percent per year. These changes in the primary energy consumption are given in Figure 3-8 for the world disaggregated into three major regions – the CMEA, LDCs and OECD countries (Rogner, 1988). Most likely this growth will continue also during the next decades. Unlike in the past, the future energy demand and growth will be increasingly influenced by the economic performance of the developing world. While the energy consumption in the industrialized countries hardly changed between 1973 and 1986, there was a steady growth in the developing countries and to a lesser extent also in the centrally planned economies.

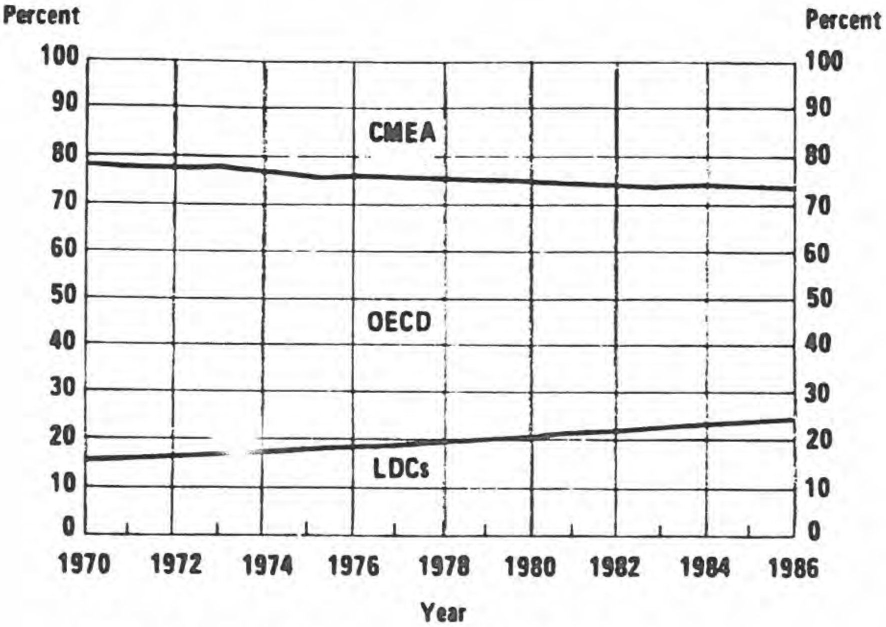
The relative shares in the global energy consumption of these three regions are given in Figure 3-9. It should be also observed that despite the fact the energy supply hardly increased during this period in the OECD region, it still accounts for about a half of the global energy consumption. However, due to the comparatively large increases in energy consumption of the CMEA and developing countries, the share of the OECD countries has substantially decreased from about two thirds of the global consumption in 1970 to their present 50 percent share.

The contribution of different energy forms to primary energy supply has also undergone some notable changes in these three world regions when compared with the primary energy mix at the global level given above. The choice of primary energy in a region depends on a variety of factors that have to be differentiated from the global averages. Typical examples include resource and technology availability, level of industrialization, government policy, price structures and environmental regulation. Despite all these regionally different factors, it has been the growth of the secondary energy carrier electricity that has had the largest impact on the development of primary energy supply. Cleanliness and convenience have apparently met consumers' preferences in the choice for electricity. The substantial increase in the use of electricity has also led to the higher consumption of nuclear energy, hydropower and coal as shown in Figures 3-10 and 3-11 for the OECD region and the developing countries (LDCs), respectively (Rogner, 1988). Since 1973, electricity grew by some 2.9 percent per year in the OECD countries, 5.0 percent per year in the developing world and by 10.2 percent per year in the centrally planned economies.



CMEA = Council for Mutual Economic Assistance
LDCs = Developing countries
OECD = Organisation for Economic Cooperation and Development

Figure 3-8 Regional Primary Energy Consumption, World.



CMEA = Council for Mutual Economic Assistance
LDCs = Developing countries
OECD = Organisation for Economic Cooperation and Development

Figure 3-9 Regional Shares in Primary Energy Consumption, World.

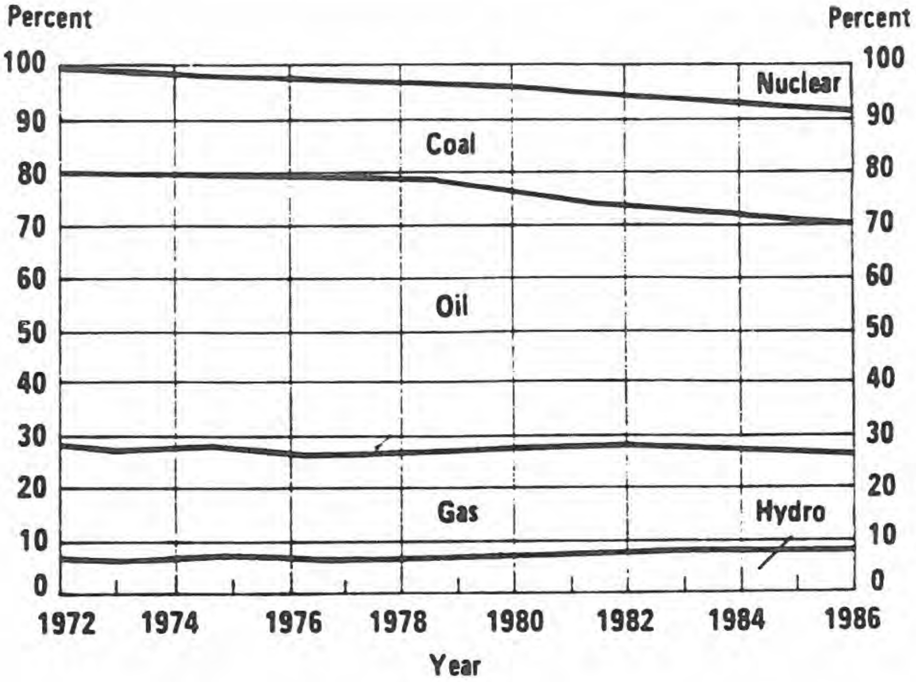


Figure 3-10 Shares of Primary Energy Sources, OECD.

Apart from the growth in electricity consumption, it was interfuel substitution in electricity generation and at the level of end-use, that facilitated the shift away from oil. In residential energy use natural gas and electricity substituted for oil as heating fuels, while industries quite often preferred coal as a substitute for boiler fuel. However, because of the efficiency differences usually associated with interfuel substitution[4] the displacement of oil by natural gas did not necessarily translate into growth at the level of primary energy which partly explains the constant share of natural gas in the OECD countries. Unlike in most industrialized countries, natural gas is not barred from electricity generation in the developing countries. Consequently, natural gas has been used increasingly also for electricity production and the share of natural gas in primary energy consumption has been steadily rising within the developing countries.

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[4] We will deal with the issue of end-use efficiencies in greater detail in the next Chapter. For example, the displacement of a barrel of oil by natural gas as a residential heating fuel usually results in less than a barrel of oil equivalent of gas sales. Many gas utilities experienced this fact when their projected gas sales based on the rate of gas furnace purchases differed substantially from actual sales figures.

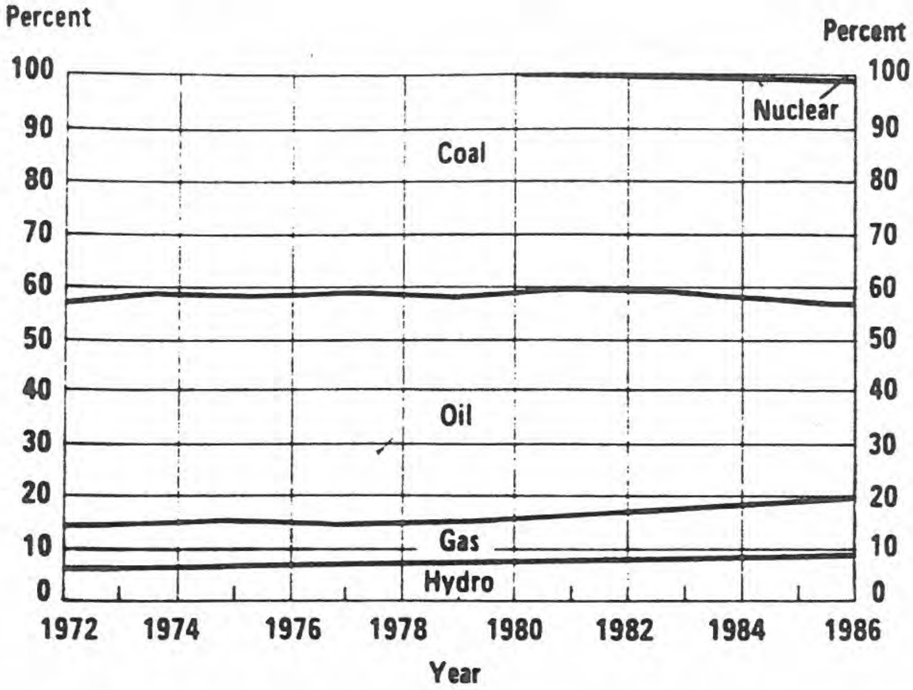


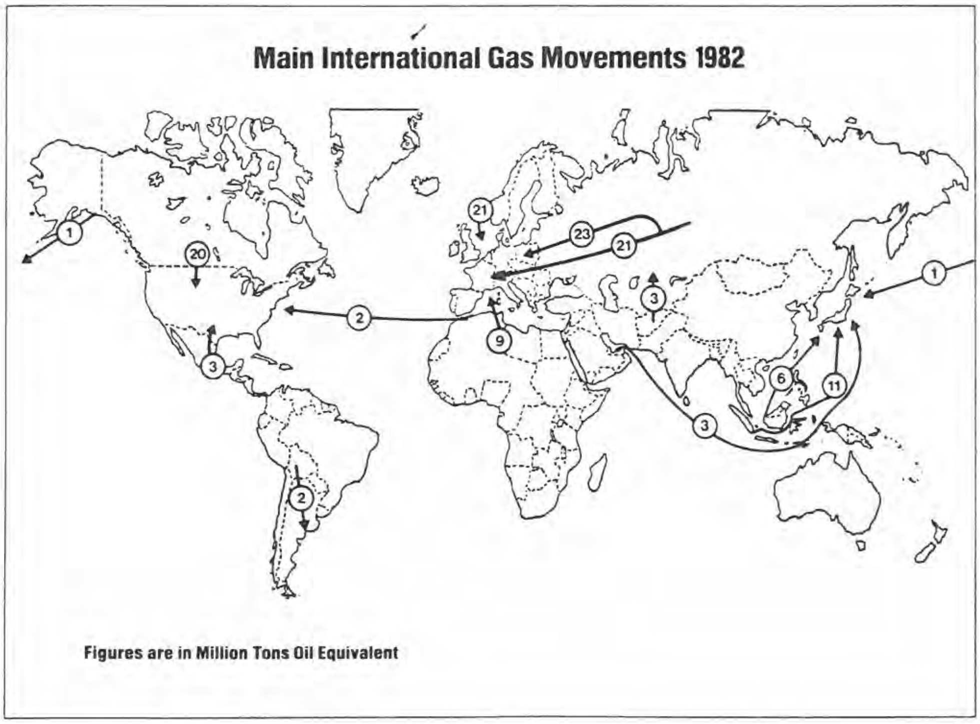
Figure 3-11 Shares of Primary Energy Sources in Consumption, LDCs.

Table 3-5 Natural Gas Production and Consumption, 1987.

	Production		Consumption	
	TWyr/yr	%	TWyr/yr	%
OECD	0.95	40.3	1.04	47.1
N. America	0.69	29.2	0.67	30.4
W. Europe	0.23	9.8	0.29	13.1
Other	0.03	1.3	0.08	3.6
CPE	1.03	43.6	0.90	40.7
LDCs	0.38	16.1	0.27	12.2
World	2.36	100.0	2.21	100.0

Source: Based on data from BP, 1988.

Table 3-5 gives the natural gas consumption and production for the three major world regions: the OECD countries (divided into North America, Western Europe and "Other" that includes Japan and Australasia), the centrally planned economies (CPE) and the less developed countries (LDCs). The table shows that the OECD region is a net importer of natural gas while the other regions are exporters at this highly aggregate level. Nevertheless, the natural gas trade is not so large compared with coal or oil, in part due to the fact that most of the exchange is through the pipeline system (although LNG transport is increasing) that is basically limited to continental distances and in part it is also related to more equal distribution of gas reserves throughout the world.


Main International Gas Movements 1982

Figures are in Million Tons Oil Equivalent

Figure 3-12 Main International Gas Movements (BP, 1982).

Figure 3-12 shows the main international flows of natural gas. In addition to the indigenous production in Western Europe (largest fields are in the North Sea and the Netherlands), major imports are from the Soviet Union and North Africa. Japan imports LNG from the Gulf, Indonesia and Alaska, while the United States imports LNG from North Africa and natural gas by pipelines from Canada and Mexico.

Unlike oil and coal, natural gas is available in many locations and the reserves are not as concentrated. As the trade flows indicate, the leading producers of natural gas are the Soviet Union, the United States, Canada, the Netherlands, the United Kingdom and Algeria followed by smaller producers such as Indonesia, Norway and Mexico. The largest gas producer is the Soviet Union with approximately 39.3 percent share compared with a 25 percent share for the United States. On the consumption side the two leading countries are the same: The Soviet Union accounts for approximately 33.4 percent of global consumption and the United States for about 27.8 percent. They are followed by other large industrialized countries like the UK, the FRG, Canada and Japan.

In North America gas consumption has been declining since the early 1970 with market losses both in industrial use and in electricity generation. In Western Europe gas market shares rose steadily until 1979 and remained almost constant thereafter. Natural gas made major inroads in the residential and commercial heating sectors and secured long-term markets. The industrial gas use increased as well, but at times met fierce competition from coal and fuel oil. The uncertainty of future gas supplies and the geopolitics of European gas trade have often discouraged bulk users to invest in natural gas plants and equipment. The increase of natural gas consumption at the global level is to a large extent due to the enormous rise in Soviet gas production and domestic consumption.

The increases in coal consumption since 1973 are primarily due to the vision of possible future oil and gas scarcity. After the first oil price increase in 1973, coal was generally considered as the *bridge to the future* (Wilson, 1980). We have shown how enormous the proven coal resources are. The vision of switching to coal in the face of possible scarcity of other energy resources appealed to government and industry alike. Furthermore, unlike oil, the world's coal deposits appeared to be more abundant but also more evenly distributed around the globe. Hence, as an initial response to the perceived insecurity of imported oil, government policies in many nations supported the substitution of coal for oil. Meanwhile, the enthusiasm for coal has subsided because of several economic blunders caused by government and industrial misinvestment in liquefaction technologies that became no longer attractive as energy prices returned to pre-1973 levels in real terms. The economics of these investments were based on the assumption of ever increasing oil and energy prices. Those were the paradigms of the early 1970s when many of these projects were initiated. Today, it is not the cost of coal and coal conversion technologies that is changing the picture, but rather the inherent environmental and social costs associated with mining, transport and combustion of coal. Even under current low costs, coal is very expensive to "clean up" with the exception of some large users such as the electricity sector. Nevertheless, many investments in coal production, transport and handling infrastructure triggered by the two oil price shocks have come onstream and have lead to an increase in coal consumption.

Table 3-6 Coal Production and Consumption, 1987.

	Production		Consumption	
	TWyr/yr	%	TWyr/yr	%
OECD	1.22	35.5	1.22	36.4
N. America	0.78	22.7	0.69	20.4
W. Europe	0.26	7.6	0.37	10.9
Other	0.18	5.2	0.16	4.7
CPE	1.83	53.2	1.80	53.1
LDCs	0.39	11.3	0.37	10.9
World	3.44	100.0	3.39	100.0

Source: Based on data from BP, 1988.

Since 1973 world coal consumption has been growing at 2.7 percent per year. This means that the long-term decline in coal's market share since the 1930s came to at least a temporary halt and perhaps even a reversal. Coal production increased rapidly in China, and more modestly in the United States and in the Soviet Union. Together these three countries account for almost 60 percent of the global coal production. Thus, global coal production is much more concentrated than, for instance, natural gas. Worldwide the production is divided into about 3.4 billion tons of hard coal and about 1.2 billion tons lignite and brown coal.

Table 3-6 shows that the OECD countries account for slightly more than a third of the global coal production and consumption, almost a half of this being produced and consumed in the United States. The only regions without any increase and some declines in coal consumption since 1973 are Japan and Western Europe. The centrally planned economies produce and consume more than a half of all coal worldwide, much of which has lead to severe environmental impacts, especially in Eastern Europe, due to acid rain. Other countries with high annual coal production (and consumption) growth rates are India, Poland, Australia and South Africa. China is not only the largest producer of coal with a 23 percent share in the world, but it also has very ambitious plans in expanding coal use.

Generally, the pattern of coal consumption shifted from metallurgical coal used for iron and steel production (as the demand for iron and steel industry entered a period of saturation) to electricity generation which in 1986 accounted for some 60 percent of global coal consumption. Most of the

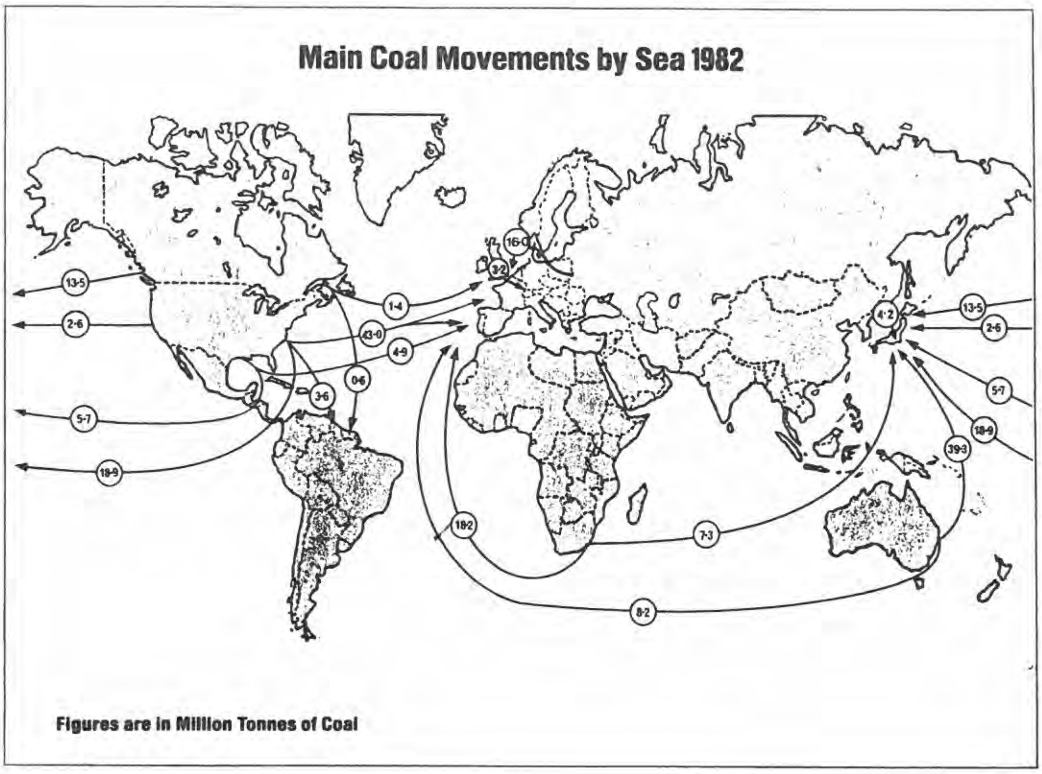


Figure 3-13 Coal Movements by Sea (B.P., 1982).

global trade in coal is for electricity generation. The largest exporters are the United States, Poland, South Africa and Australia. Figure 3-13 shows the main coal movements by sea indicating that the largest importers are Western Europe and Japan.

We have shown above that oil still holds the highest share in global energy consumption although it has dropped to less than 40 percent compared with its peak of nearly 50 percent in the early 1970s. Figure 3-14 shows the decline of OPEC's share in global oil production and a relatively constant share of production since 1983. The decline in oil's share in the global energy consumption is primarily due to its continued replacement in electricity generation by nuclear power and coal; and in addition, by natural gas in many stationary uses. Along with this decline the "oil issue" has faded in importance since the heydays of geopolitical and economic concerns that have emerged with the OPEC oil embargo. Now it is increasingly clear that the dependence of oil exporting countries on oil revenues is greater than the dependence of the industrialized countries on oil imports. The high oil prices have created expectations of further price increases in the 1970s and have thus provided incentives to explore and develop more oil and

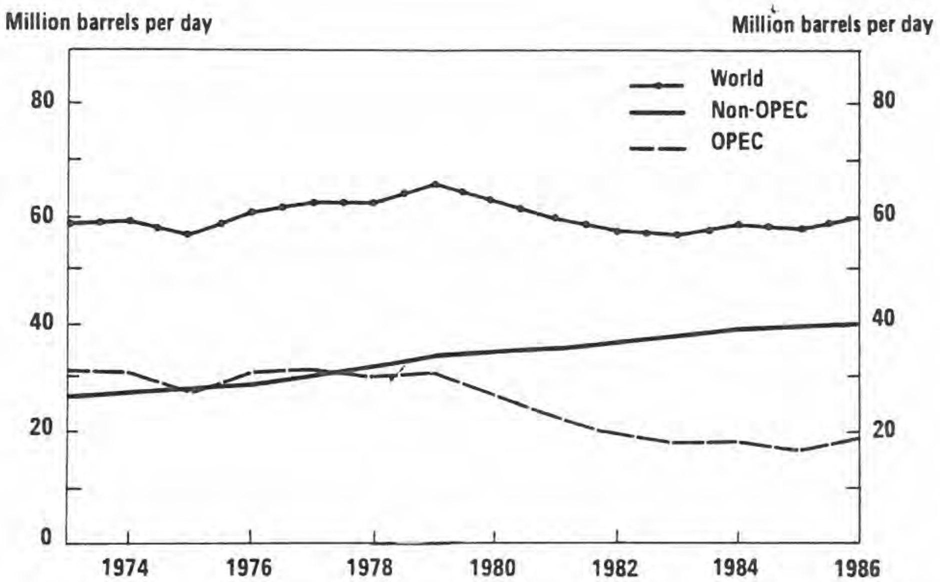


Figure 3-14 Oil Production, World.

natural gas from sources which were previously economically unrecoverable and have caused high pressures for oil replacement and conservation. The developments in the North Sea, the discovery of the giant Prudhoe Bay deposits, the Australian North Slope gas fields, the development of Siberian oil and gas deposits and the more than three-fold increase in Mexican oil production are the examples of large additional production capacity that became available since the oil embargo. As a consequence, the non-OPEC share in total oil production grew steadily since 1973.

Table 3-7 shows that OPEC's share in oil production has declined to 31.6 percent in 1987. Without OPEC, the other developing countries produce about 14.7 percent (all LDCs including OPEC have a 46.3 percent share). In contrast to the declining reliance on OPEC oil in the industrialized countries, there is a still rising oil consumption and import dependence in developing countries that usually have neither the financial resources nor the time to create a more diversified energy system due to many bottlenecks in their energy supply. The OECD countries produce now about half of their oil consumption and together account for more than half of global oil use. The centrally planned economies share about a quarter of both global

Table 3-7 Oil Production and Consumption, 1987.

	Production		Consumption	
	TWyr/yr	%	TWyr/yr	%
OECD	1.12	27.0	2.35	56.4
N. America	0.79	19.0	1.18	28.3
W. Europe	0.29	7.0	0.83	19.9
Other	0.04	1.0	0.34	8.2
CPE	1.11	26.7	0.96	23.0
LDCs	1.92	46.3	0.86	20.6
World	4.15	100.0	4.17	100.0
Of which OPEC	1.31	31.6		

Source: Based on data from BP, 1988.

oil production and consumption. The Soviet Union is now the largest producer of oil in the world with a 21.3 percent share and is followed by the United States, Saudi Arabia, Mexico and China. The largest consumer is the United States with a 26 percent share, followed by the Soviet Union, Japan, FRG and China.

Figure 3-15 shows the main oil movements by sea. It does not include the continental oil trade by pipelines. Despite the fact that the share of OPEC oil in the global production declined and that oil production is now more widely distributed throughout the world, the Middle East still remains the biggest oil exporting region. The largest importers are Western Europe, the United States and Japan.

Nuclear power has been viewed as another potential energy source for replacement of oil. After two decades of extremely rapid growth rates in many countries (see the primary energy consumption in the world, given above), nuclear energy appears to be in a transition phase marked by rapidly declining growth and many difficulties. Socio-political controversies in many countries, especially after the incidents at Three Mile Island and Chernobyl, have led to a slowdown in the commissioning and construction of new power plants worldwide. As a matter of fact a number of almost completed power stations have been abandoned. Austria was one of the first countries to decommission a brand new nuclear power plant. Today, nuclear programs are viewed as extensions of public policy and as a consequence decisions regarding the construction of additional nuclear power plants are presently beyond the capability and political competence of the private sector (Dreyfus, 1987). Despite these enormous difficulties and rather pervasive opposition to nuclear power worldwide, the potential

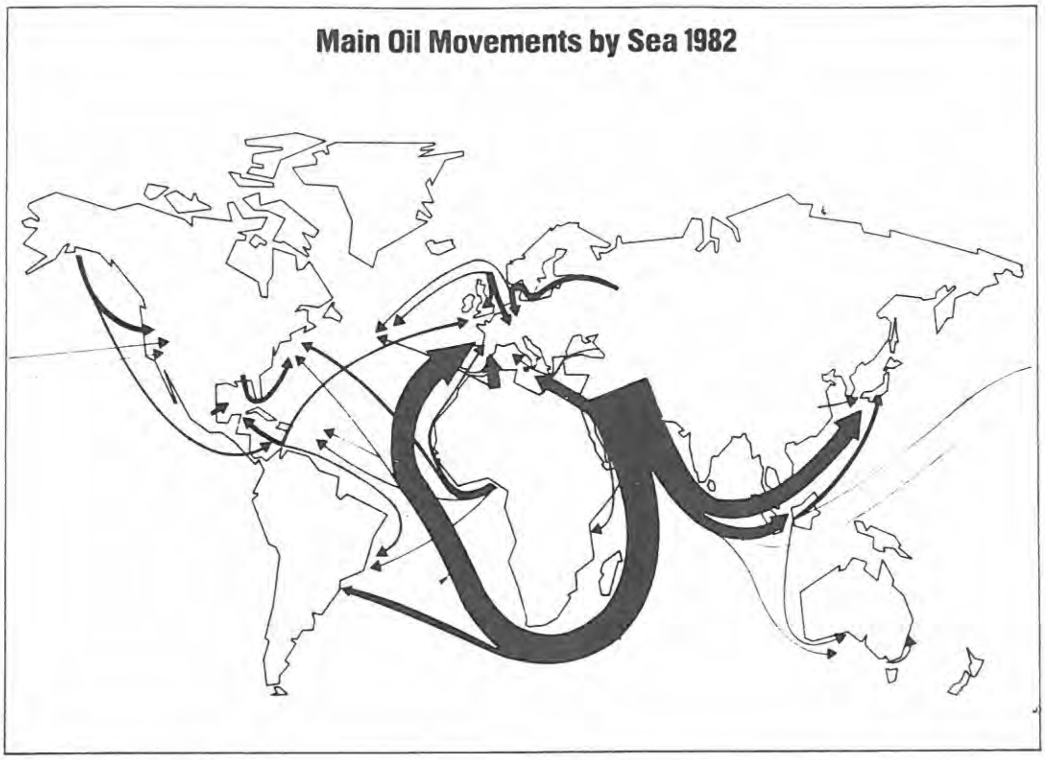


Figure 3-15 Oil Movements by Sea (B.P., 1988).

dangers of global warming associated with combustion of fossil fuels have caused a gradual reassessment of nuclear energy. It is too early to say whether these renewed discussions could have lasting effects and lead to promotion of nuclear energy. In any case, a "new nuclear era", should it become a reality in the future, will probably be based on a new generation of nuclear reactor and fuel cycle facilities with a much higher degree of inherent safety than those of the current designs.

Nuclear energy is an option of only a few percent in primary energy consumption today (see the shares of energy sources in global consumption above). About 80 percent of this contribution is due to the nuclear power plants in the OECD countries. The largest producers of nuclear power are the United States with almost a third of global production, followed by France, Japan, the Soviet Union and FRG. Thus, the developing countries are a long way from relying on nuclear energy to displace other more traditional energy sources.

Hydropower is the most important of all renewable energy sources that are exploited on commercial base worldwide. The largest producers of hydro-electricity are the United States, Canada, the Scandinavian countries, the Soviet Union and the Latin American countries. More than half of the global hydro-electricity is produced in the OECD countries. Despite continuous increase in the deployment of hydropower, its potential is close to being exploited in many regions and the public opposition is increasing. While the hydropower is one of the cleanest forms of electricity generation, it can have both large beneficial but also harmful ecological and land-use impacts.

The total mechanical power available from continental runoff of water equals about 5 TWyr/yr. In order to maintain a certain water velocity and a minimum riverine ecology however, not all of this runoff is technically feasible to be channeled for hydro-electricity (Häfele *et al.*, 1981). From a technical viewpoint the maximum upper limit of hydropower potential certainly does not exceed about 3 TWyr/yr.

In view of the variety of competing water requirements (irrigation needs, preservation of scenic and ecological values, maintenance of navigation) an upper realizable potential contribution of hydropower to the global energy balance could be some 1.5 TWyr/yr; i.e., 50 percent of the theoretical technical potential (Häfele *et al.*, 1981). This, however, would assume a massive development along the lines of large river basin management as exemplified, for instance, by the Tennessee Valley Authority (TVA) in the US, which is capturing about half of the available runoff. The figure of 1.5 TWyr/yr represents thus rather a theoretical upper boundary value, than a realistic long-term assessment of the development potential of hydropower. Still, present day hydropower output represents only about 20 percent of above presented maximum potential, indicating a considerable future growth potential which, however, will be distributed unevenly between different regions. For OECD countries about two thirds of the estimated potential is presently already exploited (WEC, 1978), for developing countries the exploitation rates are significantly lower (e.g., less than 10 percent in China), indicating that most of available development potential of hydropower remains outside developed countries.

Other non-commercial forms of renewable energy may account for up to 80 percent of residential energy consumption in the developing world. Although reliable data for industrialized countries are lacking, the share of other renewables to the energy balance is practically negligible in the industrialized world. In developing countries non-commercial fuels are generally used very inefficiently due to the lack of appropriate equipment and sometimes also due to traditional patterns in energy consumption. We have given above an estimate of about 1.1 TWyr/yr for non-commercial energy forms, most of which could be provided on sustainable basis with the deployment of appropriate technologies and consumption patterns. Unfortunately, reliable estimates are very difficult to give and the above figure is only indicative. It is entirely possible that the actual consumption of non-commercial energy is much larger especially if all use of agricultural wastes, dung and timber are accounted for. For example, Putnam (1953) suggested that dung, as a fuel source, has had a fairly constant share of 16 percent since the 1860s. This is only a rough estimate, the actual consumption of dung and other agricultural wastes was probably much higher during the last century and may be even higher than ten percent of all commercial energy today. Even the fuelwood consumption levels are not accurately known. Global estimates are very vague and difficult to make, due to enormous regional differences. In this light, Table 3-8 gives estimates of renewable energy production in five developing countries indicating that mini and small hydropower plants (i.e., in the kW range) have the greatest contribution in these countries.

Table 3-8 Production of Renewable Energy in MWyr/yr, 1987.

Country	Solar	Wind	Mini-hydro	Biogas
Pakistan	1.71[1]		55.25×10^3	0.21
Panama	3.20	0.34	10.05	1.04
Philippines	54.80		171.2	20.55
Senegal	0.06			0.02
Sri Lanka	0.46	0.91	57.08	3.31

1 Electricity generation.
Source: El Maghary and Kärkkäinen, 1988.

3.2.2. OECD Energy Balance

The energy flow through an economy can be subdivided into a number of stages, starting with the indigenous energy production, imports and exports (including bunkers and stocks), various energy transformation and distribution processes, use as feedstocks, and ending with final energy consumption such as heat, fuels and electricity. In general, the quality of provided energy services increases with each stage of the energy flow. For example, crude oil that is consumed as gasoline, after refining and distribution to final use, provides services that crude oil in its original form cannot. However, these conversions and transformation processes are associated with losses that occur in refining, storage, transport and distribution. Thus, the amount of final energy delivered for consumption is substantially lower than the total primary energy inputs to an economy. The ratio of the two quantities defines the efficiency of primary to final energy conversion at an aggregate level. The law of thermodynamics specify that there is an upper limit to improving this efficiency and this limit can never be exceeded. But it is, in principle, possible to achieve efficiencies that are very close to the theoretical limits. In comparison with these absolute levels, the current energy systems are very heterogeneous in the sense that in some areas the conversion and transformation efficiencies are relatively close to the absolute thermodynamic limits and in others are very far away from them. However, the losses that occur in these processes should not be viewed entirely as simple wastage of energy. The quality of energy forms and carriers that are obtained by these conversion processes is often much higher than the original primary energy forms. Thus, the value added and convenience for the consumer usually increases with each conversion step. (We will discuss these issues in much greater detail in Chapter 5).

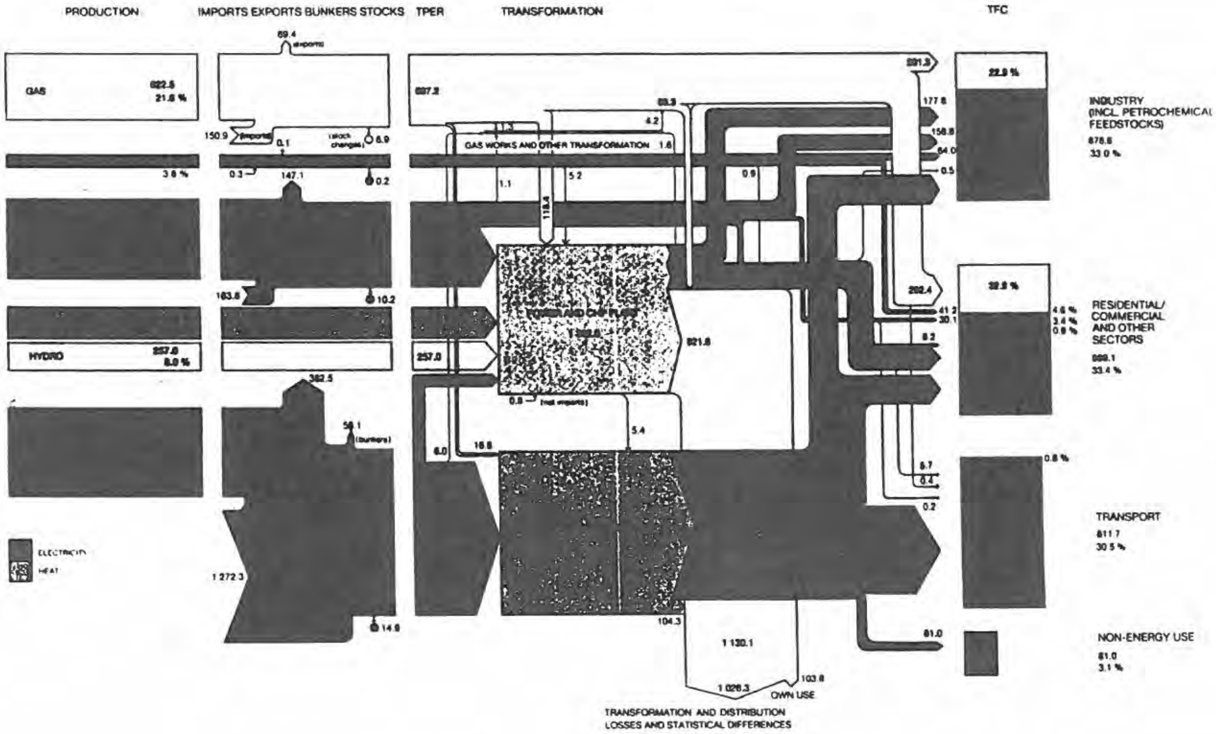


Figure 3-16 OECD Energy Flow Chart, 1986 (OECD, 1988)

Figure 3-16 shows the energy flow in the OECD countries. Four stages are distinguished – indigenous production of primary energy; energy imports, exports, stocks and bunkers; transformation and distribution; and final energy consumption. This distinction is to an extent arbitrary, it is possible to disaggregate the energy flows into more subcategories. Here, we will use the definitions as given in the OECD Energy Balances (1988). The first two stages are self-explanatory and include: indigenous production; and imports, exports and bunkers.

Transformation and distribution is perhaps the most complex. For example, it includes electricity (and some heat) production from various primary energy sources and includes crude oil refining into a number of oil products and fuels. Both electricity and fuels are so-called secondary energy carriers or forms. As such they can be directly consumed to provide energy services such as heat or motive power. Other secondary energy forms such as coal or natural gas need little or no conversion since they are already suited for consumption in their original form. Thus, negligible conversion losses are associated with this last category. At the same time, it should be mentioned that these secondary energy forms are often not suitable for some uses either because they cannot be easily stored (e.g., natural gas for automobile propulsion), or because they do not have the required quality (e.g. without transformation coal or biomass are basically only suited for generating heat), or because they cannot be transported over sufficient distances to final use (e.g. low-temperature heat). After transport and distribution, the secondary energy forms are delivered as final energy that is available for consumption. This is also associated with losses and energy costs (own consumption of pipelines, electricity grid or vehicles that carry secondary energy carriers to consumption centers).

Typical final energy consumption categories are also given in the figure, by sector and final energy carrier. It shows that the transport sector consumes mostly fuels derived from crude oil and some electricity, while the industrial, residential and commercial sectors draw more equally on final energy forms such as natural gas, electricity and oil products. A smaller quantity of oil products (and some natural gas) are also consumed for non-energy use. These are required primarily as feedstocks in the chemical industry for production of fertilizers and plastics.

Table 3-9 shows the 1986 energy balance in the OECD countries at each of the four stages of the energy flow. We have seen that in terms of primary energy requirements, the OECD countries consume about half of the global energy supply with about 5.4 TWyr/yr compared with 10 TWyr/yr worldwide (in 1986). The OECD countries are relatively energy dependent on imports from other regions of the world. With the indigenous primary energy production of 4.1 TWyr/yr and net imports of about 1.3 TWyr/yr the import dependency is about 25 percent. Most of it is due to relatively large net imports of crude oil of about 1.2 TWyr/yr, the remainder constitutes natural gas trade. Thus, the import dependency is especially large with respect to oil, although as we have shown earlier the

Table 3-9 Energy Balance in the OECD Countries for 1986, in GWyears and efficiency in percent.

	Coal	Solids	Oil	Nat.Gas	Nuclear	Hydro	Electr.	Heat	Total
Production (I)	1118.6	157.8	1148.9	883.6	421.5	364.9			4095.3
Trade (T)	9.2		1162.1	106.0			1.2		1278.6
Primary (P)	1127.8	157.8	2311.1	989.7	421.5	364.9	1.2		5373.9
To Fuels (P_1)	292.4	150.4	2140.1	813.5			1977.5		5373.9
To Electr. (P_2)	835.4	7.4	171.0	176.2	421.5	364.9	(1976.3)		
Sec. Fuels (S_1)	283.3	149.3	2031.0	775.6			683.0	13.6	3935.8
Sec. Electr. (S_2)	(275.8)	(2.7)	(59.5)	(61.1)	(149.9)	(134.0)	683.0	(13.6)	
Final (F)	268.3	149.2	2023.7	701.4			621.4	12.3	3776.4
S_1/P_1 (%)	96.9	99.3	94.9	95.3			34.6	100.0	73.2
F/S_1 (%)	94.7	100.0	99.6	90.4			91.0	90.4	96.0
F/P_1 (%)	91.8	99.2	94.6	86.2			31.4	90.4	70.3

Source: Primary to final energy balances based on OECD, 1988.

reductions of oil imports since 1973 have been indeed large. The category "Trade (T)" in Table 3-9 is somewhat misleading since it includes net imports (export – imports), changes in bunkers and stocks. Together they represent about 10 percent of net trade (bunkers about 6.2 and stock changes about 3.6 percent).

Indigenous production (I) together with net imports results in total primary energy requirements (P). With the population of about 808 million, the OECD countries have an average per capita energy consumption of about 6.4 kWyr/yr, which is about three times higher compared to the average global levels of less than 2 kWyr/yr per capita. The disparity within the OECD countries is also substantial. For example, the United States has the highest energy consumption of 10.6 kWyr/yr per capita compared with about 4.5 kWyr/yr in the Western European countries and Japan or with 1.2 yr/yr per capita in Turkey, which is about one third below the world average.

Table 3-9 also shows how much of the primary energy sources is consumed in electricity production (P_2), the amount of electricity generated (S_2) and the quantities of other secondary fuels (S_1, including also total electricity) that are available for consumption. After transport and distribution both the delivered electricity and fuels result in total final energy consumption (F). In the OECD countries about 3.8 TWyr/yr of final energy is delivered for consumption. Thus, the overall efficiency of final to primary energy use is about 70 percent. The overall efficiency of electricity is the lowest with about 31 percent, while the efficiency of fossil fuels is on average about 96 percent. This difference reflects the one-to-three ratio of primary energy inputs to electricity generation. In Chapter 5 we will deal more explicitly with this question and we will show that energy conversion must be also viewed from the point of view of "quality" or the capacity of final energy carriers to do work in addition of providing useful heat.

3.2.3. Energy End-Use

The final energy forms such as electricity, natural gas and other fuels are transformed in end-use devices and equipment into useful energy (U). Thus, the useful energy already includes additional conversion losses in furnaces, automobiles or home heating systems. Typical useful energy forms are the heat in the furnaces, power at the wheels of an automobile or warm radiators in a home. This can also be expressed in common energy units, and in the OECD countries we estimate the total useful energy consumption at about 2.0 TWyr/yr. At the aggregate level the final-to-useful energy conversion efficiency is thus about 52 percent in the OECD countries, resulting in the overall efficiency of primary-to-useful energy of about 36 percent. In Chapter 5 we will estimate the current efficiency of energy systems in much greater detail showing the prevailing efficiency of energy services delivery may be as low as only a few percent in the OECD countries.

This may sound very small, or conversely the losses in excess of 60 percent in providing useful energy to consumers might at face value appear to be very large. However, these quantities must be seen in perspective, both from the point of view of what was historically possible, how these efficiencies are changing now and how large are the improvement possibilities in the future. In addition, it is not obvious whether these efficiencies *per se* have any absolute meaning. What is important is not necessarily how efficient the energy system is, but rather what services it can deliver and what are the social costs and environmental impacts associated with energy use. In the following chapters we will return to these issues, but first we will analyze energy use patterns in the context of technological change and economic growth. We will attempt to show that the more important indicator of the quality and efficiency of an energy system is not the numeric efficiency with which the useful energy is provided but rather the efficiency and quality of energy services. We will try to show that what matters is the embodied energy in products and services, such as the warmth of a room, the passenger-kilometers traveled or tons of steel produced.

In this context it is also important to look at the longer-term efficiency changes, rather than short-term adjustments which might be the effect of price elasticities as the relative price structure changes in a rather turbulent way especially over a shorter time scale. In terms of overall measurement it is important to distinguish periods or possibilities of rather continuous development and those where you have abrupt changes in the structure. We will analyze in a greater detail the evolution of energy system with the emphasis on the changing efficiency of energy use in the industrialized regions of the world. It will be shown that these changes in the technological base and use patterns were a function and prerequisite of economic development.

4. ENERGY EFFICIENCIES AND STRUCTURAL CHANGE

4.1. International Trends

The more abundant availability of energy in the developed parts of the world is both due to higher consumption of energy and to higher efficiency with which energy services are provided. This can be illustrated with a simple example. Today the average electricity consumption in the OECD countries in about 0.84 kWyr per capita (or 7.4 $\times 10^3$ KWh per capita). About 1.9 TWyr of primary energy are consumed to generate this amount of electricity that is delivered to consumption after transport and distribution to end-uses.[1] The first electric power plants at the beginning of the century used steam engines to turn the generators at best with an efficiency of primary energy to electricity of about 5 percent. Today, the average efficiency with which electricity is generated in the OECD countries is on the order of about 36.7 percent. This represents a seven fold improvement in about 85 years, or an average efficiency improvement of about 2.4 percent per year. With the use of combined cycle natural gas power plants, the efficiency is another 50 percent better than the average of all power plants at present. At the prevailing efficiency at the turn of the century, all of the primary energy consumed worldwide (actually slightly more, about 12.4 TWyr) would have to be used to generate the electricity currently consumed in the OECD countries alone. Based on the efficiency the best natural gas combined-cycle power, plants only a tenth of that amount would be required. This illustrates that structural change in the energy system and improvements in efficiency of energy use have played an important factor in providing a more abundant supply of useful energy in addition to increases in primary energy inputs and better quality of energy sources exploited.

We will first outline some of the more important structural changes in the economy and how they relate to the transformations that have occurred in the energy system and also how the efficiency of energy uses have evolved in the context of overall economic and technological development. In this brief historical account of these transformation processes we will use mostly

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[1] The primary energy inputs to electricity generation are calculated by the substitution method for hydropower, in terms of direct inputs of hydroelectricity, the total primary energy consumption in electricity generation would be somewhat lower at about 1.7 TWyr.

the British and American experiences. The reason for this choice is twofold. First, the data availability is rather good for the historical evolution of these two economies. This is important since the objective is to give a quantitative account of these evolutionary processes. Second, Great Britain was the first country to undergo the process of industrialization and as such was in many ways a precursor of developments in other parts of Europe and later in the world. America, on the other hand, was virtually an agrarian economy in the middle of the last century and today is one of the most advanced countries and the largest economy in the world. American experience thus portrays a lot of the drama in the process of industrialization and illustrates in the course of only about one century the transformation from an agricultural society to an advanced post-industrial economy; a process that many of the newly industrialized societies may soon follow, albeit with different technological and institutional changes more typical of the twentieth century.

4.1.1. Economic Growth and Energy Consumption

Energy is one of the most important constituents of modern societies. The so-called energy crises of the 1970s, caused by the perceived temporary shortage of crude oil supply and the associated geopolitical, environmental and economic problems after more than two decades of ample and cheap energy supply worldwide, has overshadowed the long history of dramatic and profound changes in energy systems, including the numerous problems that were associated with the supply of sufficient energy for economic growth and for improving the quality of life.

Even before the beginning of the industrial age, the provision of adequate energy supply constituted one of the most important commercial and private activities. The evolution of global energy consumption (presented in Chapter 3) illustrates the slow changes in the structure of the energy system. During the nineteenth century fuelwood was gradually replaced by coal as the world's leading economies entered a period of industrialization. During the last 80 years, coal was itself replaced by new sources of energy – crude oil and natural gas. These global changes in the structure of the energy system are more pronounced in the most dominant economies of the two respective historical periods – the United Kingdom during the eighteenth and nineteenth century and the United States during the nineteenth and twentieth century.

Although fuelwood was the most important source of energy in the past, many European countries experienced the serious timber shortages during the nineteenth century that Britain had already experienced during the two preceding centuries. Only the United States were blessed with ample wood supply throughout the period, but even there the large area required for biomass harvesting and expanding agriculture provided serious competition between energy and agricultural land-use. In the United States this need for larger land areas led to further expansion into the Western Territories. However, the consequences of this vast exploitation of timber resources were far-reaching. For example, in 1934 a $75,000 (in 1934 Dollars) "tree-planting project in the middle west has been authorized," ... lending "added proof to the short-sightedness and selfishness of man in the development of the United States. Where once stood mighty forests of virgin timber will now be found vast stretches of denuded territory, swept by burning winds in the summer and stripped of fertile top-soil by the action of rains that run off unimpeded. This is the work of man, who ruthlessly cut down forests for the lumber, without thought for the future or for the effects which might arise from logging operations on an uncontrolled scale." By 1934 "the situation has become so acute as to constitute a national menace" (Scientific American, 1934).

In Europe the problems associated with fuelwood use were grave because the available land area was limited and transport possibilities of wood from areas with abundant supply (e.g., Scandinavia and Russia) were practically non-existent. The larger food requirements needed for the rapidly growing population caused expansions in agricultural activities thereby decreasing the availability of timber. In addition, the increasing pace of industrialization caused new energy needs which posed a new challenge to provide adequate fuelwood supplies. By the end of the eighteenth century a wood crisis was eminent in most of continental Europe, and its alleviation was one of the most important problems during the whole eighteenth century. In fact, fuelwood thefts were one of the most frequent crimes. The first institutionalized measures consisted in more efficient management of forests and in rationalizing and limiting wood consumption to the most strategic sectors of the economy. Other measures were directed toward improving the transportability of wood over longer distances by large canal projects, although wood transport remained to be rather cumbersome and expensive. Finally, many innovations were introduced for improving the efficiency of fuelwood use. They ranged from more efficient stoves in households to more efficient processes of iron smelting, salt extraction and so forth. All of these measures alleviated the shortage temporarily, but with further increases in energy demands the limited supply of wood could not be bypassed.

The ultimate *impasse* out of the wood shortage was solved by the slow substitution of fuelwood by coal (Nakićenović, 1984). Initially, coal mining practices had to be improved to meet the new challenge, but the biggest obstacle to the widespread use of coal was the requirement of new technologies to use coal effectively in place of wood. The first substitution of wood use, however, did not take place in the energy sector but through new construction methods. Wood was increasingly replaced by bricks and stone in building, but it continued to be the basic material for making ships, furniture, machines and tools until the coal age made large increases in iron and steel production possible.

The eventual introduction of coal as an important source of energy actually turned out to be one of the important motors of the industrial revolution, although coal and the associated steam technology did not cause it. Before the advent of large-scale use of steam for industrial processes other sources of shaft power were used such as hydro and wind power and animal and human muscle power. The new uses of coal also helped the transition to a lesser use of fuelwood in its more traditional markets, such as heating and iron production. Railroads emerged as the new transport system, based on the use of coal, which in turn improved the transportability of coal over longer distances and led to the perfection of the steam engine. Efficient steam engines made new improvements possible in coal mining, textiles, and many industrial processes.

In order not to present here a very simplistic view of the emergence of the coal era, we should mention that the concept of the industrial revolution is somewhat misleading. The beginning of the industrial revolution is usually dated back to the end of the eighteenth and beginning of the nineteenth centuries. In fact, this period does not really represent a sharp discontinuity from developments in the preceding centuries. The rise of European industry should more properly be regarded as a long evolutionary process dating back to the eighth or ninth century, when aggressive application of water power as a prime mover in manufacture and agriculture, and the use of horses for transport and agriculture as substitutes for oxen and manual labor were initiated.

Cipolla (1976) mentions four main technological developments of the Middle Ages: The diffusion of the water mill starting in the sixth century; the introduction of the heavy plow in the seventh century; the three-field agricultural system starting in the eighth century; and the diffusion of the rseshoe and the new method of harnessing draft animals starting in the ninth century (see also, White, 1972). These technological innovations were not preceded by inventions in the strict sense of the word. The water mill was known to the Romans, but was not used to replace animal and human labor, as in the Middle Ages. The horseshoe appears to have been used by the Celts, the heavy plow had a Slavic origin, and the horse harness originated in China. Cipolla points out that the Europeans displayed a remarkable capacity for assimilation between the sixth and the eleventh centuries rather than inventive ingenuity (characteristics that are often associated with the Pacific Rim countries today). Diffusion of all these important innovations allowed larger and more efficient use of available energy sources in medieval Europe.

The horseshoe and the new harness increased the effectiveness of using the horse, thereby offering new labor saving opportunities. The ox was increasingly substituted by the horse. For example, in one manor in England (Ramsey Abbey) the number of oxen was halved and that of draft horses quadrupled between 1125 and 1160. The dissemination of iron technology paralleled that of the horse (Nakićenović, 1984). The amount of iron used in agriculture and machines appears to have been extremely limited before the eleventh century. Later, iron use appears more and more frequently in the records. In the twelfth century, the new ways of using a horse efficiently and the spread of the village smithy in Medieval Europe led to the improvement of including metal parts in the heavy plow. Together these innovations made the three-field agricultural practices possible. Fitting new crops into the rotation system expanded agricultural production by reducing fallow land and eliminating the need for the fallow year. Thus, the new way for harnessing animal muscle power and the dissemination of iron processing established the conditions for substantial increases of agricultural productions.

Originally water mills were used for grinding grains, but as cities, trade and manufacturing grew in Europe from the tenth century onwards, the motive power derived from hydraulic energy was applied to an increasing variety of productive processes. The introduction of new mechanisms for vertical movement of hammers, via cams mounted on the axes of the mill, created many new uses for the mills, including the filling of cloth. Beginning in the twelfth century the spread of the water mill revolutionized the textile industry through large labor savings. At the same time mills were also introduced to power hammers and bellows in the production of iron, power saws for wood cutting, and were even used in the manufacture of paper. The dissemination of the water mill was accelerating throughout the Middle Ages. For example, in late eleventh century England, the areas under Norman rule had 5,624 water mills at more than 3000 locations, amounting to about one mill per 50 households. In the fourteenth century, more than 500 Cistercian monasteries operated water mills and many had five or more units. By the sixteenth century, water wheels were in operation throughout Europe and at some sites the concentration of powered machines was quite comparable to that in factories of the eighteenth and early nineteenth centuries. In 1694, it was estimated that France had 80,000 flour mills, 15,000 industrial mills and 500 iron mills and metallurgical works - a total of 95,500 mills some of them powered by wind. A 1666 survey of the Dnieper River in Russia lists 50 dams and 300 water wheels. One of the largest water power systems was built in the Harz Mountain region of Germany with a network of dams, reservoirs and canals to turn wheels that powered mine pumps, wire-drawing engines, ore-washing and crushing mills, and the bellows of furnaces and forges. The construction of the system started in the 1550s and by 1800 it included 60 dams and reservoirs. The largest dam, built between 1714 and 1721, was 145 meters long and fed water to 225 wheels through a network of 190 kilometers of canals. The aggregate power of the system was estimated at more than one thousand horsepower. For a more detailed treatment of the history of hydraulic power see Reynolds (1984).

Beginning in the thirteenth century, the use of wind mills also spread throughout those areas of Europe with the appropriate geographical and climatical conditions required to harness this power source. Although wind mills never became as widespread as water wheels, they were much more powerful. A single water wheel could deliver anywhere between one and seven horsepower, while the most sophisticated wind mills of the eighteenth century provided as much as 20 to 30 horsepower (Nakićenović, 1984).

"The proliferation and increasing power of water mills and wind mills, like the increased use of horses, meant more energy for productive uses. Unlike horses, however, the mills supplied inanimate energy. Their widespread use marked the beginning of the breakdown of the traditional world in which man had to depend for power on animal or vegetable sources of energy. It was the distant announcement of the industrial revolution" (Cipolla, 1976).

In spite of these crucial technical innovations of the pre-industrial era, fuelwood remained as the only source of thermal energy in addition to agricultural wastes. It is not surprising, therefore, that with the growth of population and production, fuelwood became a scarce resource since it appeared at that time to be basically non-substitutable as a source of heat and often also as a raw material. The timber crisis was actually ever present throughout the Middle Ages, starting in the Mediterranean areas already in the twelfth century. By the beginning of the sixteenth century, the southern areas of Europe entered a period of economic decline, so that the demand for fuel and materials stagnated alleviating some of the fuelwood supply problems. But in central Europe, where economic activity expanded rapidly, the shortage of wood was a serious bottleneck to further growth. In England especially, the shortage was already acutely felt in the 1630s.

As it happened, instead of destroying the basis for further economic expansion, the energy crisis served to push England on the industrialization road. England was the most successful of all European countries in substituting dwindling wood supplies by coal. Figure 4-1 illustrates the rapid growth of coal use in England by showing the large increases in coal shipments from Newcastle to London between 1655 and 1830.

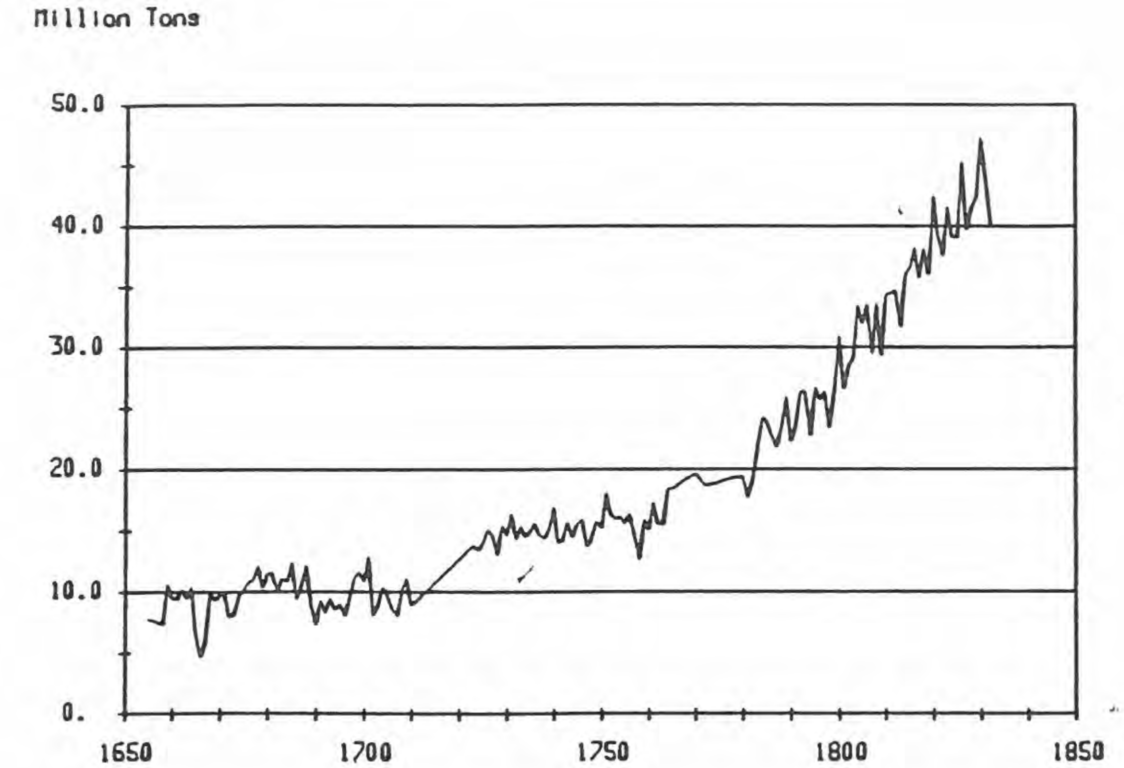


Figure 4-1 Annual Shipments of Coal from Newcastle to London (Nakićenović, 1984).

4.1.1.1. Energy in the United Kingdom

Initially, most of the available technologies for coal use were rather inefficient. For instance, steam engines were no more than one percent efficient in converting coal into motive power. This low efficiency is comparable to the motive power provided by a horse in terms of the hay necessary to feed it. Also the total horsepower rating of early steam engines was low and no better than could be achieved by water and wind mills. Most of the early mechanized cotton mills utilized only about ten to twenty of the horsepower available from water power. By 1835, the average cotton mill in England utilized less than 35 horsepower (Reynolds, 1984). The replacement of water power by steam engines, which began in the 1790s, did not represent a large technical improvement because until the nineteenth century the average steam engine output was less than 20 horsepower. The steam engine had the advantage in that it provided a more reliable source of power, whereas wind and water supply was more uncertain and irregular and necessitated the location of manufacture in windy areas or close to sufficient water supply.

The initial use of coal as a source of thermal energy was also not motivated by the supremacy of coal over other sources of energy, but rather by the acute fuelwood shortage. In fact, up to the early seventeenth century coal was considered technically and environmentally inferior to wood for both industrial and household uses. Once coal started replacing wood in heat generation, and once the technologies were developed for its widespread use, it expanded to other areas such as a source of motive power.

An important factor that helped to alleviate the dependency on fuelwood through increased coal use was the rapidly increasing price of timber caused by its imminent scarcity. The large increases in wood prices strongly resemble the oil price increases of the 1970s, which also caused the rationalization of oil use and intensive research for alternative sources of energy.

Table 4-1 Energy and Wholesale Price Indices, England.

	Price Index		
Period	Wholesale	Fuelwood	Coal
1451-1500	100	100	100
1531-1540	105	94	89
1551-1560	132	163	147
1583-1592	189	277	186
1603-1612	251	366	295
1613-1622	257	457	371
1623-1632	282	677	442
1633-1642	291	780	321

Source: Nakićenović, 1984.

Table 4-1 illustrates the prolonged increases of firewood prices compared with the general commodity price index and price of coal in England between the fifteenth and seventeenth centuries. Although the index numbers represent only rough estimates they indicate that over the two hundred year period commodity and coal price indices increased about three-fold, while the fuelwood index surged by almost a factor of eight (see Cipolla, 1976; Humphrey and Stanislaw, 1979; and Nakićenović, 1984). Thus, during this period fuelwood became more than twice as costly as coal and other goods. Between the 1620s and 1690s, the price of charcoal doubled while most other prices remained stagnant or even showed a tendency of mild decline (Cipolla, 1976). Therefore, it is not surprising that attempts to increase coal use were made well before the onset of the industrial revolution. Unfortunately, the data is very sparse about actual energy use during this period in Europe. We can rely only on spot estimates about the use of various energy sources, such as those mentioned about the use of water power and coal shipments to London.

Although the first use of coal as a fuel dates back to the twelfth century in England, the earliest useful annual energy data available is the coal production series starting in 1700. Due to the lack of any comparable time series on fuelwood use in England it is not possible to reconstruct the market penetration of coal and its substitution of wood. Nef (1932) estimates that the wood used as a fuel in 1700 in England was equivalent to about one half million tons of coal, while the coal production in Great Britain already amounted to about three million tons. Fifty years earlier about 215 thousand tons were produced, which corresponds to an annual growth rate of about 5.4 percent (Humphrey and Stanislaw, 1979). In 1700, however, coal could still not be substituted for wood in the smelting of metals. Thus, in spite of large coal production, the timber dependency persisted in iron making. The growth of coal production from the mid-sixteenth century to the late seventeenth century therefore largely represents the substitution by coal for wood as a household fuel.

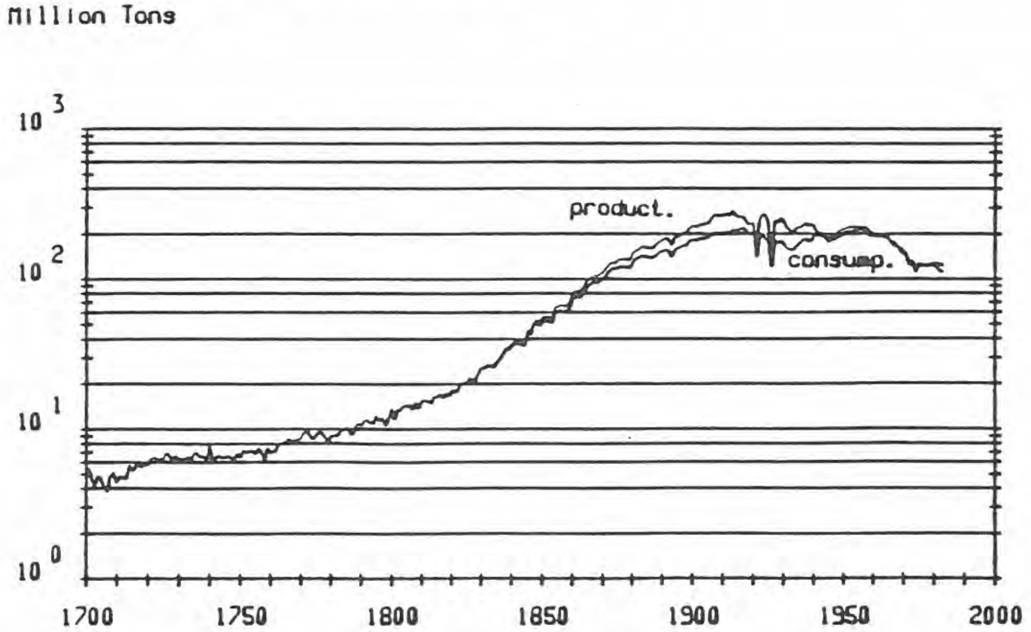


Figure 4-2 Coal Production and Consumption, UK (Nakićenović, 1984).

Figure 4-2 shows coal production and consumption in the United Kingdom from 1700 up to the present. Throughout the eighteenth century coal consumption increased continuously, but not as fast as a century later. Already in 1700 coal became the primary fuel used in the manufacture of alum, copper, saltpeter, salt, gunpowder, in brewing and so forth, although wood was still the preferred fuel for smelting. During the second half of the eighteenth century, Abraham Darby's technical innovation of using coke in iron smelting opened new markets to coal. Thus, the substitution by coal for wood in industry and the metal trade contributed to the rapid growth of coal use starting in the 1780s and accelerating after the 1820s. At the beginning of the nineteenth century, the age of canals and later of railroads greatly reduced the cost of coal transport and opened many new and rapidly growing markets.

During the eighteenth century, wind and water power were still in widespread use in addition to fuelwood. The replacement of wind and water mills began in the 1790s, so that throughout the eighteenth century hydraulic and wind power were the major substitutes for manual labor in providing shaft power. Laxton (1976) estimated that about ten thousand water mills and about two thousand wind mills were operating in eighteenth century England. Humphrey and Stanislaw (1979) showed in a rough calculation that this installed capacity provided an equivalent of about 80 MWyr of shaft power. Considering that early steam engines had a very low efficiency of only a few percent in converting coal to shaft power, the 80 MWyr of shaft power equivalent generated by water wheels and wind mills would translate to about 2.5 GWyr as steam replacement, assuming a three percent efficiency for the average steam engine of the day. In 1760, about five million tons, or less than 5 GWyr, of coal were produced in Great Britain, so that in terms of total primary energy equivalent, wind and water power provided almost one third and coal two thirds. Even if we account for fuelwood use, this rough calculation indicates that already by the end of the eighteenth century coal probably provided more than one half of all primary energy. This rough calculation actually overstates the importance of the traditional energy forms in terms of their fossil energy equivalent, because the actual input of water and wind mills was only 80 MWyr. This energy input was at the time technically and economically not replaceable by steam technologies. Later, when steam machines were further developed, their efficiency also increased. Higher efficiency of converting coal into mechanical energy not only decreases the value, in fossil equivalent terms of the hydraulic and wind mechanical power, but it also illustrates that such calculations are to a degree arbitrary. They only set an upper limit that illustrates the importance of wind and water power in manufacture and agriculture before the industrial revolution. In any case, we can conclude that coal basically became the dominant source of energy by the end of the eighteenth century in England.

Beginning in the nineteenth century, coal finally replaced most of the traditional energy inputs and the growth rate of coal consumption increased paving the way for rapid industrial development. The spectacular growth of cotton textile industries marks the beginning of this process. Later many other industries followed - iron and then steel, railroads, steam ships and so on. The age of coal lasted over two centuries, but in the 1860s crude oil emerged as a new competitor. However, another fifty years went by before oil could capture even a one-percent market share in total primary energy consumption.

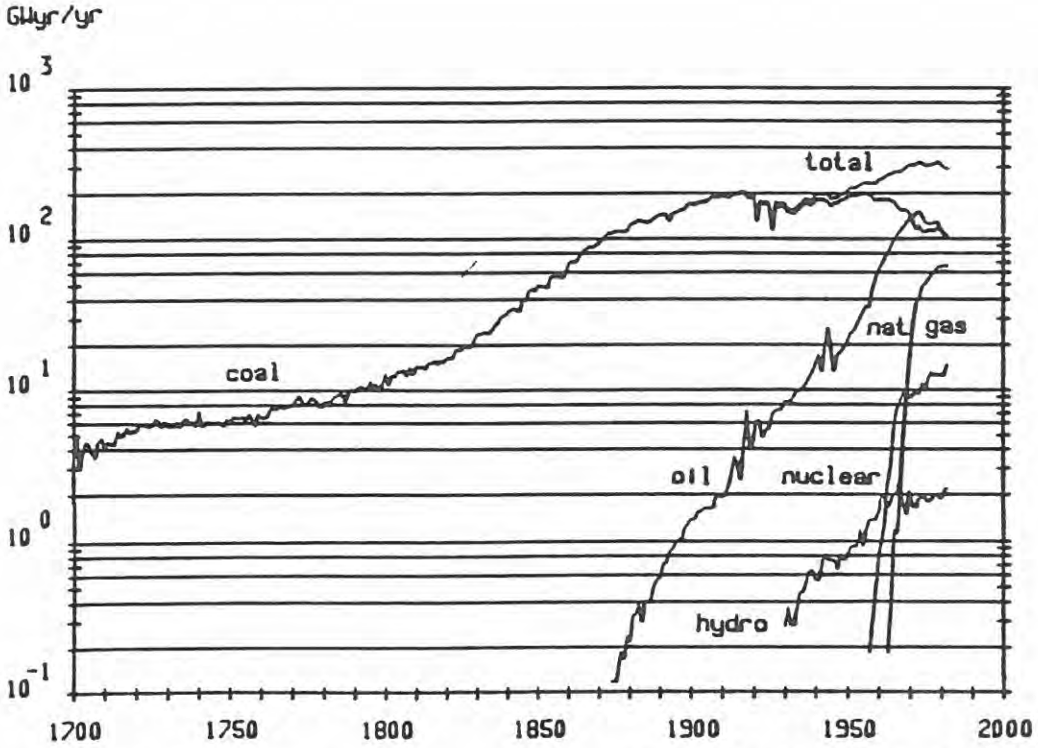


Figure 4-3 Primary Energy Consumption, UK (Nakićenović, 1984).

Figure 4-3 shows the consumption of all important commercial primary energy sources in the United Kingdom from 1700 up to the present. The figure clearly demonstrates the dominance of coal all the way from 1700 to the 1960s when oil became the most widely used source of primary energy. Crude oil was used for the first time in the 1860s and portrayed extremely rapid growth during the next two decades. From 1900 to 1960, the sustained growth of crude oil consumption was still very rapid, averaging 5.9 percent per year. In spite of such impressive sustained growth, it was not until the 1920s that oil use surpassed the coal consumption levels reached in 1700, almost 220 years earlier. In fact, an acceleration in the growth of new energy sources can be observed. Oil grew more rapidly than coal, and natural gas and nuclear energy, introduced in the 1960s, show still faster growth rates. This large expansion of natural gas and nuclear energy can in part be explained by the preemption of some traditional coal uses. Nuclear energy expanded into the electricity market - a traditional stronghold of coal. Natural gas was in a position to substitute town gas, manufactured traditionally from coal and oil, because a distribution infrastructure was already in place.

4.1.1.2. Energy in the United States

The records of energy use and production in the United States are very sparse for the Colonial Times. Historical statistics for the period after the Revolution, however, are fortunately almost complete, so that it is possible to reconstruct an annual time series for the major primary energy sources. This is particularly interesting because the United States industrialized later than the United Kingdom, thereby offering the possibility to analyze the use of older, now practically extinct forms of energy. Even during the early nineteenth century the United States remained basically an agrarian and rural society. In 1870, farming still contributed almost forty percent of the gross domestic product of the United States (U.S. Department of Commerce, 1970), so that local energy sources constituted an important component of the overall energy supply.

The consumption of mineral energy and fuelwood can be traced back to 1800 when timber certainly represented the most important source of energy. Wood was the principal fuel for domestic as well as industrial purposes. Estimates of the fuelwood use during the last century indicate that it was used lavishly, guaranteeing adequate energy supply. In contrast to Europe, and especially the United Kingdom, the United States had vast territories at their disposal, and timber production was usually not limited through resource availability, but rather by the logistics of harvesting and transport opportunities. In practice this means that there was ample supply for local uses. Larger cities in the East were supplied mostly through a growing network of turnpikes, and in case inland transport of wood was not possible, by imported coal from England. However, water and wind power and work animals also provided substantial inputs to the overall energy supply. As in the Medieval Europe, water and wind power supplied the greater part of inanimate mechanical energy. The rest was provided by animal muscle power and human labor. Horses and mules represented a very important source of the motive power needed in agriculture and transport. Even as late as 1920, work animals provided larger aggregate horsepower in farming than tractors and all other agricultural machinery (more than 22 million compared to 21.5 million horsepower respectively, see US Department of Commerce, 1970).

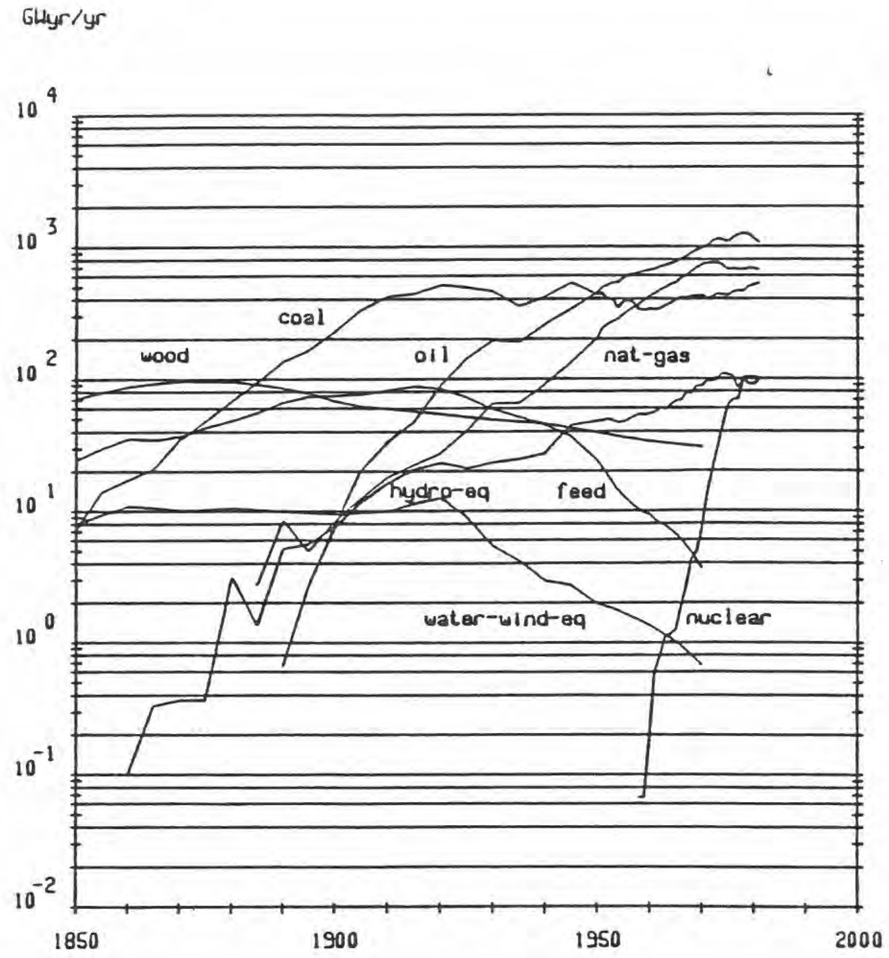


Figure 4-4 Primary Energy Consumption since 1850, US, Substitution Method (Nakićenović, 1984).

Figure 4-4 shows the primary energy inputs for the United States from 1850 up to the present in five-year intervals. We have included all major energy sources including fuelwood, the energy content of work-animal feed, mechanical wind and water power (calculated after the substitution method), coal, crude oil, natural gas, hydropower and nuclear energy. In 1850, fuelwood, animal feed and wind and water mills supplied ninety percent of all primary energy, and coal the other ten percent. Thus, the transition from traditional to commercial energy use was initiated in the United States during the middle of the last century, marking the beginning of the industrial age. In absolute terms, the use of all traditional sources of energy has been declining since 1850, with the exception of slight increases in fuelwood consumption up to the 1870s. This decline continued so that today, basically all primary energy use originates from commercial sources and the marginal use of traditional energy forms disappears in the "noise" of the statistical records. During the second half of the last century, coal not only accounted for all of the increases in total energy use, but it also substituted for the losses incurred by traditional energy forms. This explains the very rapid growth of coal during these fifty years with an average annual growth rate of 6.7 percent. During 1870, both crude oil and natural gas entered the energy market, but the enormous expansion of energy use was primarily due to coal until the end of the century. Between 1900 and 1950 the consumption of crude oil and natural gas increased by an average annual growth rate of 8.5 and 6.6 percent, respectively. Overall energy consumption increased from about 100 GWyr in 1850 to over 2400 GWyr in 1981 which corresponds to an average annual growth rate of 2.4 percent.

Among all traditional energy sources, fuelwood was by far the most important supplying almost seventy percent of all primary energy inputs in 1850. Unfortunately, data on the use of all traditional energy forms during the last century must be taken to represent orders of magnitude rather than precise quantities since they are all based on fragmentary information. Reynolds and Pierson (1942) based their estimates of fuelwood consumption on the population size and distribution, climate, housing conditions, and the availability of wood in the various regions of the United States. Historical records on actual wood use are sparse. As an explanation of this fact, Reynolds and Pierson remarked that there was probably no need to "write about firewood, or even record statistics about it" since "cordwood was about as plentiful as air" in the United States and "nobody wrote about air" use either. Fisher (1974) estimated the feed energy content of work animals by multiplying the number of farm and nonfarm horses, mules and oxen in use with the annual average energy content of the feed required by them. This calculation is based on an annual energy requirement of 3 kWyr per animal, derived from an average animal weight of about 750 kilograms, an average daily consumption of 1 kilogram of feed per 50 kilograms of animal weight, and an average energy content of about 0.5 Wyr per kilogram of feed. Computed in this way, the energy content of work animal feed was the second most important traditional energy source in the United States. It is interesting to note here that although oxen constituted almost 30 percent of all work animals in 1850, horses and mules had displaced them all by the 1900s. Thus, we have here another example of technological change during the early period of American economic development.

Wind and water mills and sailing vessels constitute the last traditional energy source accounted for in our statistical account of US energy consumption. An appropriate treatment of this traditional energy source is the most intricate of all energy forms. The difficulty arises from the fact that it can be accounted for either in terms of the direct mechanical energy (inputs) provided, or in terms of the amounts of other energy forms required to produce the same mechanical work. During the last century only animal and human work could have been substituted for the mechanical power provided by wind and water flow. These two possible accounting methods are equivalent to the two alternatives of calculating hydropower consumption either in terms of energy inputs (i.e., amount of electricity generated, sometimes called primary electricity or equivalence method) or in terms of fossil energy requirements to produce the same amount of electricity (substitution method). In Figure 4-4 both mechanical water and wind power and hydropower are given in terms of fossil and animate energy requirements.

Water and wind consumption are calculated in terms of the feed energy that would have been required by work animals to generate the same mechanical energy. Hydropower is given in terms of the fossil energy needed to generate the same amount of electricity at the prevailing average efficiency of power plants in corresponding years. This calculation method has the disadvantage of overstating the importance of these two energy forms, especially the contribution of wind and water power. The average efficiency of work animals in converting the energy content of feed into mechanical work is very low and does not exceed four percent. This means that the mechanical energy of wind and water power has to be multiplied by at least a factor of 25 to obtain the feed energy requirements. In addition, it is simply unrealistic to calculate total energy inputs to the American economy by implicitly assuming that all wind and water mills could have been substituted by horses and mules had it been required. Furthermore, with the onset of the coal age wind and water power were not replaced by work animals but rather by steam.

In contrast to Figure 4-4, Figure 4-5 shows the primary energy inputs of the United States with the difference that the actual, direct mechanical energy of wind, hydraulic water and hydropower are given in energy terms at prevailing conversion efficiencies of energy inputs to mechanical power and electricity. This does not affect the overall pattern of energy use, since both of these energy sources provided marginal energy inputs that never exceeded more than a ten-percent share.

In the case of the United States we have the unique opportunity to analyze the substitution of traditional energy forms by commercial energy sources. This substitution process can almost be considered as a "proxy" indicator for the pace of industrialization and the economic structural change from agricultural to industrial production. The historical shares of these two broad classes of energy sources are shown in Figure 4-6.

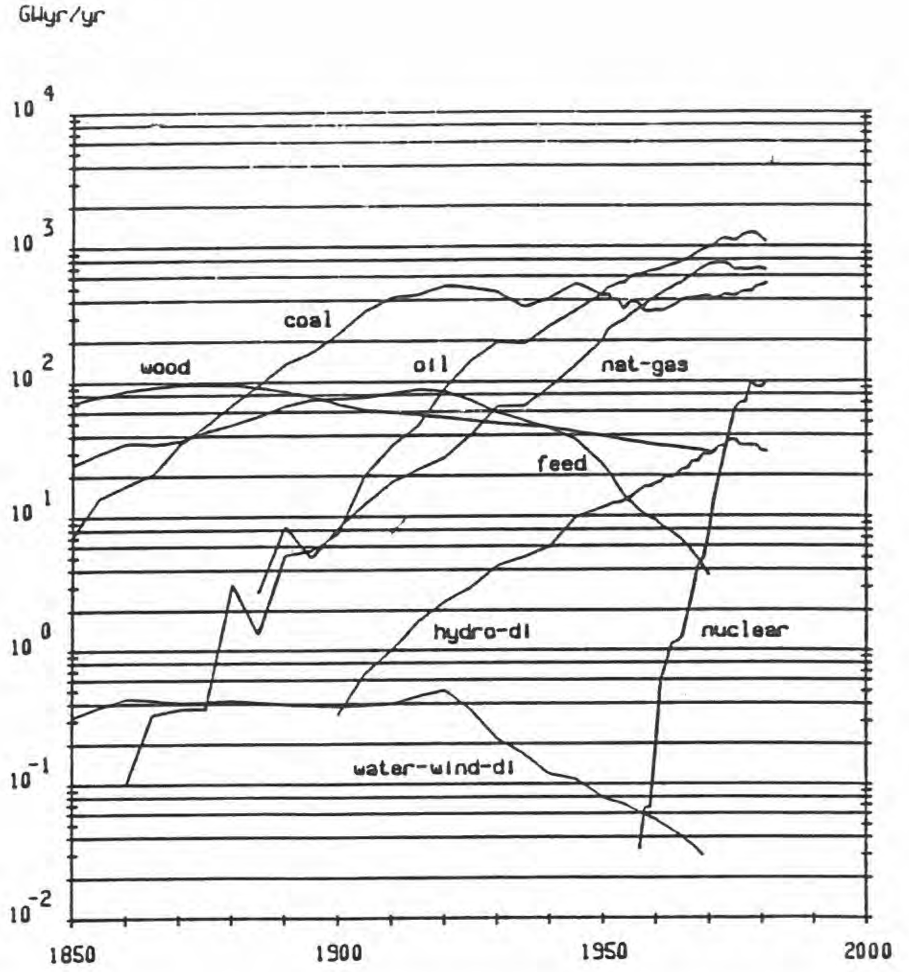


Figure 4-5 Primary Energy Consumption since 1850, US, Equivalent Method (Nakićenović, 1984).

We have grouped fuelwood, animal work, and wind and water mills under the umbrella of traditional energy sources. They all represent renewable energy forms that were basically only suitable for local use by a rural society with small concentrations of industrial production in a few urban areas. The traditional energy forms are shown in competition with commercial energy forms including coal, crude oil and natural gas. Until the 1900s almost all fossil energy consumption was based on coal use. The plot shows the two classes of energy use in terms of their respective fractional market shares in total primary energy consumption and in linear transformation of the logistic substitution pattern. It is interesting to note that the fifty percent mark, in the substitution of commercial for traditional energy, was

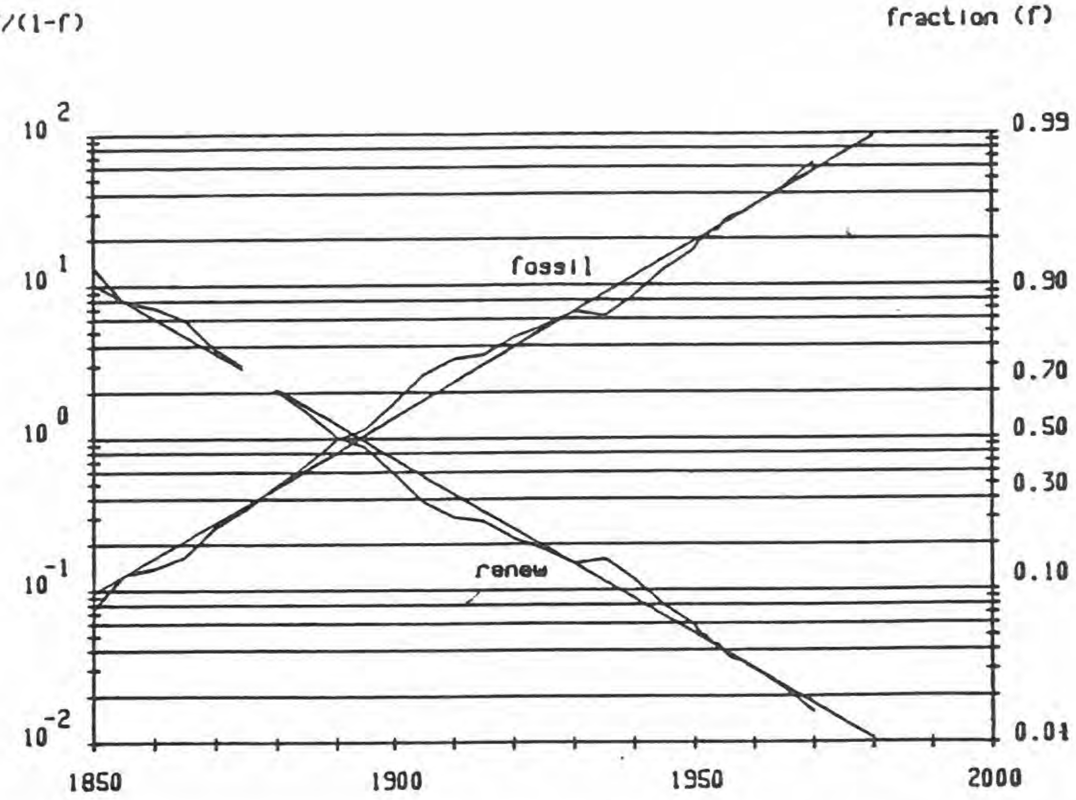


Figure 4-6 Commercial-Fossil for Traditional-Renewable Energy Substitution, US.

reached shortly before the turn of the century. In the United Kingdom this mark must have been achieved at least one hundred years earlier, although this represents only a rough estimate as we have argued in the preceding section. This difference in the shift from traditional to commercial energy use roughly indicates the temporal difference of the industrialization process in the two leading economies during the industrial age. If we extrapolate this substitution process of traditional by commercial energy sources in the United States back into the past, the emergence of coal (commercial energy) dates back to the 1820s. In fact, we will show later that this is a very accurate estimate. The replacement process of non-commercial by fossil energy sources is remarkably long. More than 80 years were required before commercial energy sources could capture a fifty percent share in total energy supply. The corollary of this observation is that traditional energy sources also sustained their decline for over 80 years from the fifty-percent share to the one-percent mark in 1980.

The evolution of commercial energy use in the United States has a longer recorded history than the use of traditional energy sources. Figure 4-7 gives the annual consumption of all commercial energy sources

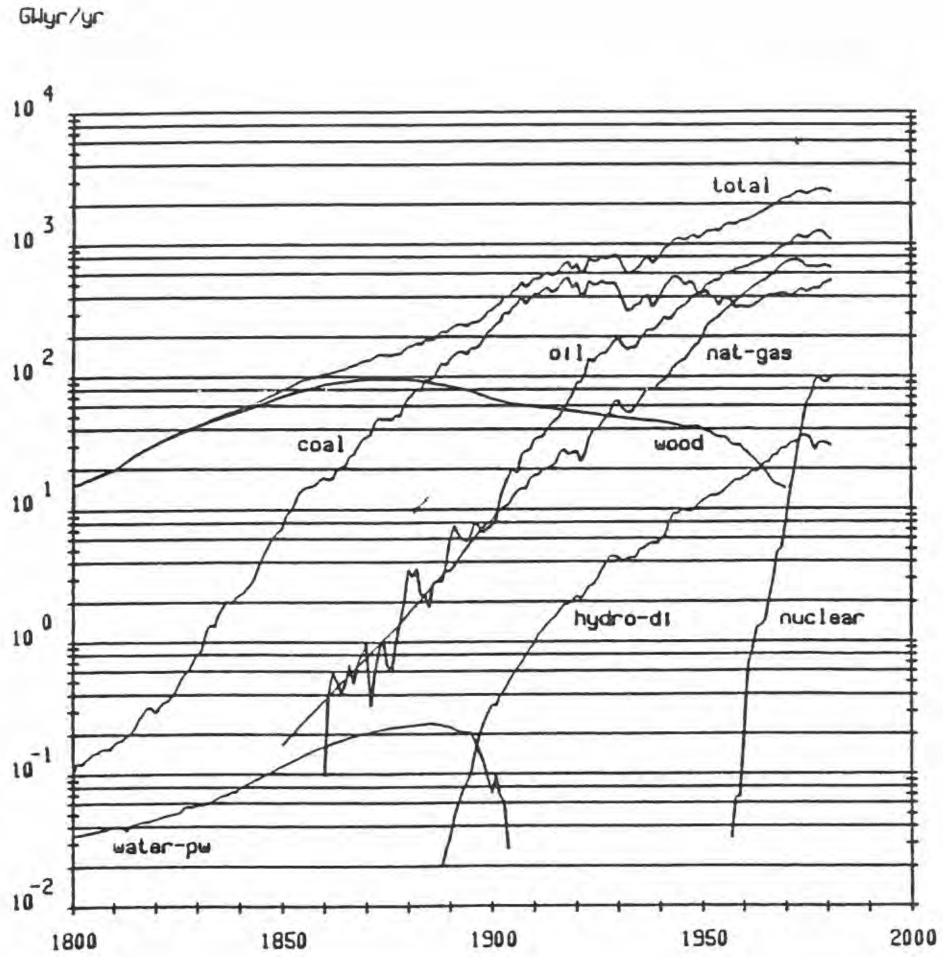


Figure 4-7 Primary Commercial Energy Consumption, including wood, since 1800, US (Nakićenović, 1988).

and fuelwood starting in 1800. Here again we have two possible representations of hydropower. In Figure 4-7 only the direct inputs of hydropower are given at prevailing efficiencies. The method of substituting hydropower by the required fossil energy inputs tends to overemphasize the actual contribution especially during the first few decades of the twentieth century, because the prevailing efficiencies of coal to electricity conversion were very low at that time. For example, in 1900 the prevailing efficiencies were about five percent and in 1920 the average efficiency of installed power plants did not exceed ten percent compared with well over thirty percent in 1980. In any case, hydropower shares of the primary energy inputs were not very large, reaching slightly more than four percent in terms of fossil equivalent or little more than one percent in terms of direct energy inputs during the 1970s.

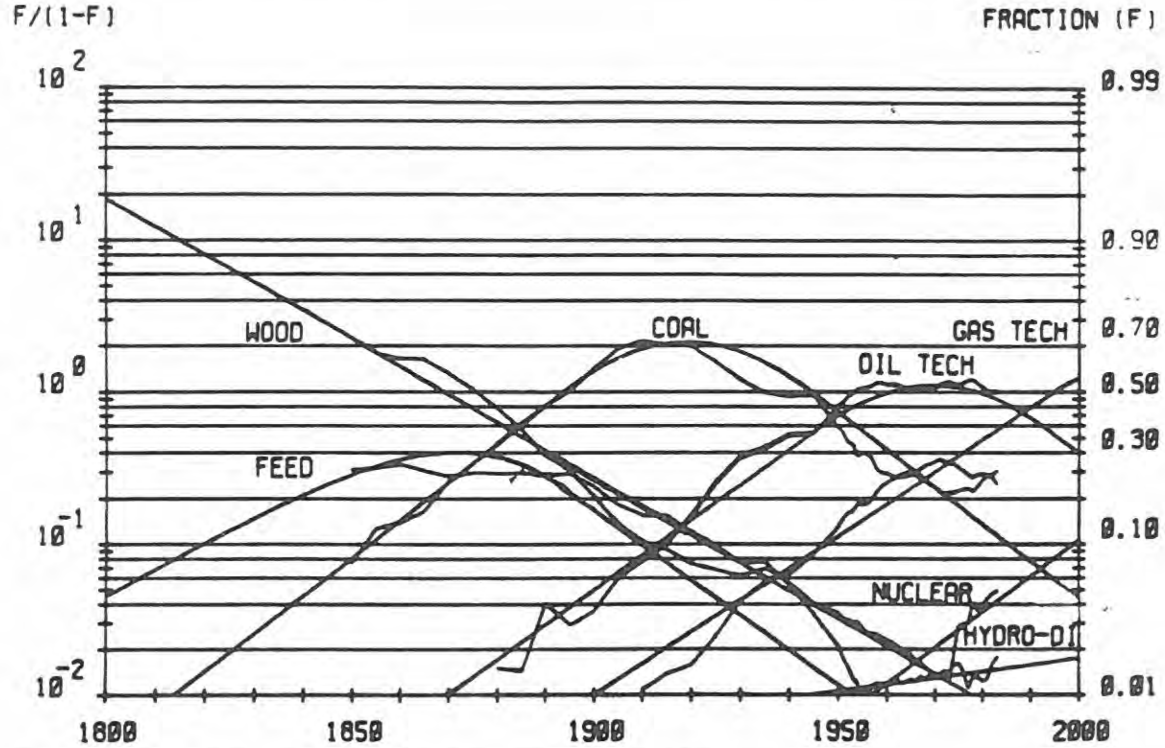


Figure 4-8 Primary Energy Substitution, US.

Figure 4-8 shows the substitution of the five most important commercial sources of energy, fuelwood and animal feed energy inputs. Due to the dominance of fuelwood as the major source of energy during most of the last century, the information loss associated with the lack of adequate annual estimates for animate mechanical inputs to the energy system is not very large. Direct wind and water power are included in the data set, but due to their low contribution to total energy supply, when expressed in terms of their actual energy input, they are not observable above the one percent level. Thus, before the 1820s fuelwood and animal motive power provided for virtually all the energy needs of the United States. Coal entered the competition process in 1817, which corresponds almost exactly to our extrapolation based on the previous example of fossil energy substitution for non-commercial energy sources.

This example illustrates the senescence of fuelwood and animal power and the rise of coal very clearly. Up to the late 1880s it was essentially a two technology market - whatever gains coal made were translated into losses for the two traditional renewable energy sources. Thus, the spectacular increase in the per capita commercial energy (i.e., coal) consumption usually associated with the process of industrialization has to be put into perspective that a not insignificant amount of this increase served to replace traditional renewable energies. Bairoch (1983) for instance estimates, that as much as 20 per cent of the increase in per capita coal consumption in industrialized countries (from about 0.1 to 2.0 kWyr/yr between 1750 and 1913) served the replacement of fuelwood and agricultural wastes.

The prolonged use of fuelwood in the United States compared with Europe and especially Great Britain, shows that wood was an important source of heat and power for early industrial purposes well into the second half of the nineteenth century. In the United States the steam age had already begun in the economy based on wood use. The first steam-boats and locomotives were fired with wood, which remained the principal fuel used by railroads until about 1870 (Shurr and Netschert, 1960). The only other large use of wood was found in the iron industry. Around 1850, more than half of all the iron produced was still smelted with charcoal. Nevertheless, during this early period of industrialization, the United States was still basically a rural society, so that the total amount of fuelwood consumed in manufacturing and transportation was small compared to the huge quantities used in households. In 1880, the domestic use of fuelwood still accounted for more than 96 percent of fuelwood consumed (Shurr and Netschert, 1960). At the same time, however, coal already supplied almost one-half of all energy needs, most of it being used by emerging industries. In 1880, coal supplied almost ninety percent of the fuel used for smelting iron. Thus, the end of the last century marks the beginning of the industrial development period in the United States.

In the United States the first use of crude oil dates back to 1859 when Colonel Drake successfully completed his famous Pennsylvania oil well. The first uses of crude oil were mainly for the production of a purified distillation product, kerosene, that was used in lamps. During centuries fats and vegetable oil (e.g. olive oil in the Mediterranean) were used as lighting fuels and for manufacture of candles. In the late eighteenth century whale-oil (or sperm-oil) was increasingly used as lamp fuel. Whaling harbors were regions of prosperity during these times, perhaps comparable with areas rich in crude oil during the last decades. Toward the mid-1800s whale oil became scarce and very costly and was increasingly substituted by coal oil. The advent of the oil age brought a cheap derivative of crude oil, kerosene, as an ideal replacement the dwindling supply of whale oil and more complex process of producing coal oil. Later a somewhat inferior form of kerosene – stove oil – also competed for a significant share of the cooking market. These were, for almost half a century, the premium products of crude oil refining. In addition, crude oil became the preferred source of lubricants, wax and bituminous construction materials (Linden, 1988).

The first uses of natural gas were to dry salt from drilled brine. This was a traditional use of natural gas even in earlier ages dating back to China as reported in 600 B.C. by Confucius. First uses of natural gas for lighting actually predate those of coal oil and kerosene. According to Schurr, *et al.* (1960), the earliest recorded commercial use of natural gas in the new world dates back to 1821 (at the time when coal was supplying just one percent of primary energy and fuelwood and draft animals the rest), when it was used as lighting fuel in Fredonia (New York). Natural gas continued to be used sporadically throughout the nineteenth century. The first pipeline was constructed from Murrysville to Pittsburgh (Pennsylvania) in 1883, after the discovery of a large well in 1878 (Grübler and Nakićenović, 1987).

Despite such pioneering projects by the emerging oil and gas industry, the associated methane was in general considered a waste product. By 1878, both crude oil and natural gas surpassed a one percent share in primary energy consumption, but most of the natural gas consumed in the following decades was used in the vicinity of the oil fields.

Oil captured the rapidly developing automotive fuel market at the turn of the century because of the widespread availability and low price, especially in the United States. Initially gasoline (or naphtha) was a straight-run by-product of kerosene distillation. It was simply the lightest, most volatile of the liquid fractions obtainable by distillation of crude oil and consisted mainly of light paraffins. Only about 15 percent of the refinery output was directly usable as motor fuel. It had an octane number of around 50, which limited gasoline engines to a compression ratio of about 5:1 due to otherwise excessive engine knocking (Ayres, 1989). This uncracked naphtha fraction was inferior as a fuel in the internal combustion engines compared with more costly and less plentiful alternatives, notably, wood alcohol (methanol), grain alcohol (ethanol) and the benzol fraction of the liquid products of coal carbonization (Linden, 1988). This is perhaps one of the reasons for the enormous diversification in propulsion technologies of the early automobiles ranging from electric, steam, coal powder, alcohol to gasoline engines. Thus, right from the start, the marriage of gasoline and the automobile was a compromise that required superior engine technology to overcome the inherent limitations of the fuel. Advances in refining technology helped to solve some of these problems and provided fuels for engines with higher compression such as were required in the piston aircraft. Thermal cracking was developed in 1913 by William Burton of Indiana Standard which both enabled doubling of the gasoline output and increased the achievable octane rating of the fuel. The catalytic cracking was developed in 1938. This sharply increased the octane level, permitting 100-octane gasoline for aircraft and other high-compression engines (Ayres, 1989).

By the 1940s crude oil already provided about 30 percent of primary energy needs. From this point on the use of crude oil expanded somewhat faster as time progressed. In 1950, crude oil consumption surpassed that of coal, and natural gas use had surpassed coal nine years later. It should be noted that as late as the 1920s the use of crude oil was not much larger than the consumption of fuelwood.

It is remarkable that the structure of energy consumption changed more during the period of oil dominance when compared with earlier periods. The 1950s, when oil became the dominant source of energy, represented the beginning of more intense competition between various energy sources both in the United Kingdom and the United States. Until this period, coal had essentially been the only important source of energy in the United Kingdom for almost two centuries. In the United States this role was held initially by fuelwood and after the 1890s by coal. Up to the 1950s, the energy source that dominated the energy supply at the time also contributed more than one-half of all primary energy consumption. After the 1950s, in both countries, each primary energy source contributed less than one half of primary energy. In both countries crude oil was close to achieving a fifty percent share during the 1970s, but before actually surpassing this mark proceeded to decline. Thus, during the last three decades three important sources of energy shared the market with no single source having a pronounced dominance, which is contrary to the pattern observed during earlier periods.

The changes within the energy system are easier to record in terms of a long time series, since a natural common denominator is available for measuring the contribution of each important component of the system - the contributions of all energy sources can be measured in common energy units. Unfortunately, such a relatively simple and common unit is not available for describing the evolution of other systems. To describe changes in other sectors of the economy, only one obvious common unit is available - the monetary value of the various technologies and value generating activities of the sector. This is not, however, an appropriate measurement unit for very long time periods, since the price system itself changes with the structural changes of the whole economy. The energy content of a ton of coal depends only on the quality of coal and it is independent of the time period when the coal is mined or used, but one Pound Sterling in 1700 represents a different monetary system than the same unit of value two hundred years later. If a commodity is essentially free because of its abundance (as was the case with fuelwood in the rural areas of the United States during the last century), then that commodity also has no real economic price in the same sense as the air that we breathe. This, of course, does not mean that a cord of wood had no value at the point of collection. Wood was actually critical for survival but since it was in abundance, its price was insignificant representing basically the cost of timber cutting and processing.

4.1.2. Structural Change and Energy Intensity

There are many ways of determining the efficiency of energy use. The most obvious indicators are the efficiencies of primary energy conversion to secondary and final energy forms. Another possibility is to estimate the efficiency of energy end-use. Examples include the amount of fuel needed for travel, or for space conditioning. All of these efficiencies have improved radically since the beginning of the industrial revolution along with the introduction of more efficient technologies. In some cases the improvements span almost an order of magnitude. For example, in 1920 the average efficiency of natural gas power plants in the United States was nine percent, whereas today the best gas turbines can operate with efficiencies above fifty percent. This improvement spans a period of about fifty years. The efficiency of lamps for lighting improved almost three orders of magnitude during the last hundred years.

All of these efficiency improvements of individual technologies are translated into a more effective use of energy and other materials at the level of the overall economic activity. Some efficiency increases result from improved technologies, others from substitution of the old by new technologies and finally some improvements are due to changing consumption patterns. The extent of these changes and improvements can be expressed at an aggregate level by the amount of primary energy consumed per unit of gross national product in a given year. Figures 4-9.A and 4-10.B show the population and gross national product for the United Kingdom and the United States and Figures 4-9.B and 4-10.B show the ratio of energy consumption over constant gross national product (energy intensity) for the two countries, respectively. In the United States the average reduction in energy consumed to generate one Dollar of gross national product was about one percent per year during the last 185 years. The ratio decreased from more than thirteen kilowatt-years per (constant 1958) Dollar in 1800 to slightly more than two kilowatt-years per Dollar in 1987. Thus, a regular decline in energy intensity of the whole economy prevailed over a long historical period indicating that improving energy efficiency is a historical process that was rediscovered as a concept during the last decade.

In the United Kingdom the energy intensity at the aggregate level of the whole economy portrays a more complex development than in the United States. Initially, energy intensity increased up to the 1870s and then proceeded to decline also at an average rate of one percent per year between 1900 and 1982. This indicates an interesting parallel development in

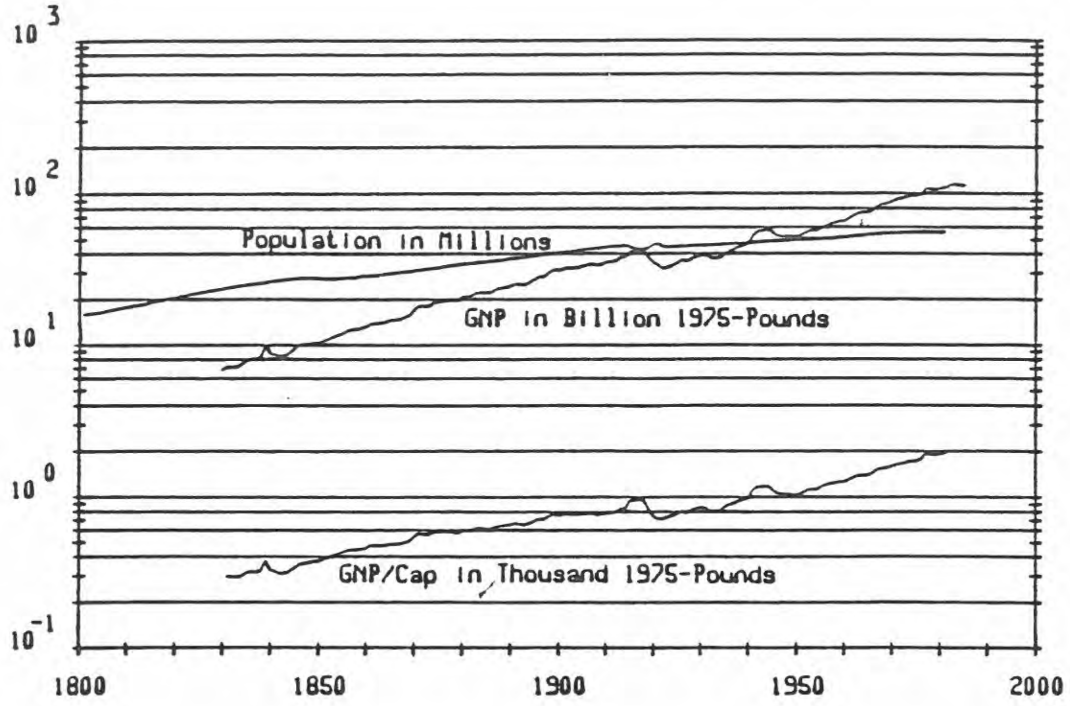


Figure 4-9.A Population, (constant 1975) Gross National Product and Per Capita Gross National Product, UK.

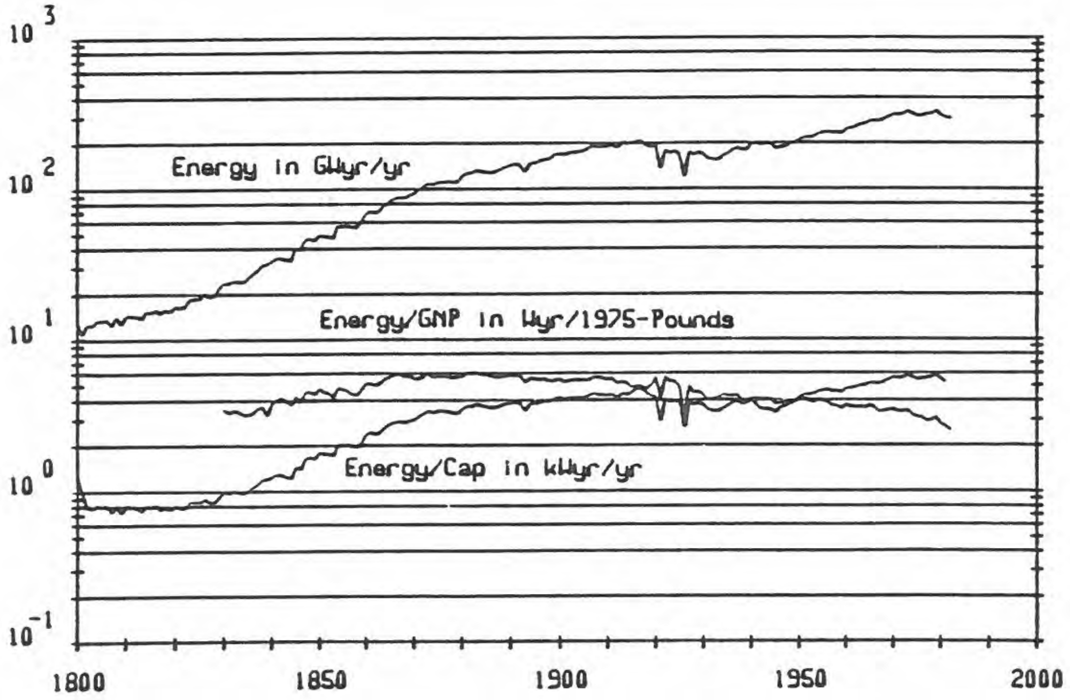


Figure 4-9.B Primary Energy, Per Capita Energy and Energy Intensity, UK.

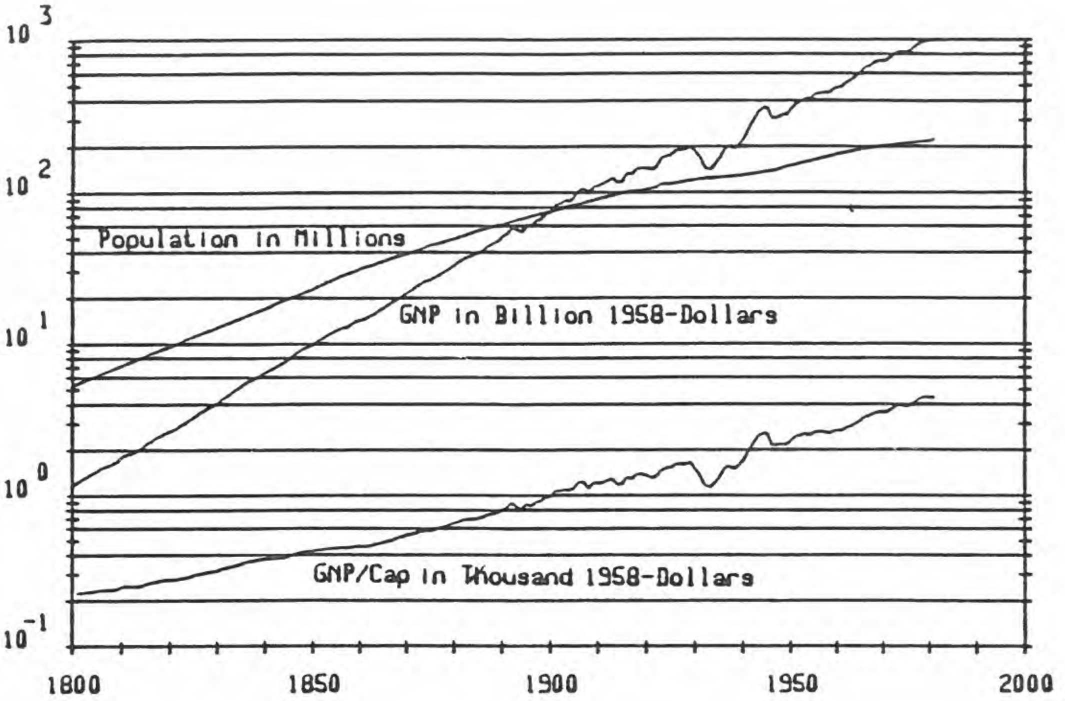


Figure 4-10.A Population, (constant 1958) Gross National Product and Per Capita Gross National Product, US.

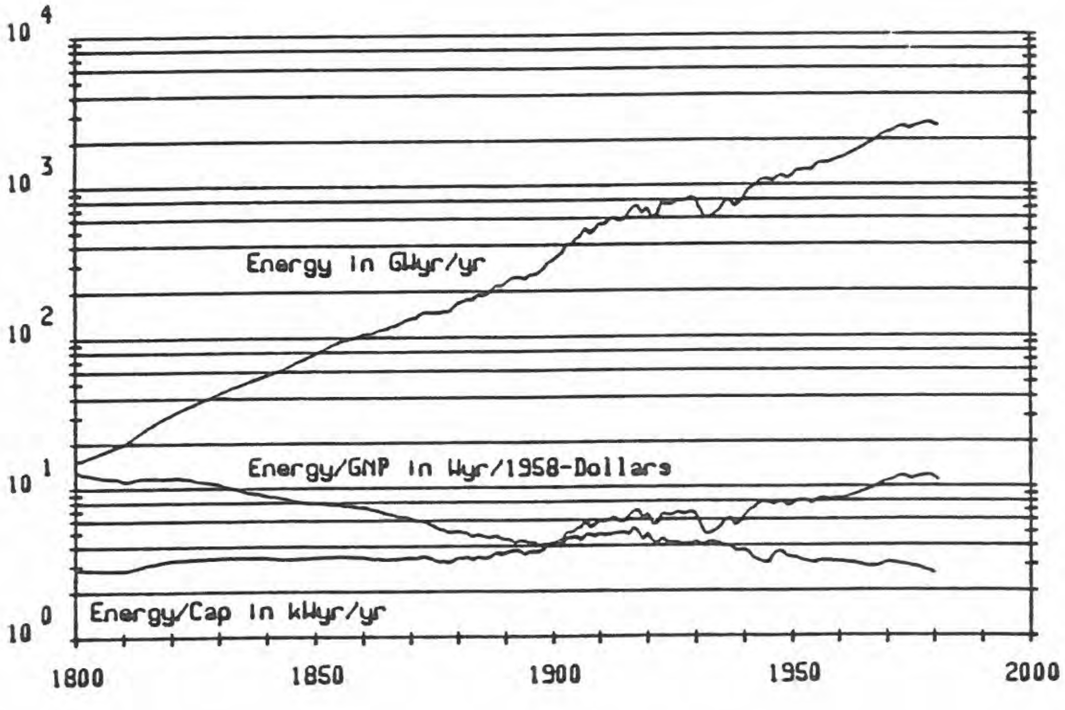
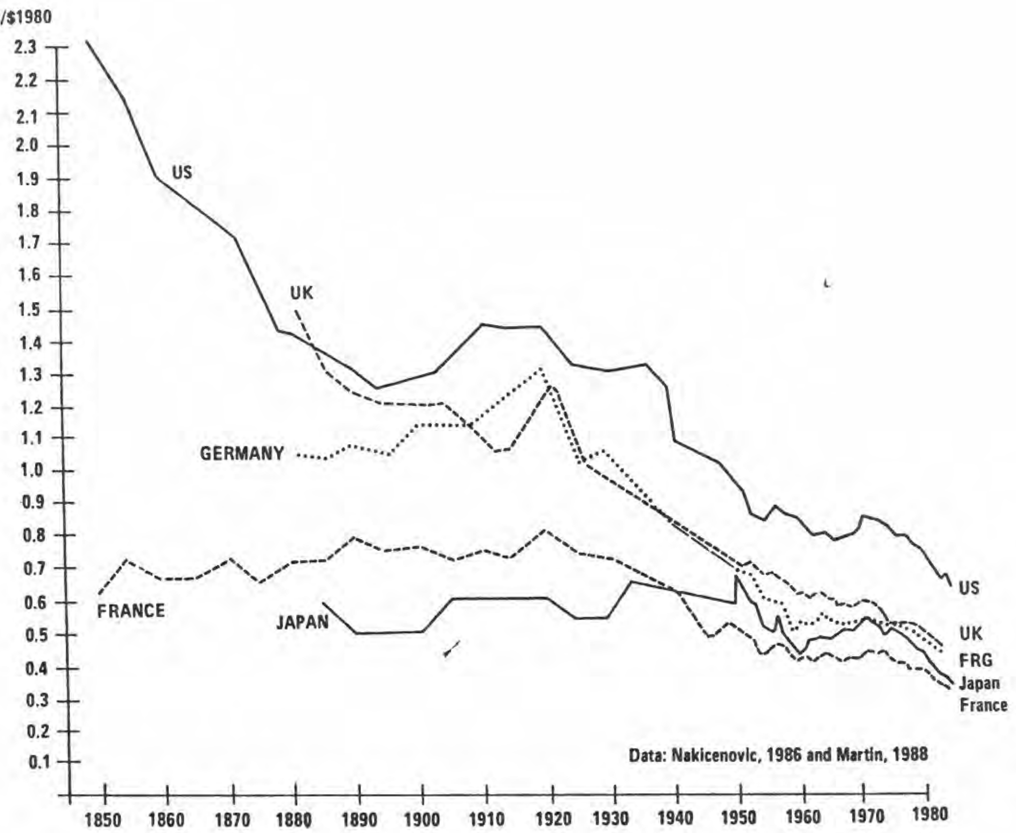


Figure 4-10.B Primary Energy, Per Capita Energy and Energy Intensity, US.

aggregate energy use in the two countries after 1900 and also poses the question why the energy intensity decreased in the United States during the nineteenth century and increased in the United Kingdom. Much of this difference is certainly due to the fact that non-commercial energy use is not accounted for in the primary energy consumption for the United Kingdom. If the fuelwood consumption is excluded from the ratio of energy over gross national product in the United States, the same secular trend as in the United Kingdom is obtained: energy intensity increases up to 1920 and than proceeds to decline at a rate of about one percent per year. The lag of 20 years in reduction of fossil energy use per unit value of gross national product, between the two countries, is due to the fact that fuelwood was the primary source of energy in the United States throughout the nineteenth century. Therefore, the initial increase in energy intensity in the United Kingdom appears to be due to the substitution of non-commercial by fossil energy sources and not by the actual increase of energy consumption per pound sterling of gross national product. If this was actually the case, then the reconstruction of the ratio of energy consumption over gross national product, at an annual one percent decrease throughout the nineteenth century, would offer a method for estimating non-commercial energy use in the United Kingdom.

Figure 4-11 shows the long term evolution of energy intensity (primary energy, including fuelwood, per constant gross domestic product) in selected industrialized countries: UK, US, France, Germany and Japan (based on data by Nakićenović, 1986 and Martin, 1988). We have pointed out above, that the frequently used argument of increasing energy intensities in the early industrialization phase may be misleading. This is, because increasing commercial energy intensity in the process of industrialization is actually an indicator of the replacement of traditional renewable energy forms such as fuelwood, as shown above in the case of the US. Consequently, we have included also estimates of fuelwood consumption (Martin, 1988), because of the predominance of fuelwood in the energy balance of most industrialized countries throughout much of the 19th century.

Seen from this perspective, and also bearing in mind that the earlier (pre WWII) data estimates are approximative, one can nevertheless draw useful conclusions on the basis of Figure 4-11. Improving energy efficiency appears as a long-term, inherent feature of economies as they develop, primarily due to continuous restructuring and technological change that goes along with the process of industrialization. The "breaking of the energy coefficient" since 1973, is from this perspective no new development, but consistent with a long term evolution of the energy use towards higher efficiency, although the rate of improvement since 1973 was on average about twice as high as the long term historical average.



Data: Nakicenovic, 1986 and Martin, 1988

Figure 4-11 Energy Per Constant GDP Since 1850 in Selected Industrialized Countries.

Also visible from Figure 4-11 are distinct differences in 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 GNP than Western–European countries or Japan, does not necessarily imply that improvements are easier to achieve than in other countries. Also, normative approaches, e.g., suggesting that it is possible for all countries to achieve similar low energy intensity figures, appear highly questionable in view of the path dependency shown in Figure 4-11.

At the same time, it also becomes clear, that industrialization and development is possible by following alternative lower energy intensity paths, as illustrated by the long term energy intensity in the case of France and Japan, compared to the pattern in Germany and the UK or even the US. This is of particular relevance for developing countries as it shows that development can also be achieved by not following traditional resource and energy intensive smoke-stack industrialization strategies. Future economic growth in developing countries could thus also be more consistent with current restructuring in industrialized economies in direction of more information intensive, but resource and energy extensive activities.

This decrease in the energy intensity in industrialized countries fluctuates considerably around the decreasing secular trend of around one percent per year. In fact, there are clearly visible periods when the amount of energy needed per unit value added increased, while in other periods the rate of decrease appears to have accelerated. Much of this variation is not clearly visible in Figures 4-9 and 4-10 due to the logarithmic "compression" of the data nor in Figure 4-11, where available data were given in 5 year intervals. Figure 4-12 shows the long term energy intensity on a linear scale together with the increases in per capita primary energy consumption on an annual basis for the US since 1800. It is interesting to note that the major periods without longer-term improvements in energy intensity occurred in the 1820s, 1900 to 1920 and most recently from about 1955 to the early 1970s. After the OPEC oil embargo another phase in improving energy efficiencies has been initiated.

During the last 185 years, the cumulative improvement in energy intensity was above a five-fold decrease from approximately 13 Wyr/$ (in constant 1958 Dollars)[2] in 1800 to 2.2 Wyr/$ in 1987. This means less than 20 per cent primary energy inputs are needed today to generate a Dollar of value added in the American economy compared with the 1800s. Figure 4-12 also shows that during the same period the per capita primary energy consumption increased three-fold from less than 3 kWyr per capita (which is almost 50 percent higher than the current global average, indicating how abundant fuelwood was in the United States) to about 12 kWyr per capita in the 1970s. In 1987 per capita energy consumption in the US has decreased to 10.7 kWyr/yr. The increase in the efficiency of energy use in the American economy at an average rate of about one per cent per year corresponds in terms of the implied elasticity to a (constant) value of above 0.6 during the period 1800 till present. We will use this historical trend in the change of energy intensity in the American economy as a yardstick for assessing the improvements achieved since the so-called energy crisis of 1973 in a few selected OECD countries.

Table 4-2 shows that the highest improvement in reducing the energy intensity (of GNP expressed in constant 1980 Dollars) since 1973 occurred in Japan, followed by the United States and the United Kingdom. Comparable improvements were also realized in Italy, the Netherlands and FRG. Australia and Canada, as countries, are rich in domestic energy sources and

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[2] Note the different intensity figures stemming from a different base year for calculating GNP in constant Dollars compared to Figure 4-11.

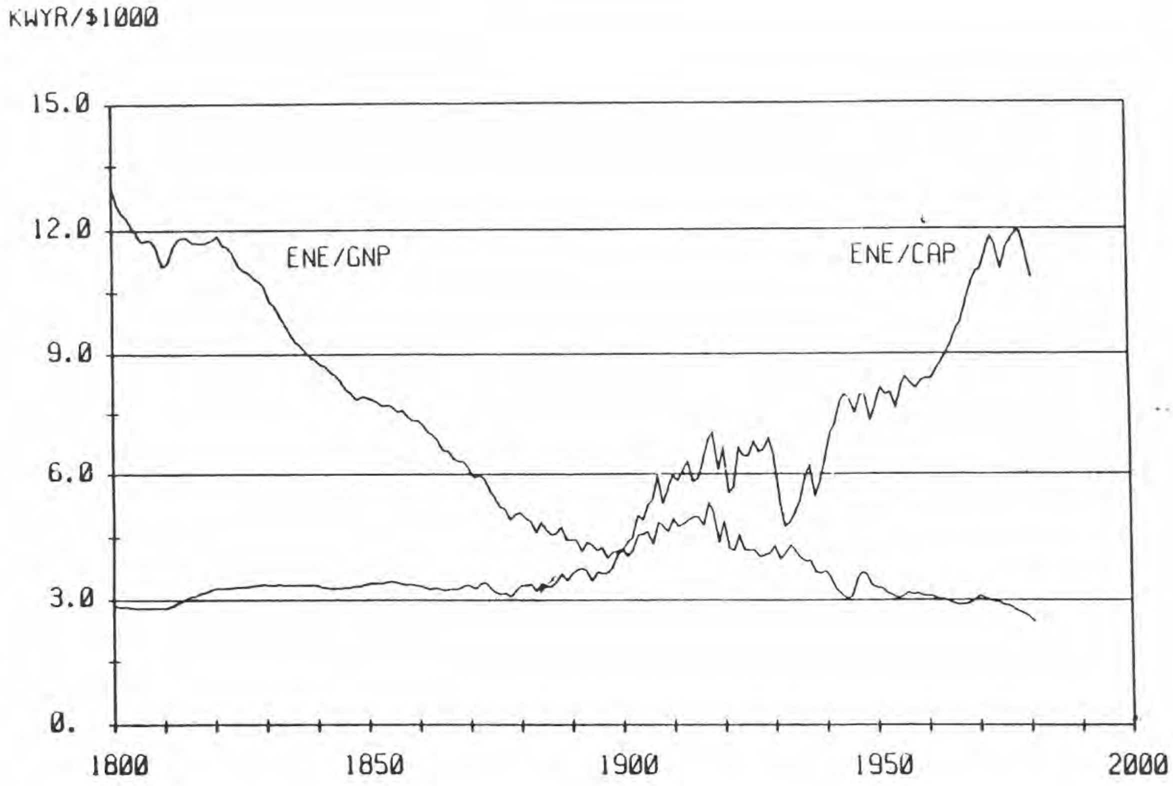

Figure 4-12 Energy Per Constant GNP and Per Capita Consumption, 1800–1987 US (Nakićenovic, 1984).

achieved much lower reductions. In contrast, the energy intensity of the Greek economy increased by 16 percent during this period, primarily due to the development of energy intensive industries such as metal processing. A similar trend can be observed in Turkey since 1979, although it is not as pronounced. This last example, illustrates that all savings in energy were not achieved through rationalization and introduction of more efficient technologies and organization, but also by decreasing the energy-intensive economic activities. Most of the countries with relatively high energy savings reduced the output of basic industries with a simultaneous shift from manufacturing to service sector. This aspect of structural change in the economy had a fundamental impact on reducing specific energy needs during the last 15 years.

It is interesting to note that an average decrease of about one percent per year, observed in the United States over the last 185 years, corresponds to a change of -12 percent over the period from 1973 to 1985, which is about the reduction in energy intensity observed for Turkey. Thus, the energy intensity decreased twice as fast since 1973 in the United States than its

Table 4-2 Primary Energy Intensity of Selected OECD Countries.

Country	1973	1979	1983	1985	Change 1973-85
	(megajoules per 1980 Dollar of GNP)				(percent)
Australia	21.6	23.0	22.1	20.3	−6
Canada	38.3	38.8	36.5	36.0	−6
Greece[1]	17.1	18.5	18.9	19.8	+16
Italy	18.5	17.1	15.3	14.9	−19
Japan	18.9	16.7	13.5	13.1	−31
Netherlands	19.8	18.9	15.8	16.2	−18
Turkey	28.4	24.2	25.7	25.2	−11
United Kingdom	19.8	18.0	15.8	15.8	−20
United States	35.6	32.9	28.8	27.5	−23
West Germany	17.1	16.2	14.0	14.0	−18

[1] Increase is a result of a move toward energy-intensive industries such as metal processing.

long-term historical rate and in Japan almost three times as fast. While these are very impressive achievements, they are not as large as could be expected from many programs and investments directed toward using energy more effectively. The increases in the international competitiveness would also suggest additional attempts to reduce the specific energy requirements. Apparently this was not the case, or at least the effect was not as large as could be expected on the basis of the long-term historical trends. We will try to further elaborate this aspect in subsequent sections of this chapter.

Figure 4-13 shows the improvements of primary energy intensity of Gross Domestic Product (GDP)[3] expressed in constant 1980 Dollars for the United States, the United Kingdom, FRG, Japan and France. It illustrates the developments since 1950 in contrast to the reduction achieved since the oil shock of 1973 given in Table 4-2. It clearly shows that the United States not only consume much more energy per unit value added than the other leading OECD countries, but also that during the 1960s there was a

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[3] In contrast to the Gross National Product, the Gross Domestic Product does not include factor transfers from abroad.

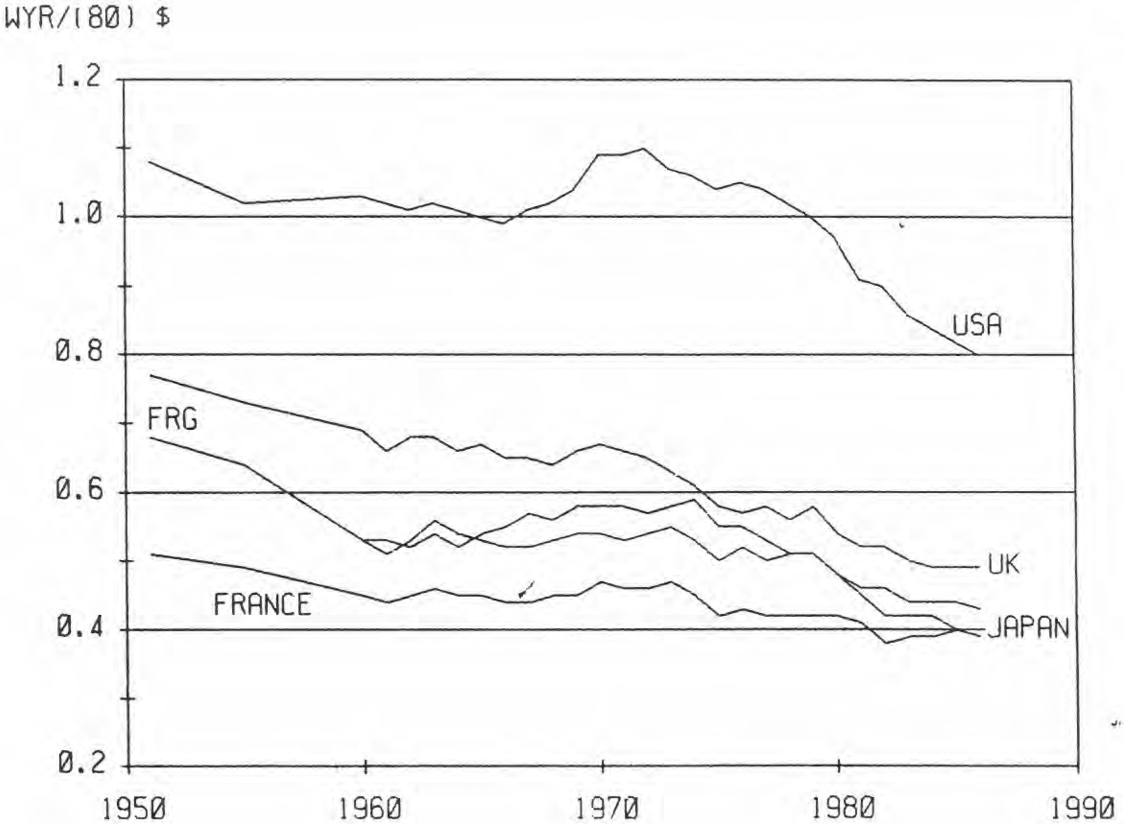

Figure 4-13 Primary Energy Intensity in Selected OECD Countries.

substantial increase in the energy intensity in the United States that is hardly perceptible in the development trajectories of the other four countries. The average improvement in the energy intensity for the United States since 1950 is thus reduced exactly to the long-term average of one percent per year despite the large improvements since 1973! Apparently the rapid economic growth and expansion of the 1950s and 1960s has led to retardation in improvement of the energy efficiencies at the level of the whole economy, and the accelerated energy savings and efficiency programs launched after 1973 can be seen as a correction and a reversal that brought the trajectory back to the historical average. While the other four countries use energy much more efficiently than the United States, the relative improvements since the 1950s have been on the order of 1.3 percent in the United Kingdom and FRG, about 1.1 percent (since 1960) in Japan and about 0.6 percent in France. It should be also noted that the evolution of energy intensity in the other four countries appears to be convergent within a range of between 0.4 and 0.5 Wyr/$, while the United States with the current level of about 0.8 Wyr/$ is not only twice as high but is currently also higher than any of the other OECD countries of Figure 4-13 had in 1950.

We have presented an aggregate view of changing energy intensity of the five selected OECD countries that also illustrates average improvements in the overall energy efficiencies. Nevertheless, it is quite clear that energy use and economic growth have evolved in unison. This fact prompted many researchers to go as far as to claim that energy use is a good proxy for the level of economic development. In economic terms this would mean that energy use is rather inelastic. However, the experience of the last two decades demonstrated that the energy elasticity can indeed change when compared with the strong coupling of the two indicators during the 1950s and 1960s.

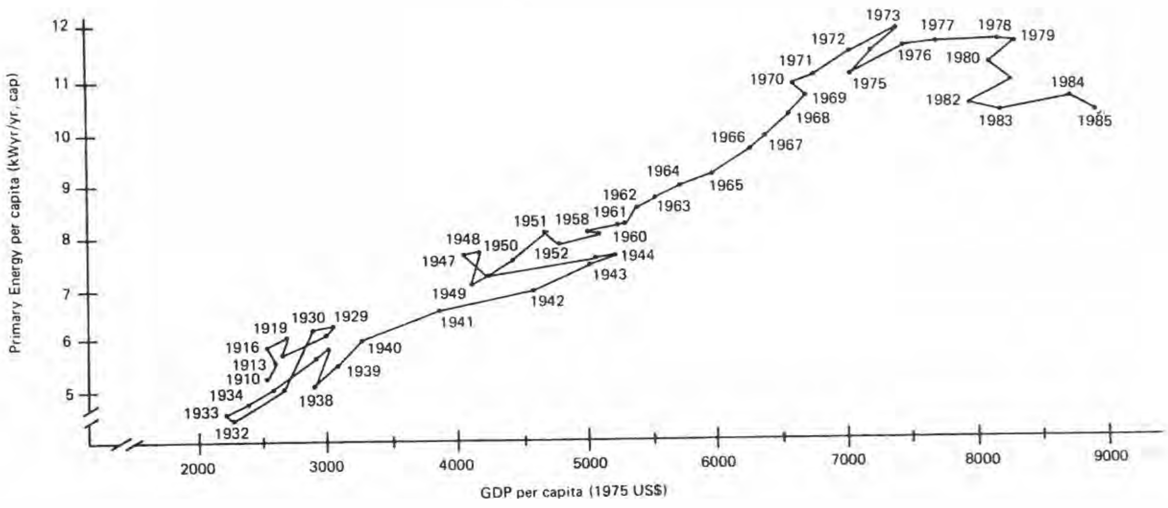

Figure 4-14 Primary Energy and GDP, US.

Figure 4-14 shows the changes in the energy/GDP relation in the United States since the beginning of the century. Over this longer period there were three clear discontinuities and reversals in the energy intensity in the 1930s, 1940s and 1970s. These discontinuities are also reflected in the changes of the long-term elasticities of energy and GNP in the United States, given in Figure 4-15. The average elasticity was about 0.6 during the last two hundred years. Elasticity is defined as the ratio of relative change in energy growth in a given period divided by the relative change in economic growth during the same period. During periods of changing relationship between energy and economic growth, the elasticities varied more rapidly reaching values in the range of between -7 and 12. This means, that while in the long-run energy growth was lower than the economic growth, there where periods when the energy use grew more rapidly than the economy and periods where energy use decreased, despite increasing economic output.

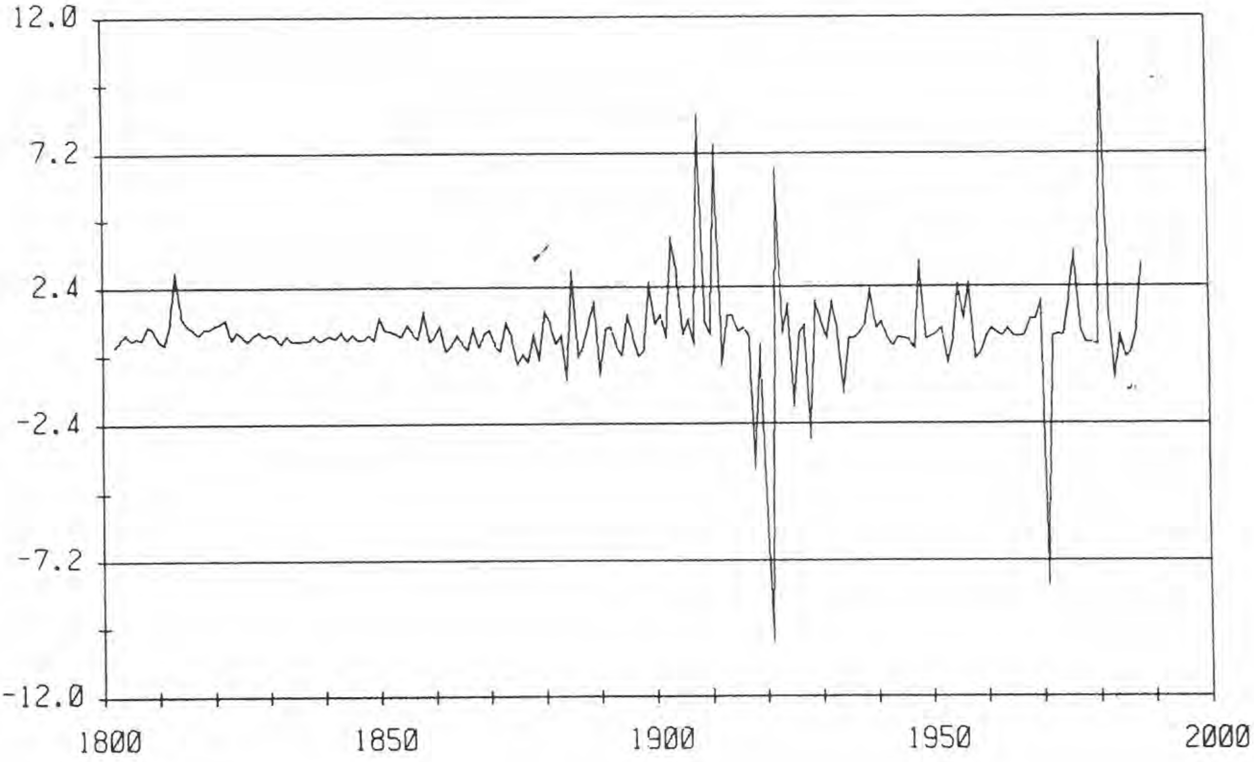

Figure 4-15 Primary Energy and GDP Elasticity, US.

Our discussion shows that the energy intensiveness of economic growth is by no means homogeneous even among the industrialized countries. Thus, the aggregate efficiency improvements have to be differentiated in terms of the individual development path of each society. Often in many complex social and economic processes it is not the absolute levels that should be used as a yardstick of performance, but rather relative improvement compared to prevailing initial conditions. It amplifies the fact that energy is but one factor in determining techno-economic development trajectories in the maze of complexity of social and economic processes. This observation should, however, not hinder the importance of improving overall energy efficiencies. We have shown that at the aggregate level the reductions in relative energy intensity are important features of development in all most industrialized countries, both in terms of the historical perspective and during the last two decades. Less energy and other factor inputs in the economy also means that productivity, output and competitiveness are improved.

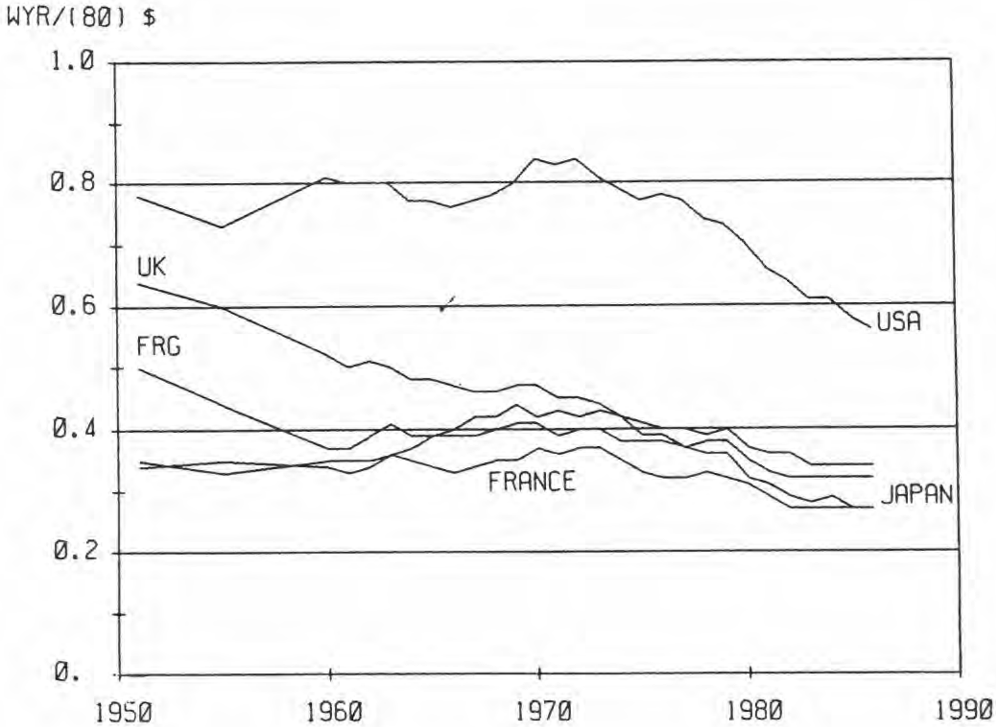

Figure 4-16 Final Energy Intensity in Selected OECD Countries.

Thus it is understandable to strive to raise the efficiency with which primary energy is converted to other and more useful forms. We have seen in the previous chapter that the efficiency with which energy, contained in any fuel, is converted to useful form varies widely, depending on the method of conversion, the available mix of fuels and the end-use desired. Due to these differences in the structure and efficiency of the energy system in different countries and regions, it is useful to compare the actual intensity of GDP with respect to the final energy forms actually delivered to consumption. This measure gives a more direct indication of the actual energy inputs after the conversion, transportation and distribution stages within the energy system. To a limited degree this measure excludes the efficiency of the energy system and allows for comparison of actual energy intensity per unit of value added at the level of final energy consumption. This is true only to a limited degree because the mix and quality of delivered final energy carriers can influence the end-use efficiencies. For example, heating by fuelwood in an open fireplace is at least eight times less efficient than by a modern electric or gas furnace; consequently the final energy requirements of fuelwood would be eight times higher than those of electricity or natural gas for the same kind of service, namely space heating.

Figure 4-16 shows the final energy intensities per unit value added (GDP in constant 1980 Dollars) for the United States, the United Kingdom, FRG, Japan and France. It shows clearly that the difference between the energy intensity of the American economy and the other four industrialized countries is smaller when expressed in terms of final energy requirements compared to the primary energy/GDP ratio analyzed in Figure 4-13 above. This indicates the possibility of two overlapping differences; namely that some energy conversion and distribution systems from primary to final energy are more efficient in other countries and also to some extent that the final energy carriers with smaller conversion losses have higher shares.

Modern industrialized countries can be viewed as a complex machine for degrading high-quality energy into waste heat while extracting the energy needed for creating an enormous catalogue of goods and services (Summers, 1971). As a result of steadily increasing efficiencies in the conversion of energy to useful heat, light and work, the GNP increased above the increases in primary energy requirements in most of the industrialized societies since the shift from traditional to fossil energy sources has been initiated. It is evident, however, that these favorable improvements are not possible in all phases of economic development. During the periods of rapid economic growth and expansion the annual increases in fuel consumption rise as fast and sometimes outpace the growth in GNP. This indicates that gains in fuel economy are not easily achievable under the conditions of rapid expansion and balanced growth. In contrast, the period since the mid-1970s, with the onset of economic restructuring and saturation of many traditional industries, made larger improvements possible. For producers of goods and services increased efficiency means lower production costs; for the consumer it means lower prices; for countries it means higher competitiveness; for everyone it means reduced pollution and environmental burdens.

4.1.3. Sectoral Energy Intensities

We have shown that the aggregate intensity of energy use in the industrialized economies has to be seen in the context of their past techno-economic development trajectories. A differential assessment of the importance of energy use in various economic activities appears to be more appropriate than a simple comparison of absolute numerical values. Only with such a complex view is it possible to analyze the future improvements in energy efficiencies at the global level and in individual countries. Furthermore, the aggregate view based on the level of the whole national income (GNP or GDP) masks the changes that are occurring at the sectoral level and individual energy use activities. In the following chapter we will more explicitly analyze the latter in terms of the efficiency of energy consumption and supply. Here, we will outline the changes in energy intensity at the sectoral level. This is again, to an extent, a static view since the structural change in an economy slowly transforms the various activities that are associated with a given sector and at the same time also the allocation of different activities among the economic sectors. For example, in the agricultural societies basically all activities associated with food production, processing, transport and marketing are defined to be a part of the agricultural sector. Through the process of industrialization many of these traditional activities become commercialized in the newly emerging industrial, transport and service sectors. Consequently, any changes in the energy intensiveness of food production are no longer associated only with agriculture but also with the food industry, transportation, retail and restaurants. Over shorter periods this definitional problem is not so significant. Thus, we will outline the changes in energy intensity in the three most important sectors (industry, transport, residential and commercial) of the industrialized countries, over the last 30 years. This assessment will be based both on the aggregate changes in each sector and the effects of structural changes within the individual sectors.

4.1.3.1. Industry

Industry is the most energy consuming end-use sector in most of the industrialized economies, accounting for 33 percent of the total final energy consumption in the OECD countries (see OECD energy flow chart for 1986 above). Since 1973 the industrial energy consumption declined by about 1.3 percent per year in the OECD region, while industrial output increase at an average rate of about 2 percent per year. These differential developments resulted in the overall reduction of industrial energy intensity of more than 30 percent.

Figure 4-17 shows this decline in the United Kingdom, Japan, the United States, FRG and France. The reduction in energy intensity exceeded 50 percent in the United Kingdom and Japan. Since 1970 this corresponds to an annual decline rate of more than 4 percent. In all countries there were no significant reductions in intensity during the 1960s. In fact, in Japan the intensity increased primarily due to the very rapid expansion of energy intensive industrial activities, such as the automobile and metal working

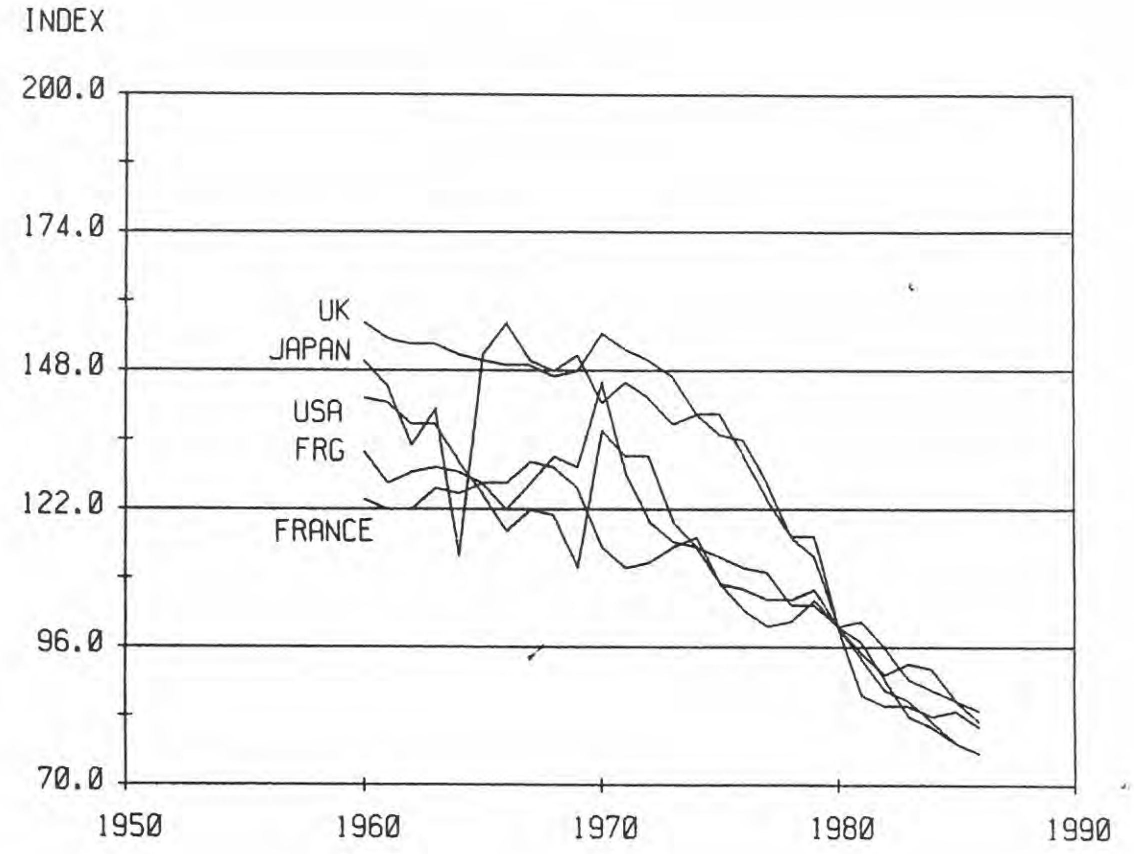

Figure 4-17 Industrial Final Energy per Unit of Output in Selected OECD Countries (Index is 100 in 1980).

industry. These reductions were achieved through energy efficiency improvements and up to now to a more limited extent also through structural changes (changes in output mix). A recent study on Energy Conservation in the IAE Countries (IAE, 1987) concludes that higher efficiencies were a major factor in reducing energy intensity. It summarized the improvements achieved in FRG, Italy, the United Kingdom and France. Several other studies of both United States and Japanese industries come to similar conclusions (IAE, 1987). In all cases, energy efficiency improvements accounted for more than half of the decline in energy intensity during the last 15 years.

These efficiency improvements in industry encompassed the full range of measures. However, the replacement of older by new capital vintages and equipment that is, in general, much more energy efficient, probably made the highest impact in reducing energy intensities. Rationalization measures concerning the organization of production and public energy saving incentives and programs naturally also had a large impact. However, new investments and higher productivity of newer capital vintages, in creating value added with lower factor inputs, was one of the most effective measures in both improving competitiveness and improving industrial energy efficiency in the industrialized countries.

The traditional explanation that is often heard is that the efficiency improvements and reductions in demand for industrial products were caused by increases in real energy prices after 1973. It is claimed that rising energy prices have not only accelerated the adoption of energy-efficient technologies, but that they have also provided added stimulus to structural shifts towards less energy intensive production methods and output mix in the goods produced. As such it has supposedly slowed economic growth. After the energy price collapse in the mid-1980s it is no longer clear that this traditional explanation of cause and effect is valid. It is certainly not convincing in the face of the longer-term historical evidence that reductions in energy efficiency resulted from both continuous and more sudden changes in the structure of the economy and energy system. Less efficient energy forms and production methods were replaced by new ones even during the prolonged periods of relative stability in energy prices. The above "consensus" is progressively vanishing; today environmental concerns are becoming a more stringent constraint on further growth and an important explanation for the need to improve overall efficiencies including energy use. It is more correct to say that the socio-economic development trajectories of the post-war expansion phase are reaching their limits of validity.

In the previous development phase, productivity increases were primarily obtained by increasing economies of scale in the mass production of energy and material intensive products. We argue, that the paradigms are shifting toward system integration, flexibility and quality, environmental compatibility and toward higher value and information intensiveness of products and services. Unlike in the previous economic expansion phase, productivity increases will no longer be based on increasing economies of scale, but rather on increasing *economies of scope* (Grübler and Nowotny, 1989). Conventional wisdom holds that economies of scale and cost reductions via labor saving technologies will constitute the major future driving forces in the manufacturing sector. We argue, however, that the emerging future development trajectories will be characterized by a shift in the value generating activities away from energy and material intensive products towards value and information intensive ones. There are strong indications that the philosophy of the production system is shifting toward higher reliance on just-in-time methods, high turnaround times and inventory minimization, unprecedented quality and precision levels and so on.

4.1.3.2. Transport

The transport sector accounts for 30.5 percent of total final energy consumption in the OECD countries. Over the last three decades the development in the transport sector has been one of the major concerns of private and public energy policy because of a high dependency on oil. Oil products constitute about 99.2 percent of all transport energy needs, and road transport is responsible for about 80 percent of this amount. Thus, energy savings and improvement in efficiency has been one of the major imperatives in the transport sector. Oil products are particularly difficult to replace in the road system due to the lack of appropriate substitutes that would not necessitate elaborate infrastructural changes and replacement or at least fundamental modification of the vehicles. There are very few alternative energy carriers that are suitable as direct replacement of motor fuels. As a consequence, large investments were made both by industry and governments in improving the fuel efficiency of motor vehicles. In some cases the achievements are indeed impressive.

However, a vehicle fleet has an average replacement time in the range of ten to fifteen years. This means that this time interval is needed to replace about half of the fleet by more modern and energy efficient vehicles. In addition, energy efficiency is but one performance characteristic for both private and commercial vehicles. Due to all of these reasons, the average fuel consumption has decreased per vehicle-kilometer much less drastically than what the best models on the market can achieve. Furthermore, air transport expanded rapidly during the last 30 years and it is again completely dependent on jet fuel and other oil products. The above mentioned shifts toward higher value intensities in manufacturing and services, higher flexibility and quality have all led to increases in road and air transport activities due to better quality of service and higher speed as compared with other more traditional modes, such as rail and water transport.

The trend toward higher mobility and the whole philosophy of just-in-time production and inventory minimization tend to increase the need of transport services. This is probably best illustrated by the case of the Cadillac Allanté, a car body manufactured by Pininferina in Torino, Italy and transported by air freight over 5000 km to Detroit for final assembly of engine, power train and electronics by General Motors. This "production line" over 5000 km is apparently economic considering all the direct and indirect costs of potential damage risks, insurance and the production inventories that would be locked in an ocean freighter for weeks.

It is, of course, difficult to measure the output or productivity of all transport activities in common units other than in a monetary terms. In the case of energy intensity in industry, we have used the aggregate output as a measure of economic activity; for the transport sector we will measure the energy intensity in terms of the value added generated by commercial transport activities (i.e. the GDP share of the transport sector).

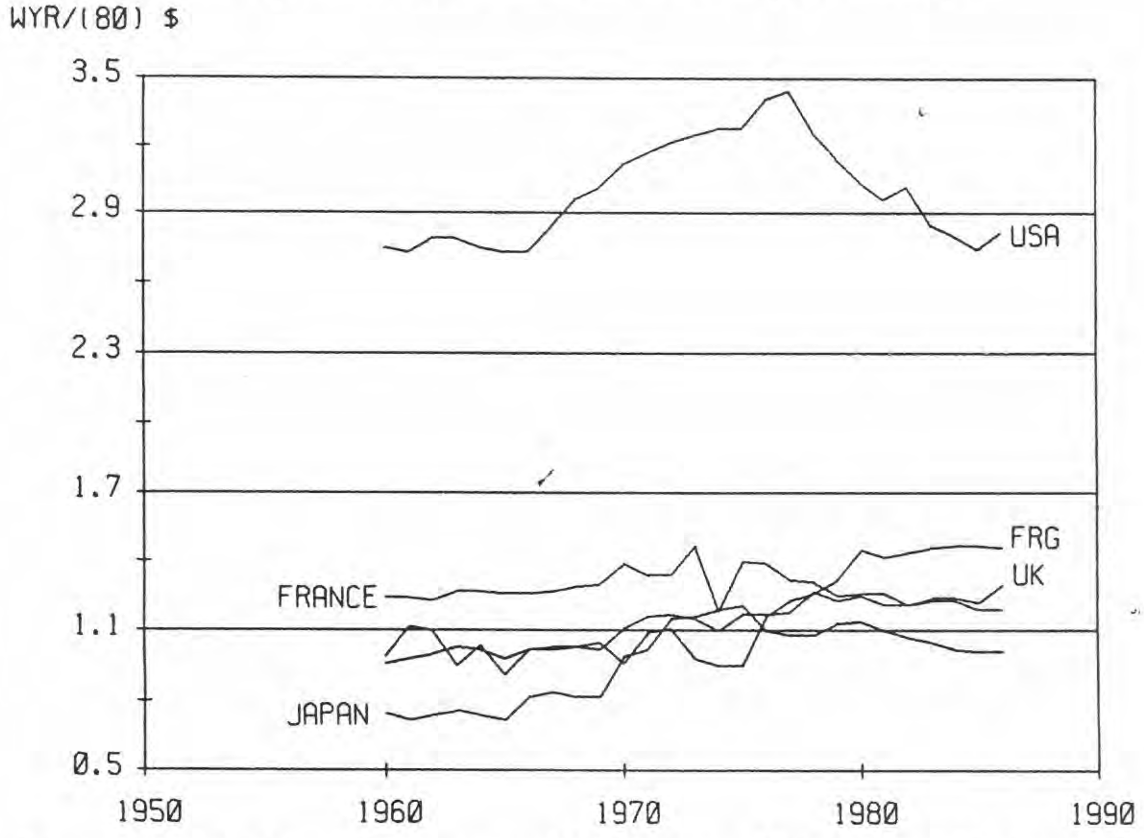

Figure 4-18.A Final Energy per GDP Share of Transport Sector in Selected OECD Countries.

Figures 4-18.A and B show the development of final energy intensity in the transport sector in terms of the GDP share (in constant 1980 Dollars) in the United States, the United Kingdom, FRG, France and Japan. The United States has again by far the highest intensity, although there have been substantial improvements since the late 1970s. This is primarily due to the high level of private car ownership and use both for commercial activities as well as for private ones. The aggregate effect of the post 1973 improvements has been to reduce the intensity back to the levels prevailing in the early 1960s. In France and the United Kingdom there was only a slight increase over the last 26 years in energy intensity of the transport sector. Japan and FRG show a much stronger increase in energy intensity, indicating that the shift toward faster transport services and more mobility has been particularly strong in these two countries. Due to the fact that the final energy intensity changes in these four countries are confined within a rather narrow band, Figure 4-18.B highlights the mentioned differences

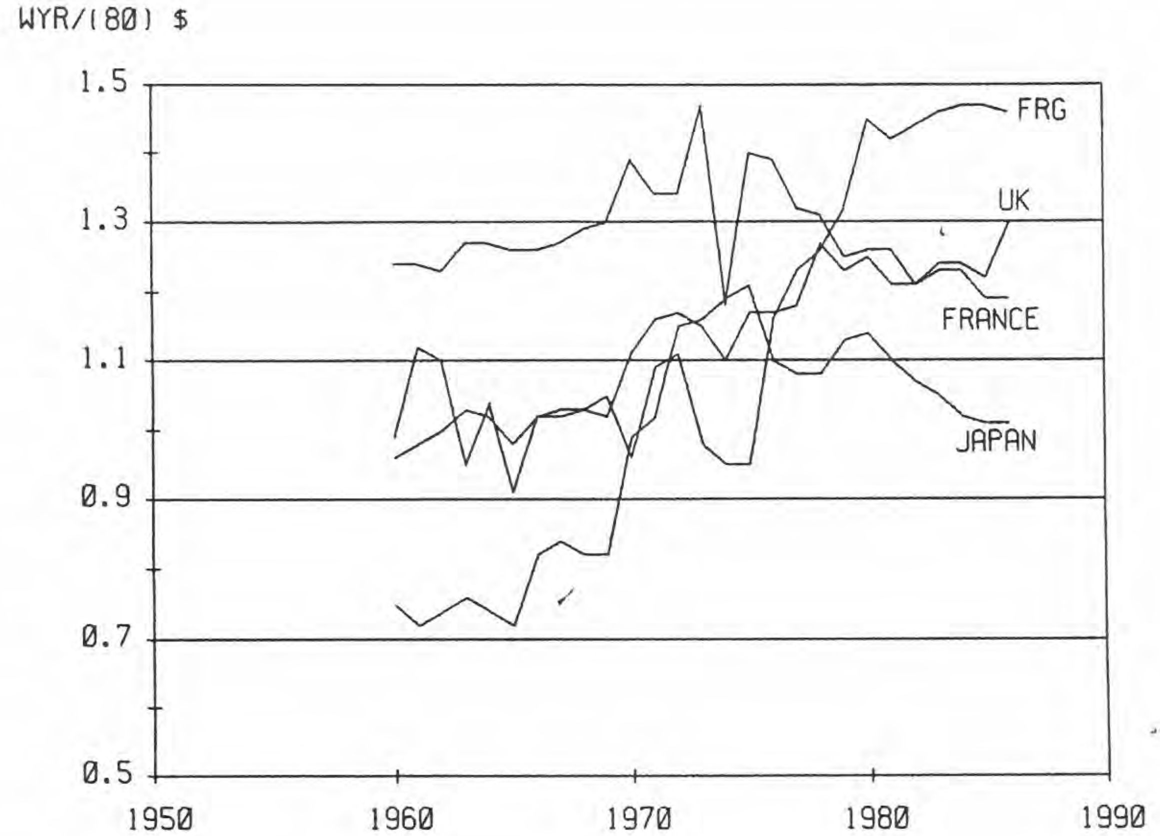

Figure 4-18.B Final Energy per GDP Share of Transport Sector in Selected OECD Countries.

through a higher resolution.

There is no doubt, that large efficiency gains were achieved in the transport sector during the last decades. From the historical perspective, the replacement of horses by automobiles represented an important efficiency improvement, just as did the introduction of railroads seven decades earlier. In the same sense, the energy intensity of contemporary vehicles is much higher for the same performance as that of earlier models just a few decades ago. The efficiency improvements of passenger cars have, in general, decreased their share in total motor fuel consumption, while the expansion of road goods transport has led to a higher fuel use despite substantial improvements in vehicle efficiencies. The same is true with the replacement of the piston by jet aircraft in commercial air transport. Per passenger-kilometer the energy efficiency of jet aircraft is better than that of earlier piston transports and the performance has increased substantially, but the large expansion of global commercial air transport operations has led to an increase in fuel consumption. In the case of rail and marine transport the efficiency improvements were not so large due to the longer average longevity of the capital structure. In any case, the point is that new demands on travel and transport have substantially increased the operations worldwide, and especially in the industrialized countries that have to a large extent offset the savings in energy use, achieved through efficiency improvements and voluntary and legal measures in reducing energy consumption.

4.1.3.3. Residential and Commercial

Residential and commercial sectors has been traditionally one of the most inefficient consumers of energy. Most of the energy uses provide space conditioning (heating and more rarely cooling), lighting, cooking and other services associated with end-use devices such as household and commercial appliances. It is thus not surprising that much of the energy conservation efforts during the last two decades focused on improving the efficiency of end-uses in this sector and on changing consumption patterns. Both technological and institutional measures are equally important here in reducing the specific energy demand. The efficiency improvement alone is not sufficient without changes in life-styles and user oriented conservation measures. In industry and transport economic rationality already dictates a continuous effort toward reducing costs and since energy is an important component of these costs there are strong incentives for using energy as rationally as possible. They do not always suffice as the history of energy conservation indicates, but nevertheless in principle they are one of the overriding components of business and public policy. In the case of residential and commercial energy consumption this is not *a priori* the case.

Another important reason is that the residential and commercial capital stock tends to have a much longer lifetime in contrast to the transportation and industrial equipment. It is true that the infrastructures also have very long useful life both in industrial production and transport systems, but the installed equipment tends to have a more frequent turnover than say household heating systems or residential and commercial buildings. Nevertheless, through numerous improvements it is now possible to reduce energy inputs of an office or residential building by a large factor. Some measures are more direct and concern the installed heating systems and appliances, others are indirect and increase the thermal and radiation insulation of the buildings themselves.

There are a number of offsetting factors that tend to reduce the potential energy savings. An important one concerns the changing demographic trends, such as family size and age distribution, the others concern the changes in life styles such as leisure activities, housing patterns and much greater demands for services as affluence in the industrial countries increases. Urbanization is increasing and in many areas the settlement density increases as well. The number of single person households is increasing in most of the industrialized countries, as well as the living area per person. The growth of services is one of the major structural changes in the industrialized countries. The financial sector is growing along with the dramatic increase in information oriented activities. Much of the development in the industrial sector toward increasing flexibility, quality and just-in-time operations is increasing the activities in the services sector. This is also true for health care, sport and education. In the industrialized countries especially, the growth of services and reallocation of many activities that were originally part of the industrial sector, have led to the notion of service industry due to the very large increases in value added in these economic activities. All told, the energy efficiency and conservation measures have been to a large degree overcompensated by growth in the residential in industry and commercial sector. Today, this sector is the largest consumer of energy in the OECD countries with a 33.4 percent share in total final energy. This energy requirements are supplied by almost equal amounts of natural gas, electricity and oil products.

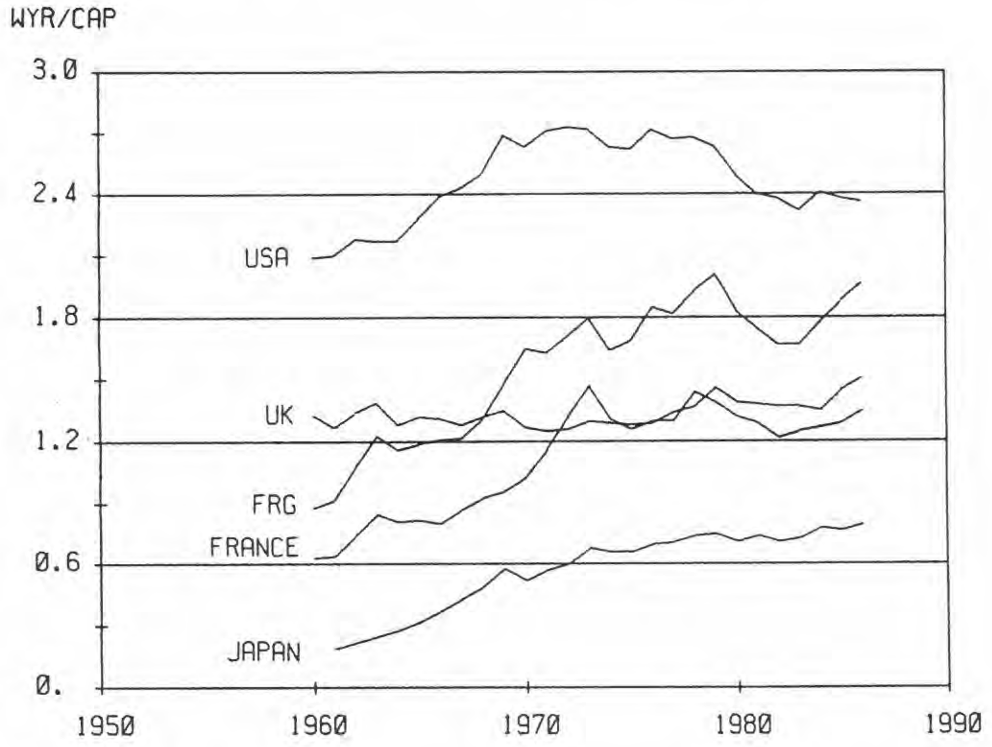

Figure 4-19 Final Energy per Capita in Residential and Commercial Sector in Selected OECD Countries.

Figure 4-19 shows that the final energy requirements have increased in the commercial and residential sector in per capita terms in the United Kingdom, FRG, France and Japan, while in the United States there has been a steady decline since the early 1970s. The United States especially has been a lavish consumer of energy for space conditioning, lighting and for household appliances. Due to the already high degree of penetration of these uses in the United States, and a resulting virtual saturation in further diffusion of household appliances, air conditioning, office machines and other equipment, the energy efficiency improvements that have been achieved during the last 20 years are more clearly visible in per capita terms at the aggregate level. In the other countries the efficiency improvements were also large, but due to the increase in ownership of household appliances, more widespread use of office equipment, increasing penetration of central heating and so on, the aggregate level of per capita final energy is still increasing in residential and commercial applications.

4.1.3.4. Electricity

The growth of electricity use in most industrialized countries has been a multiple of both total and nonelectric energy consumption growth since the turn of the century. As a result, the share of electricity in total final energy increased to a value between 15 to 20 percent of all final energy consumption (Figure 4-20). It is interesting to note, that the share of electricity in final energy is highest in Japan, not only because final energy demand per GDP is among the lowest in Japan, but also because many measures, which have contributed towards efficiency improvements in final energy use are linked to further electrification.

The other OECD countries have shown a similar pattern of increasing electricity intensity. In the United Kingdom the share of electricity has the slowest and diminishing growth rates probably due to domestic resources of natural gas and oil that have relieved some pressures toward electrification. During the last few years the growth rates are also declining in the United States and FRG. Another exception is France with rather rapid growth in the share of electricity starting with the aggressive development on nuclear energy in the early 1970s. At that time the share of electricity was significantly lower than in the other countries, but due to the vigorous growth of nuclear power France is now second only to Japan. Figure 4-21 illustrates this development from another perspective. It gives the increase in the use of electricity in comparison to other fuels in the OECD countries. This increase is measured as a percentage of each fuel supplied indirectly as electricity with respect to the total direct and indirect uses of each fuel, e.g. the amount of coal that is used as electricity divided by total coal use.

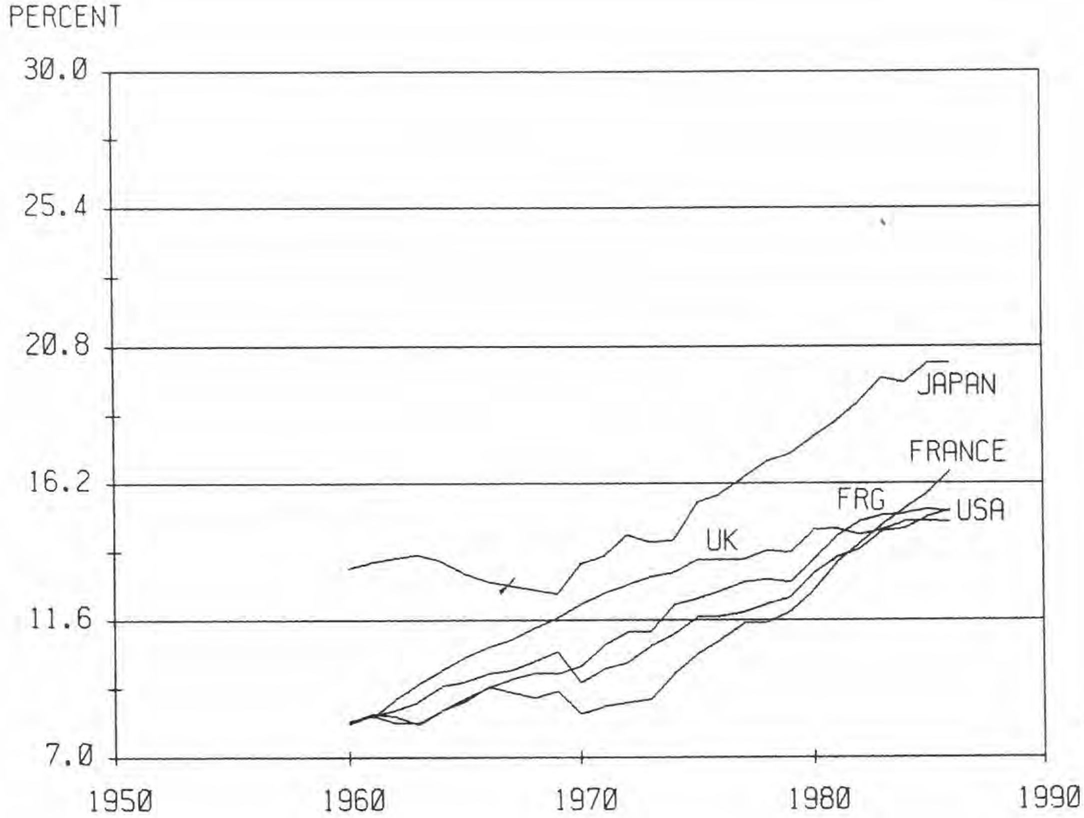

Figure 4-20 Share of Electricity in Final Energy in Selected OECD Countries.

Hydro and nuclear energy are by their very nature exclusively converted to electricity. 75 percent of coal are converted to electricity and only the remaining 25 percent are used in direct form, primarily in basic industries (steel and cement). The share of oil products being converted to electricity has been decreasing since the early 1970s as a result of policies aiming at a reduction of the dependence on oil products in all OECD countries. Noteworthy is also the constant share of 20 percent of natural gas being used for electricity generation ever since 1970. This is due to the fact that in many OECD countries additional natural gas fired power plants were basically prohibited by regulatory measures after 1973. These regulations are currently increasingly challenged in view of abundant supply sources of natural gas and of significant economic and environmental advantages of natural gas in electricity generation, especially when compared to coal. Gas fired combined cycle gas turbines for electricity generation could offer also an additional advantage in terms of efficiency as the conversion efficiency to electricity of latest models is with 52 percent thermal efficiency significantly higher than in conventional fossil power plants. Social acceptability and very low emission levels allow installation of smaller decentralized units close to the consumer and increase the conversion efficiency above 80 percent by combined production of heat and electricity (cogeneration).

The highest relative growth of electricity versus other final energy carriers occurred in the residential and commercial sector. On the other extreme final energy demand growth in the transport sector was almost exclusively based on fuels, with the share of electricity declining, along the decreasing market shares of rail based transportation.

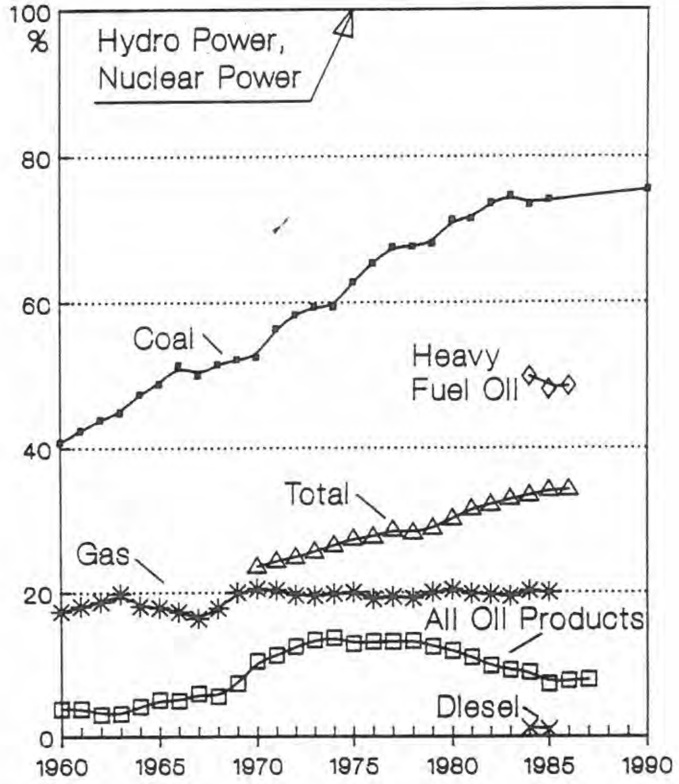

Figure 4-21 Percentage of Indirect Use of Some Fuels Via Electricity to Total Use, OECD Countries (WEC, 1988).

The largest increases in the relative share of electricity in final energy have occurred in the industrial sector as can be seen from Figure 4-22. As expected from the previous figure, Japan's industry is clearly the most electricity intensive followed by FRG. The other three countries are clustered very closely, with France in the lead. Incidentally, the discontinuity in the American data is due to the change in statistics and may not indicate a drastic change in industrial energy consumption between 1969 and 1970. These tendencies clearly indicate that the numerous improvements in industrial energy efficiency have been associated with replacing other energy forms by electricity.

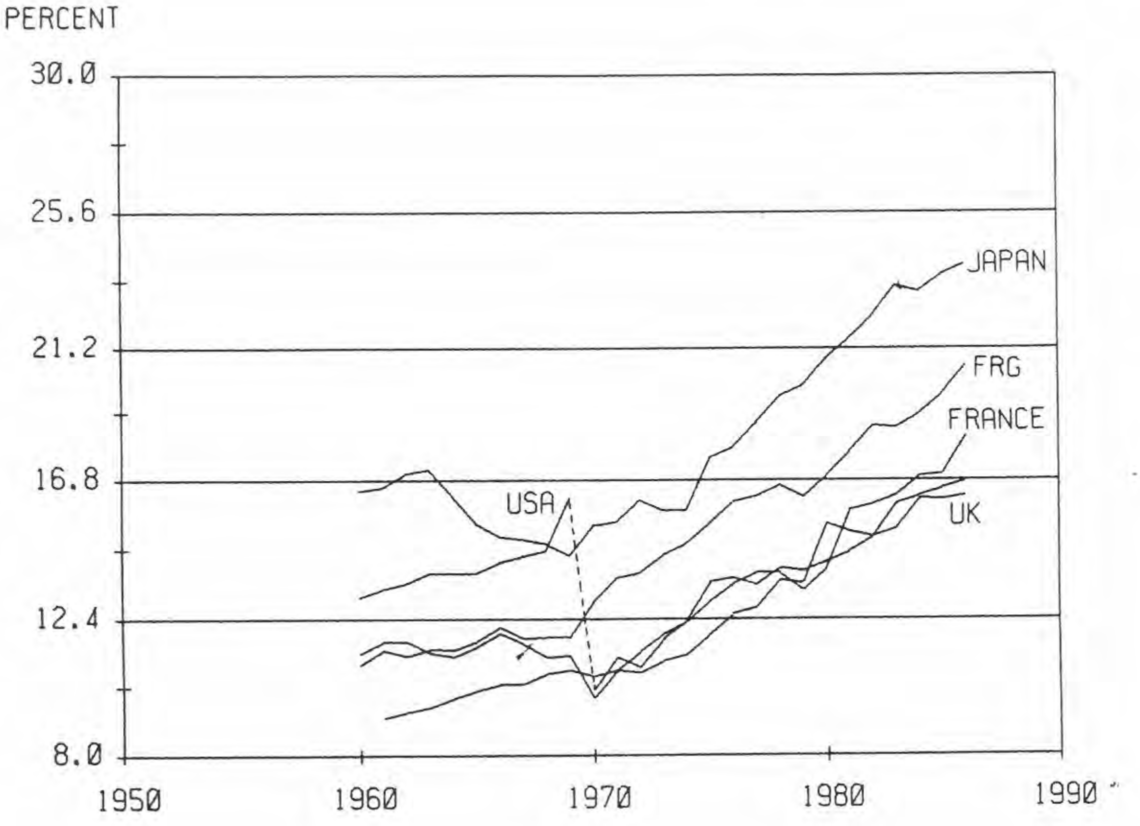

Figure 4-22 Share of Electricity in Final Energy of Industrial Sector in Selected OECD Countries.

In Figure 4-23 an analogous trend can be observed in the increasing share of electricity in the final energy consumption of the residential and commercial sectors. Residential and commercial applications have the highest electricity shares in final energy demand in all OECD countries. Highest shares are observable in the United States followed by Japan with almost identical growth rates. The extensive use of electricity in the United States is probably due to both a relatively large demand for air conditioning and to the rapid growth of the service industry. Increases are also large in France as a function rapid expansion of nuclear power. In the United Kingdom the shares of electricity did not increase during the last decade, while there is a trend reversal with declining electricity shares in FRG. However, it is interesting to note that the average share of electricity in final energy for all other countries but Japan clusters about 16 percent and that the shares in industrial uses, in households and commercial sectors vary considerably. It is a rather heterogeneous development process with different degrees of electricity intensity. The relative electricity penetration is on average the highest in the households and commercial sector with the shares ranging between more than 15 and 33 percent.

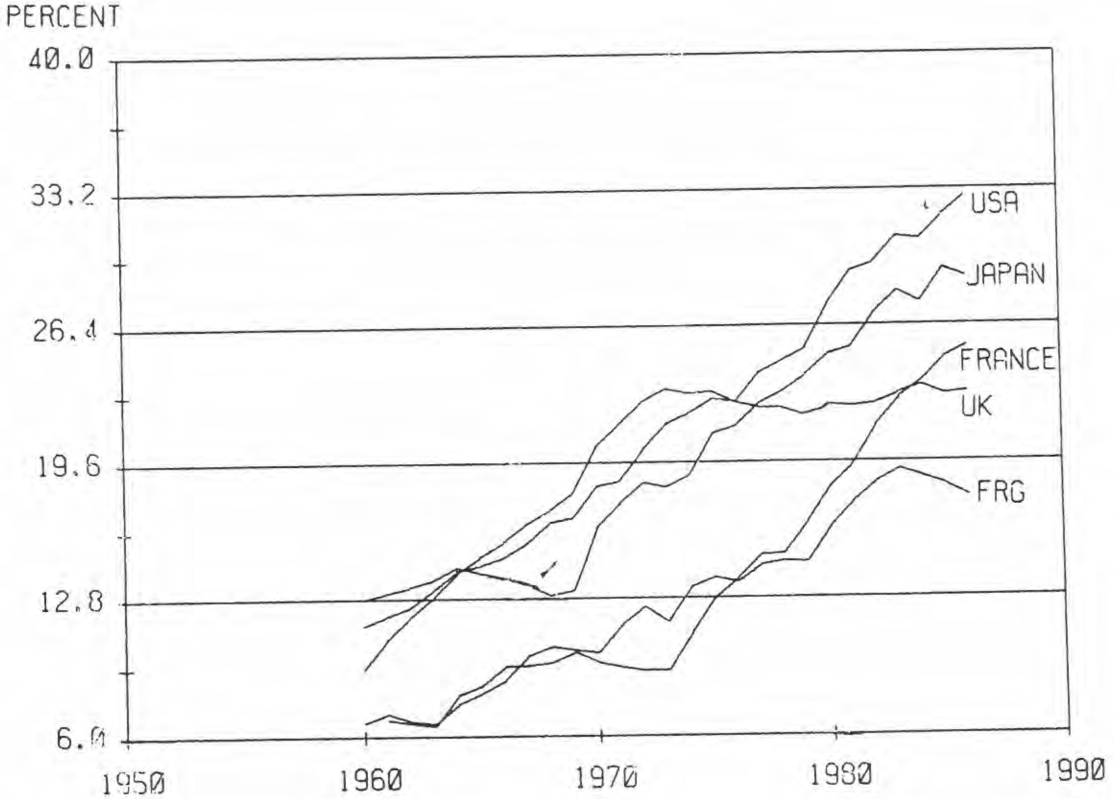

Figure 4-23 Share of Electricity in Final Energy of Residential and Commercial Sector in Selected OECD Countries.

The situation is quite different in the transport sector as shown in Figure 4-24. This is an area where oil products as motor and jet fuel have been extremely difficult to replace. Not only were no significant replacements possible, the electricity share has even declined, as a result of decreasing shares of railroads, in the modal split. The United States have the lowest electricity shares due to an almost complete phase-out of railroads in passenger transport. Other rail services are not electrified. The total consumption of subways and other electric transport means are relatively small compared to the total final energy consumption in transport. Due to the higher share of railroad transport, the other countries portray a slightly higher degree of electrification. This all illustrates the fact that more than 90 percent of the total final energy consumption in the transport sector is oil based and that the substitution of motor fuels by alternative energy carriers is rather unlikely in the foreseeable future.

Due to the fact that the transport activities are a relatively small consumer of electricity, the major changes in electricity requirements have occurred in trend households and commerce (growing service sector) and

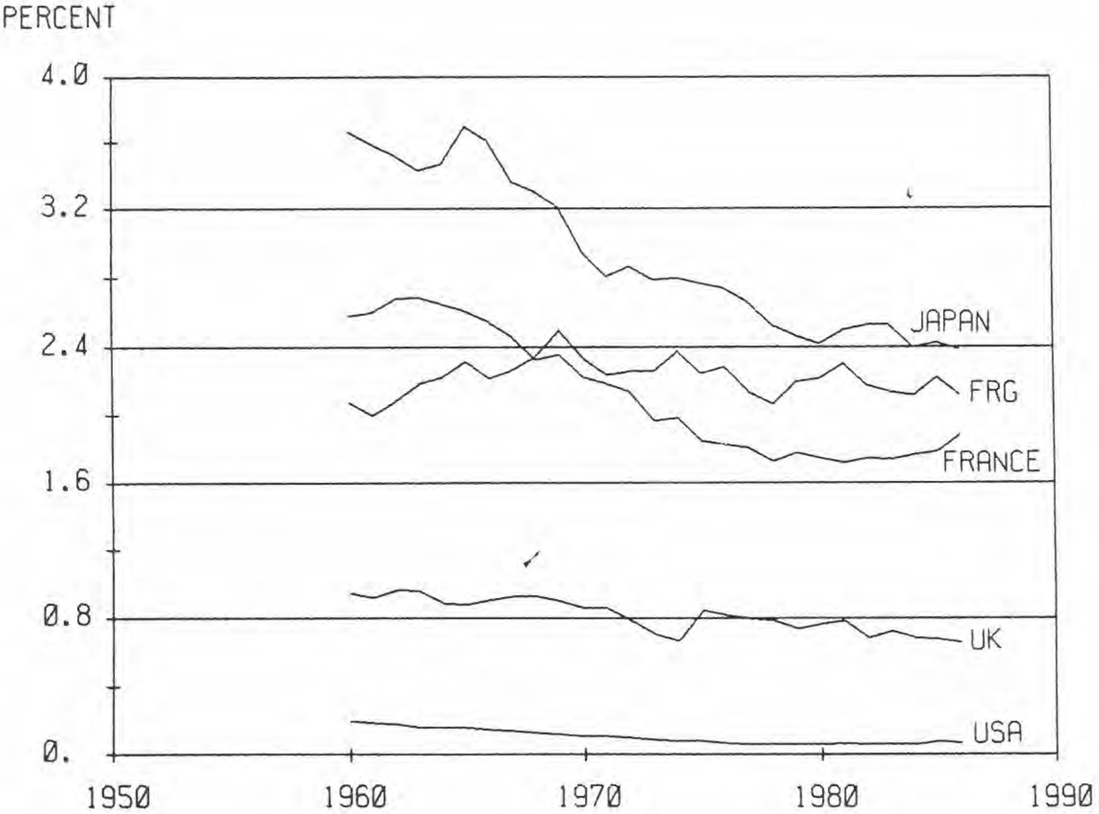

Figure 4-24 Share of Electricity in Final Energy of Transport Sector of Selected OECD Countries.

industry. In all three sectors, the shares of electricity in final energy have increased considerably since the so-called energy crisis and are consistent with the long-term in electrification since the World War II. The major difference, however, is that while the energy intensity of industrial activities decreased dramatically, the energy intensity of households and commercial sectors has increased during the last two decades. This proves that electricity use expanded under two different overall energy market trends.

This means that the growth of electricity consumption has been much higher than the growth of total final energy use. We have shown this continuous trend at the global level where the share of primary energy consumed for electricity generation is growing, while the share of all other primary energy uses is declining. The primary energy intensity of GNP in industrialized countries is declining. We have illustrated that this is an evolutionary historical development which can be traced back even to the times when noncommerical energy sources provided most of the energy supply. This decline characterized the continuing efficiency improvements and increases in energy productivity at the aggregate level. An obvious correlation of this historical trend is that the electricity intensity of GDP is either decreasing slower or is even growing due to the long term substitution of electricity for other final energy forms. In fact, the electricity intensity of GDP portrayed sustained increases in all industrialized countries. Apparently many of the measures and economic restructuring which contributed to increasing energy efficiency in general have contributed toward further electrification.

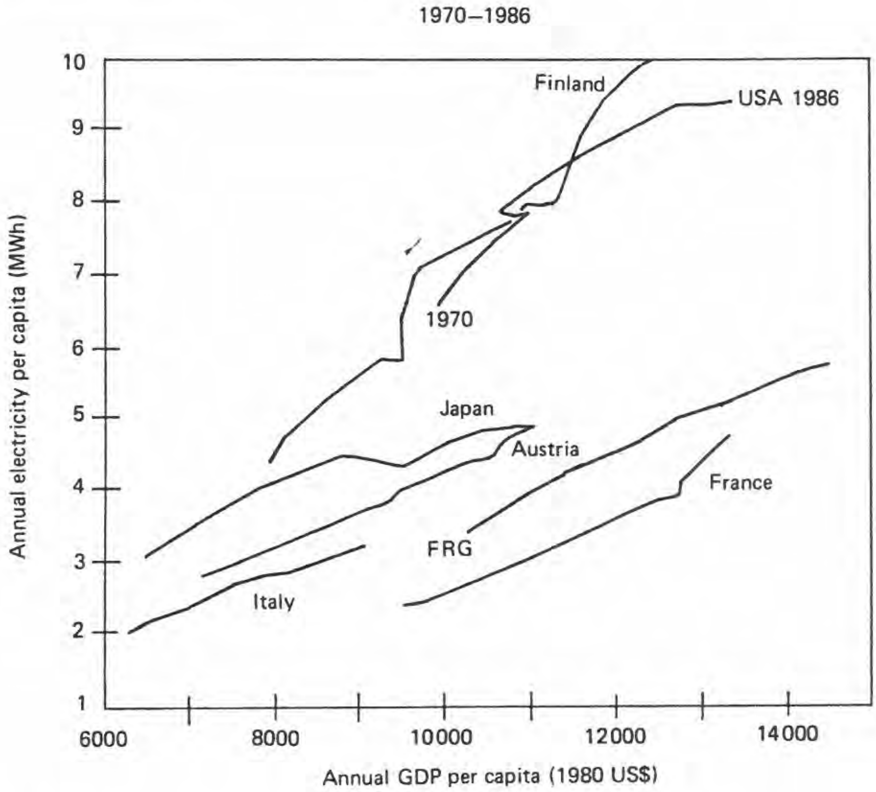

Figure 4-25 Electricity Intensity of GDP, Selected OECD Countries.

The average GNP intensity of electricity consumption in most OECD countries has been increasing since the 1950s with the increases in real GNP. However, since the early 1970s a number of divergent trends have become apparent as is shown in Figure 4-25. Linden (1988) investigated, in great detail, the relationships between electrification of energy supply, electricity intensity and economic performance in 15 industrialized OECD countries in order to gain a better understanding of their historical development and future trends. We will report here only on his results without presenting in detail the original numerical evidence, which can be obtained in the original reference.

According to Linden there is a strong linkage between economic growth and electricity supply of industrialized and even developing countries. In the years since World War II, these relationships are roughly linear or consist of two linear segments with a breakpoint related to significant changes in the energy market and in energy policy in all 14 OECD countries (see for instance Figure 4-25). These slopes represent the marginal electricity intensity of an economy; whereas, the ratio of the electricity supply and the deflated GNP in any given year is the average electricity intensity at that time.

In the United States, the United Kingdom and Japan, the average electricity intensities have followed a downward trend, while in FRG (and according to Linden also in Italy, The Netherlands and several other smaller countries) the intensity appears to have stabilized. The decline in electricity consumption per unit value added in the United Kingdom was most pronounced (followed with a somewhat slower decline in Norway). This may be due (in both countries) to the access to domestic natural gas and oil resources which may have eased earlier pressures to electrify energy end-use. Another significant exception is France with steep electrification by nuclear energy, (see the discontinuity in the electricity intensity in Figure 4-25).

The United States is the best example of a major economy with limited hydropower resources, relatively high nuclear power and low fossil-fuel costs, and very large transportation and other fuel requirements. As we have shown, only around 17 percent of energy is supplied in the form of electricity in the US. Linden (1988) argues, that this could be one of the reasons for substantially higher primary energy consumption per unit GDP (see the international comparisons above) than for the OECD membership as a whole and higher than in any of the other four selected OECD countries. The electricity share in the total energy requirements of a representative group of European members of OECD ranges from 12 to 23 percent and is lower than in Japan with 24 percent. Exceptions are Finland, Norway and Sweden whose energy supply is 30 to nearly 50 percent electrified. The economics of these three countries benefit from abundant hydroelectric pow resources and, in the case of Finland and Sweden, also from a large supply of relatively cheap nuclear power. Abundance of hydropower is similarly reflected in relatively high percentages of electricity of two other OECD members – Austria and Switzerland, with the Swiss nuclear program an added factor.

This apparently consistent relationship between electricity intensity and economic growth illustrates that during the last decades many industrial and service activities, with a relatively high share in value added, depended to a large degree on electricity as an energy carrier. In other words, electricity has a high form value. It is available when needed from the grid and does not have to be stored by the consumer. Additional advantages is that it is easily converted into mechanical energy and is basically the only energy form suitable for ever-increasing share of electric and electronic equipment. Therefore, the quality aspect of an energy carrier plays an important role in end-use. Some of the efficiency losses associated with the generation of high quality energy carriers have thus to be reconsidered in view of the form of quality of an energy vector, delivered. Increasing quality both in corresponding better to evolving economic and societal requirements, but equally in terms of improved environmental compatibility will become in future an even more important decision criteria for energy supply choices.

4.1.4. Evolution of Energy Prices

Much of the structural change and improvement in efficiency of the energy system over the last two decades has been attributed to the sudden increase in oil prices following the OPEC oil embargo. No doubt, this is true as was evidenced by many trend changes in energy intensities and numerous programs focused on improving energy efficiencies, energy saving measures and finding alternatives to oil. These efforts were successful both in creating conditions for more rational energy use, introducing appliances, vehicles and means of production with higher efficiencies and commercializing additional sources of energy not so vulnerable to the political will of a few countries or regions. What has surprised many experts in the field, as well as the public in general, is that the price hikes of the 1970s were rather short lived. Although, their immediate effect will most likely be longer lasting due to the shift of emphasis from resource limitations to avoidance of adverse environmental impacts of energy use. Many of the measures and policies introduced to bypass the short-lived energy scarcity are also beneficial in reducing the environmental impacts.

From the historical perspective, energy prices have been astonishingly stable, fluctuating only within rather narrow margins. However, the long-term development of energy prices must be seen in comparison to changes in prices of other goods and commodities. Figure 4-26 shows one of the widely used indicators for the prevailing prices in an economy, the index of wholesale prices for the United States starting in 1800. The second and third series gives the index of fuel prices and oil prices respectively in the United States. With hindsight, we see the occurrence of four pronounced flares in the wholesale prices. Three upper turning points are clearly visible in the raw data occurring in the 1820s, 1860s and 1920s. In comparison we show below in Figure 4-27 the wholesale and fuel price indices and the price indices (in nominal terms) of three major fuels: coal, oil and natural gas.

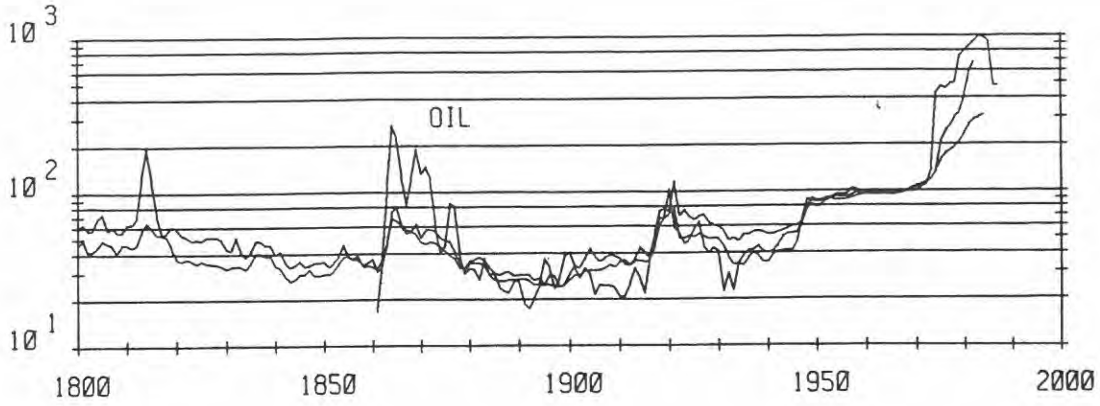

Figure 4-26 Energy and Wholesale Price Indices, US.

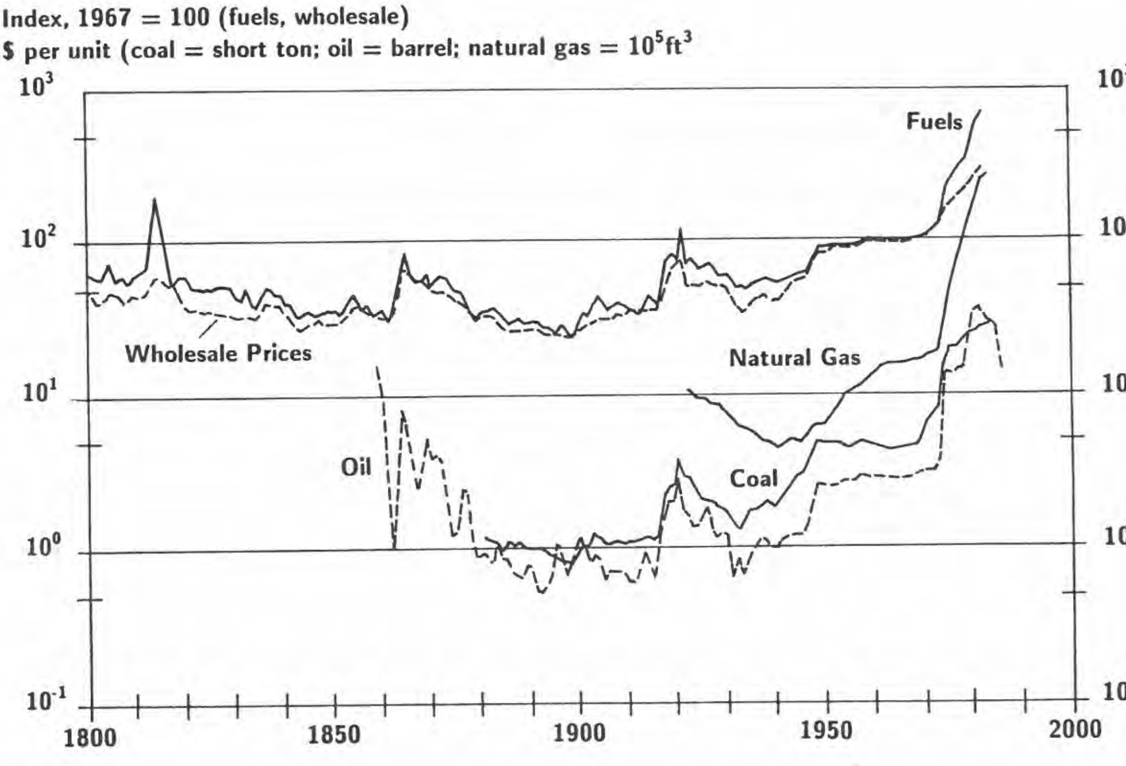

Figure 4-27 Wholesale and Fuel Price Indices and Energy Prices, US.

Since the peak of the energy prices and other basic materials in the early 1980s the curves portray deflationary tendencies over the last few years. In the meantime, oil and natural gas prices have returned to their pre-1970 levels in real terms.

Despite many turbulent events and acute crises, and the complete transformation of the United States from an agrarian to industrial society over the last two centuries, the long term price trends have been surprisingly stable with the exception of four pronounced flares with the duration of about 10 to 15 years each.

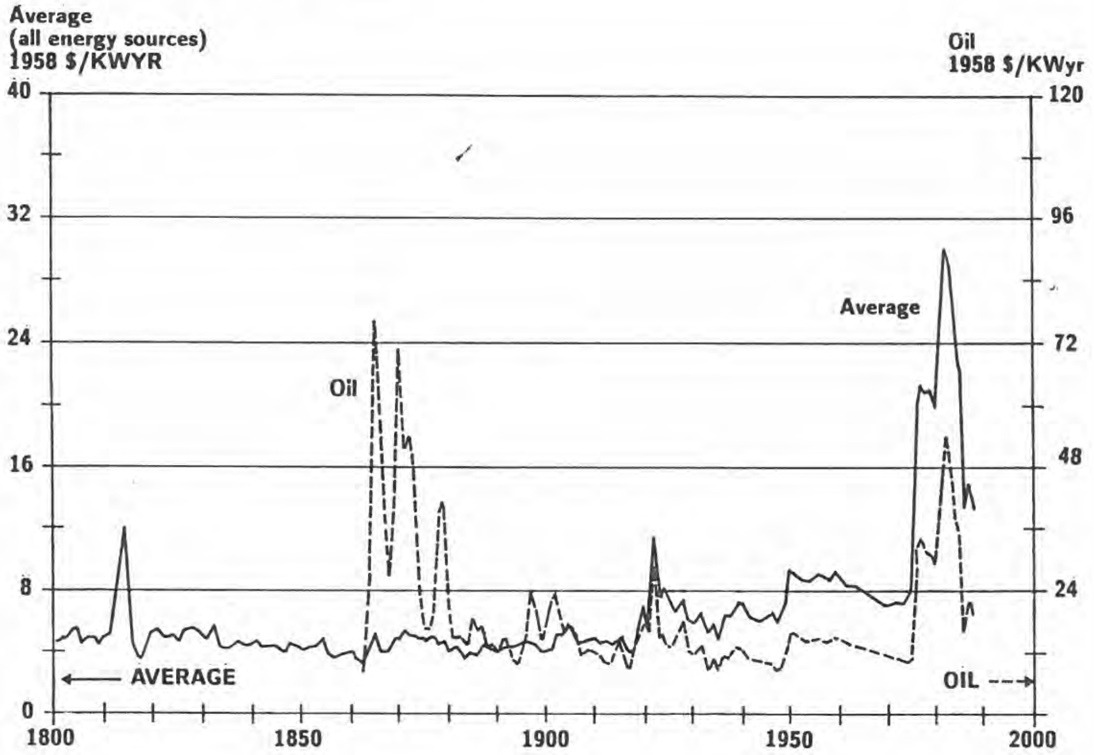

Figure 4-28 Real Oil Prices and Composite Price of all Energy Sources, US.

Figure 4-28 emphasis this remarkable long term stability of energy prices. It gives the price of oil since 1863 in constant 1958 Dollars per kilowatt year. The second curve shows the composite price of all primary energy sources in the American economy, weighted by their relative shares in total primary energy for each period also in constant 1958 Dollars per kWyr. The figure clearly demonstrates that the price flares since the OPEC oil embargo have been deflated back to historical levels. Thus, in spite of the recurring brief episodes of extreme price volatility, over its more than a century-long history as one of the major world commodities, crude oil (energy in general over the last two centuries) has shown rather remarkable price stability in real terms. With the exception of three prominent price flares in the 1860s and prior to the Great Depression, the price of crude oil fluctuated within the relatively narrow range of about \$13/bbl (in 1987 Dollars, or about \$18/kWyr in constant 1958 Dollars as shown in the figure).

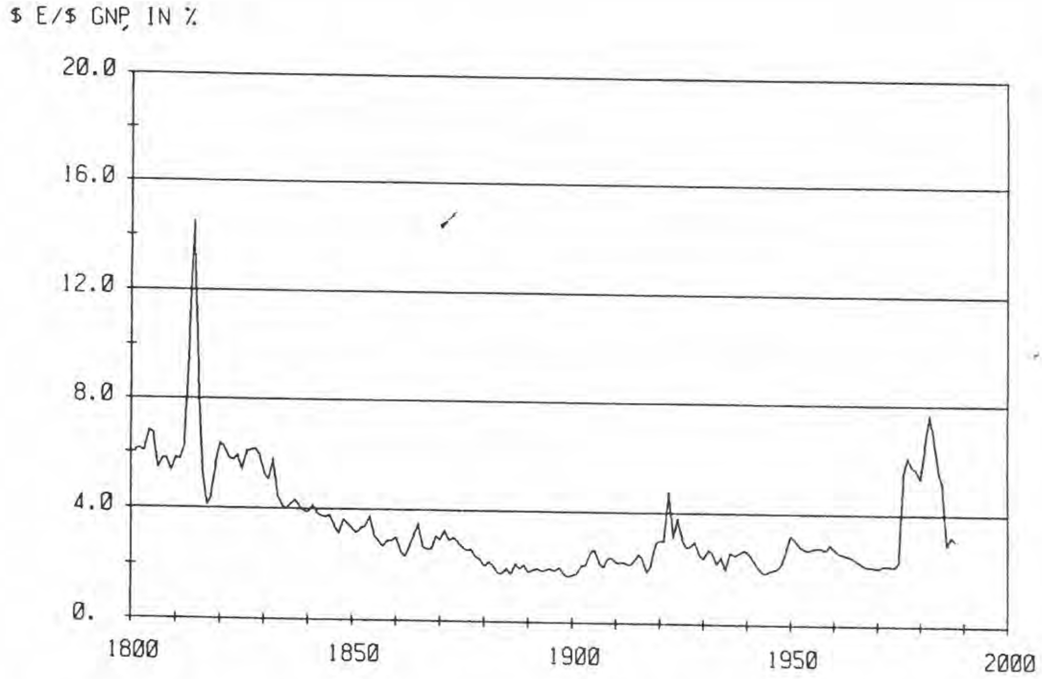

Figure 4-29 Cents Spent on Primary Energy Sources per Dollar Value Added, US.

This relatively stable long term development of energy prices indicates that the oil price shocks of the 1970s can be seen as a relatively short lived episode in comparison to almost two centuries of persistent price stability. In retrospect, this may be exactly the reason why the rapid price increases in 1973 and 1979 have caused such dramatic impacts after decades of very stable energy prices. Figure 4-29 indicates the importance of these price flares in the historical perspective. It gives the cost of primary energy sources per Dollar of value added in the American economy (cents spent on primary energy per Dollar of GNP in constant 1958 Dollars). At the beginning of the last century about 7 cents of each Dollar value added were spent on primary energy inputs to the economy and this share decreased consistently to about 2 cents by the 1870s. This was primarily the result of substituting fuelwood and charcoal by relatively cheap coal, which lowered the energy requirement per Dollar GNP from 13 kWyr/yr per Dollar in 1800 to around 6 kWyr/yr per Dollar in the 1870s (for comparison the present intensity is 2.2 kWyr/yr per Dollar). With the exception of the brief increase of energy costs during the early 1920s the real trend reversal in the energy costs did not occur before 1973, more than quadrupling to about 8 cents per Dollar. This illustrates the magnitude of the price shock of the 1970s. With the price decreases in crude oil and other energy sources since the mid 1980s, the costs of primary energy inputs into the American economy have returned to their long term level of above 2 percent of the value generated.

Table 4-3 Energy End-Use Prices (Including Taxes) Per Product Category, for Selected OECD Countries, 1988, in US $/kWyr/yr.

	Transport		Household			Industry			
	Gasoline	Diesel	Gasoil	Gas[1]	Electricity[1]	Residual	Gas[1]	Coal	Electricity[1]
Austria	612.4	425.1	259.5	288.5	1160.5	n.a	128.8	85.1	531.6
France	682.9	385.1	247.9	335.3	1043.6	75.4	114.6	106.7	385.9
Germany	507.5	347.8	151.9	246.5	1151.0	75.7	117.6	128.7	670.8
UK	561.9	424.4	158.5	203.6	696.3	83.2	117.8	89.3	471.3
OECD Europe	621.5	352.0	224.0	291.2	876.9	90.0	111.7	87.0	522.8
US	212.8	212.5	176.3	164.0	637.6	61.1	80.2	44.5	398.2
Japan	765.2	420.6	244.5	693.3	1541.4	141.9	380.8	102.6	1122.1
OECD	352.6	300.1	212.5	207.8	767.2	86.6	94.9	56.7	552.6

[1] 1987 values

Source: OECD, 1989

Thus far we have discussed energy prices at the level of primary energy carriers, which are input to further transformation and distribution by the energy sector. Table 4-3 presents prices for various end-use products as charged to the final consumers (e.g., industry or private households), for selected OECD countries in 1988. The wide variation of the prices of final energy forms, between different products and end-use sectors and between different countries becomes particularly apparent.

High quality energy carriers or those used in specific applications, where no interfuel competition exists (e.g., electricity and motor fuels) have generally significant higher prices. Another important factor in the price differences between products are the different taxation rates prevailing in various countries. Table 4-4 compares, therefore, net prices (excluding

Table 4-4 Energy End Use Prices (Without Taxes) and Taxes Per Product Category, 1988, in US $ kWyr/yr.

			NET PRICES			
	Austria	France	FRG	Japan	UK	US
Transport						
Gasoline	234.8	156.8	181.1	409.0	184.8	146.1
Diesel	215.7	156.2	147.8	272.2	179.2	140.3
Household						
Gasoil	176.1	155.6	125.4	244.5	142.5	165.1
Gas[1]	240.4	282.7	216.2	690.0	203.6	164.0
Electricity[1]	991.9	826.9	950.4	1479.1	696.3	637.6
Industry						
Residual	n.a	59.7	69.5	141.9	73.3	61.1
Gas[1]	128.8	114.6	117.6	377.5	117.6	80.2
Coal	85.1	106.7	128.7	102.6	89.3	44.5
Electricity	531.6	384.0	631.1	1082.4	471.3	398.2

			TAXES			
	Austria	France	FRG	Japan	UK	US
Transport						
Gasoline	377.6	526.1	326.4	356.2	377.1	66.7
Diesel	209.4	228.9	200.0	148.4	245.2	72.2
Household						
Gasoil	83.4	92.3	26.5	0.0	16.2	11.2
Gas[1]	48.1	52.6	30.3	3.3	0.0	n.a
Electricity[1]	168.6	216.7	200.6	62.3	0.0	n.a
Industry						
Residual	0.0	15.7	6.2	0.0	9.9	0.0
Gas[1]	0.0	0.0	0.0	3.3	0.0	0.0
Coal	0.0	0.0	0.0	0.0	0.0	0.0
Electricity	0.0	1.9	39.7	39.7	0.0	n.a

[1] 1987 values.

Source: OECD, 1989

taxes) and taxes of selected energy products in OECD countries. Taxes constitute a dominant factor in end-use energy prices, particularly for motor fuels. We will not detail the different price formation mechanisms for various products and sectoral end-users prevailing in the OECD countries. Price formation depends on a diverse and constantly changing multitude of factors in various countries. Costs of primary energy sources, availability of domestic production, structure and costs of required transformations (e.g., refining and electricity generation), distribution of these costs between different product categories (e.g. between light and heavy products from a refinery), or even between the same products like diesel or gasoil are all important factors. In addition distribution costs, size of product sales (bulk versus small quantities), ease of end-use (reflecting end-use costs and convenience for consumers) and politically motivated regulated tariffs add to the complexity of the energy price formation in different countries. Finally, also the existence of competitive market structures or of supply and/or distribution monopolies have also to be emphasized.

Still, Table 4-4 supports from an economic (price) rationale, our above discussion of the differences in the energy intensity of economies. Countries with low energy prices like the US, where lower net prices are accentuated by much lower tax rates than prevailing in most other OECD countries, show also higher energy intensities than in countries with high energy prices. The high energy costs prevailing (with the exception of coal) for industry in Japan compared to other countries, relativate frequent arguments about the importance of energy costs in international competitiveness, especially of advanced economies moving progressively away from energy intensive basic materials production and consumption as discussed in Chapter 3. When considering net prices, (i.e., excluding taxes) it is interesting to note that next to Japan, Austria is the OECD country of Table 4-4 with generally the highest energy prices.

The importance of the supply structure on energy prices can also be identified in Table 4-4. The high share of indigenous energy sources in the energy supply of the US as opposed to the practically complete import dependence in the case of Japan are reflected in the price difference between the two countries. The lower electricity prices (particularly for industry) indicate the large availability of relatively low cost base load nuclear electricity in France. On the other hand, the high share of hydropower in the electricity supply of Austria appears not to be translated into significantly lower electricity prices for private households or industry.

Table 4-4 also shows the structure of taxes in the energy prices, particularly of motor fuels and for residential end-use fuels. Once again, the particular situation of the US with its low taxation of energy carriers is demonstrated. Table 4-5 illustrates the importance of taxation in energy prices for 1984, the latest year data are available outside the OECD countries. Taxation of motor fuels in Western Europe is particularly high. About 50 percent of the retail price for gasoline consists of various taxes, for diesel this percentage is on average between 40 and 50 percent in Western Europe. Taxation rates of motor fuels in the US as well as in developing and OPEC countries are on average only half of the rates prevailing in Europe, with

Japan having a taxation rate in the middle between Europe and the US.

Table 4-5 Energy Taxes as Percent of Retail Price Per Product Category, 1984.

	Transport			Household			Industry	
	Gasoline	Kerosene	Diesel	Gasoil	Gas	Elec.	Residual	Coal
Austria	50.3	0.0	49.1	26.5	16.7	16.7	16.7	0.0
France	56.5	0.0	43.9	22.9	15.7	20.8	17.8	0.0
FRG	47.7	0.0	44.6	14.4	11.9	15.2	2.8	0.0
UK	48.7	1.1	49.6	3.1	0.0	0.0	3.5	0.0
Western Europe	52.7	8.9	37.8	24.5	n.a	n.a	12.0	n.a
US	24.9	0.3	19.9	0.0	n.a	n.a	0.0	0.0
Japan	37.5	34.9 ✓	0.0[1]	24.5	0.6	4.0	5.3	0.0
OECD	38.8	10.4	32.1	24.5	n.a	n.a	8.7	n.a
Devlp. Countries	21.4	16.0	16.4	17.5	n.a	n.a	12.6	n.a
OPEC	25.8	20.4	27.1	0.0	n.a	n.a	5.0	n.a

[1] 235.3% in 1988.

Source: OPEC, 1986.

Taxation of residential energy carriers are significantly lower than for transportation fuels, consisting mostly of value added tax or equivalent taxation mechanisms. This also explains why taxation of industrial fuels does not show up as particularly high figures in Table4-5.

Final energy prices constitute certainly one of the most important economic decision criteria for interfuel substitution. At the same time it has to be emphasized that prices are not the single driving force for the future evolution of energy use and fuel choices. Quality and appropriateness for specific end-use applications (discussed in more detail in Chapter 5), convenience of use, and finally also environmental characteristics will become in future an even more important criteria than prevailing prices alone.

The prices of various energy carriers do up to now reflect only production, transformation and distribution (i.e., technical) costs proper, mining rents (royalties), margins and finally taxes. However, external (environmental) costs to the economy, such as environmental costs arising from harvesting, conversion and end-use of different energy carriers are up to now not yet reflected in the energy price levels and price structure.

Thus, past and actual energy prices and price differentials may in future become less decisive decision criteria. For instance, the present price differential between a kWyr coal, gas or hydroelectricity would change drastically if all external environmental and social costs (land disturbance of mines, accidents and health hazards of miners, particulates, SO_2, NO_x and CO_2 emissions and resulting deposition damage) were to be considered. We will discuss in more detail in Chapter 6 that the inclusion of hitherto neglected "externalities" will become of increasing concern in the future. Including environmental externalities for instance by abatement measures required by regulation, will be progressively required in the future, especially under the auspices of the globalization of possible impacts stemming from energy use.

4.1.5. Summary of Major Trends

The achievements of industrial societies in terms of the level of economic development, the quality of life of their people, their impacts on other societies and on environment, are determined in large part by the quantities and the kinds of energy resources they exploit and also by the *efficiency* of their systems for converting available energy via work and heat into products and services. Advanced industrial societies are further characterized by increasing reliance on high form-factor energy carriers like electricity, a trend that has direct effects on energy consumption and indirect effects on environmental quality.

The improving efficiency of energy consumption and the value added generated by the substitution of human and animate work by energy services has made an enormous increase in human welfare possible over the last two centuries. This was an evolutionary process that is punctuated by many structural changes both in the energy system and the economy and society at large. In particular, the replacement of traditional energy, gathered from natural energy flows usually at rather low efficiencies and densities, by the advent of fossil energy has contributed toward increases in output, productivity and improvement of working conditions and standard of living. We have shown that the energy intensity has been improved by a factor over five during the last two centuries in the United States and by similar orders of magnitude in other industrialized countries. Thus, efficiency improvements led to energy inputs that are by a large factor smaller than would have be required to provide similar energy services without the structural change, introduction of new technologies and energy sources and the multitude of institutional and organizational reforms. The important feature of this process is that the largest leaps in the improvement of the overall efficiency of the energy system were achieved by replacement of old by new energy technologies throughout all stages of energy production, conversion, transport, distribution and end-use. The dynamic aspect of these processes is important, since diffusion of new systems, along with associated social and institutional changes, was not always smooth and often required very much time. At the level of primary energy the substitution of older by new energy forms lasted up to a hundred years. Even end-use technologies diffuse slowly because they are often tied to the structure of capital stock so that the old systems are replaced as older capital vintages become obsolete. In the sectors where the capital replacement is faster such as machines or vehicles, the transition processes are faster and take on the order of a few decades and in some exceptional cases even less time.

Traditionally, much of the efficiency improvement during the last two decades has been attributed to the quick upsurge in energy prices following the OPEC oil embargo. In comparison to the longer-term historical trends these improvements do not appear to be unique. Furthermore, their effect was to a large extent just offsetting the less than average efficiency improvements during the post-war period of rapid economic growth that often led to increases in energy intensity of many activities. The conservation measures, economic structural and technological changes initiated after the early 1970s had many positive benefits in rationalizing energy use and reducing environmental impacts, but from the historical perspective they appeared long overdue after decades of stagnation in energy efficiency improvements. Should these trends continue during the next decades in the industrialized countries, then the cumulative effect could indeed result in above average efficiency improvements even when measured against the long-term yardstick. Paul Gray (1989) refers in this context to what he calls the paradox of technology. Technological change, especially in the energy sector, has brought about unprecedented levels of prosperity while at the same time creating environmental disruptions. Often, however, it was the further advancement of technologies and institutional frameworks that offered new opportunities to reduce environmental problems and eventually improve environmental quality.

Thus, not only in terms of recurring periods in transition from old to new systems, but also from the point of view of its side-effects, the advancement of techno-economic systems is disruptive. At the same time only the process of change opens opportunities to respond to emerging environmental challenges and to restructure the techno-economic system to better correspond to evolving societal values and needs. Thus, in some sense both the resource exploitation, and the environmental quality are a function of our social institutions and technology. The improvement in the efficiency and quality of energy inputs in our modern society should be seen through the prism of the dynamic processes of change that have created a set of new technologies and institutions that enable an alternative energy source to better satisfy the end-use demand of society. Such fundamental substitutions of old by new ways of fulfilling human needs, entailing major changes in societal behavior, tend to require more than a century.

5. EFFICIENCY OF ENERGY USE AND ENERGY SUPPLY

5.1. General

Modern societies depend on elaborate and complex systems for converting energy from less to more desired forms. For example, crude oil is refined into fuels that propel vehicles, coal is converted into electricity that powers appliances and industrial motors, natural gas is burned to provide heat. The overall effectiveness of energy systems depends on the structure of energy supply and conversion systems, and on the patterns of energy end uses. In the previous chapters we have discussed many of the large and complex set of issues associated with energy systems and patterns of energy supply and demand that have technological, economic, social and technical components. In the next chapter we will consider environmental and ecological issues of energy use. Here we will analyze the efficiency of current energy systems and attempt to outline the potential for efficiency improvements.

We will analyze technical aspects of energy use with emphasis on assessing the prevailing efficiencies in the OECD countries and Austria. This assessment will encompass the whole energy system focusing on end use. Much has been already written about the efficiency of energy conversion devices, but little attention has been given to the overall efficiency of energy use. The overall efficiency is the result of compounding the efficiencies of the whole chain of energy supply, conversion and distribution processes. The weakest link in the analysis of the overall efficiency of energy chains is in fact the energy end use. There is a considerable lack of quantitative and detailed information in this area and we will attempt to assess representative measures for end use efficiencies and combine these with prevailing efficiencies of energy conversion, transport and distribution devices in order to provide an estimate of the overall efficiency of current energy systems. Building upon this more consistent appraisal of current efficiency of energy systems, we will then assess how large is the potential for future efficiency improvements.

The efficiency improvements are desirable and in the long run necessary more in view of environmental constraints than because of eminent resource limitations. Efficient provision of energy services not only reduces the required amounts of gathered or extracted energy but in general also reduces adverse environmental impacts. However, it should be mentioned that efficiency is an important, but not the only determinant of energy systems performance. Other determinants include for example the availability of power, controllability of energy flows, capital and operating costs and so on.

The previous chapter has shown that the efficiency improvements have been very large for many components of energy chains during the last 15 years when compared with the longer-term historical trends. The same was the case with the reduction of energy intensity in the industrialized economies. These historical rates can be seen as a reference base to judge how fast (or slow) future improvements could be depending on whether it will be easier (or more difficult) to exploit the potential for further efficiency improvement. These should be balanced, however, against possible increases in demand for energy services. While focusing on more technical aspects of energy efficiencies we do not underestimate other important determinants that shape the structure and patterns of energy supply and use, but rather our objective is to establish a standard measure of efficiency against which other important and complex issues must be considered that will determine the actual energy requirements in the future. Energy and the available work from various energy forms can be used more or less efficiently; this sometimes depends on technical factors or the capacity utilization, but more often it is the question economic and social choice, i.e., the question of life-styles and also consequently the kinds of energy services that are demanded and provided.

In order to evaluate how large these improvements might be, we will take a novel approach in assessing efficiencies. In the case of direct conversion of one energy form to another, the traditional and established method of defining efficiency is intuitively clear and in principle relatively easy to assess as the ratio of the amount of energy transferred to the ultimate purpose of the conversion system divided by the actual energy input to the system (see, Olivier, 1983). In this context the term "efficiency" is a physical measure, or a ratio of output to input. For example, a certain type of thermal power plant is said to have an efficiency (electric energy generated per unit heat of combustion) of 30 percent. This is the conventional heat-balance method of evaluating system efficiency, system "losses" or the amount of energy transferred to the purpose of the conversion system. In the case of the mentioned power plant with an efficiency of 30 percent, 70 percent of the combustion heat results as waste heat and is not converted into electricity. Because of the first law of thermodynamics, which holds that energy is conserved, that it is neither created nor destroyed, this concept of efficiency is often called the *first law efficiency* or *energy efficiency.*

This concept of energy efficiency has a number of weaknesses when applied to estimate the actual effectiveness and the potential for improving efficiency of the whole energy system. The focus of the measure on a particular system or conversion device does not provide the required yardstick for estimating the theoretical minimum energy requirements for performing a particular task by *any* possible system or device (see, AIP, 1975). In other words, the use of the first law of thermodynamics is inadequate for assessing minimum task energy. Since energy is always conserved and not consumed, there is no theoretical framework for assessing the minimum requirement for performing a particular task. Instead, it provides a measure of efficiency of a given system or device. To assess the effectiveness of whole energy systems, a realistic measure of energy utilization must be applied that provides a *measure of consumption* in performing a task and a measure of theoretical minimum task consumption. The "available work" or "exergy" method of analysis provides such a *true* measure of effective energy use through its application of principles of both the first and the second laws of thermodynamics (Ahern, 1980). For this reason the measure is often called the *second law efficiency*. After assessing the energy efficiency of the current energy systems, we will derive estimates for exergy efficiency of these systems and than compare these with potential improvements measured against the theoretical minimum exergy requirements were an ideal device available for performing the specified energy tasks. Before deriving measures for energy and exergy efficiency, next we will describe the overall features of energy conversion systems distinguishing between various stages of energy conversion and end use.

5.1.1. Energy Conversion

Primary energy is the energy directly recovered or gathered from the nature. Typical examples are fossil energy forms recovered from the sediments such as mined coal or produced crude oil and natural gas, collected biomass or harnessed hydraulic power, solar energy absorbed by collectors and heat produced in a nuclear reactor from extracted and processed natural uranium. Only rarely can primary energy be used directly. For the most part, primary energy is converted first into *secondary energy*. Secondary energy forms can be used over a broad spectrum of applications for which primary energy sources do not have appropriate quality forms. Examples are electricity, gasoline, jet fuel, heating oil and charcoal. On the other hand, natural gas, coal and fuelwood need little processing or conversion to be used as a fuel.

Primary energy is converted into secondary energy in several different ways. Typical conversion facilities are refineries and power plants. Central power plants produce electricity and sometimes district heat. Refineries convert crude oil, which is difficult to use directly, to a range of more convenient forms of liquid fuels such as gasoline, jet fuel, diesel and lower quality products. More complex conversions are also practiced. When crude oil is not available, natural gas or coal conversion plants can produce liquid fuels. Sometimes the conversion plant is the only step in production of secondary energy from delivered primary energy, as is the case with electricity generation from natural gas, coal or nuclear energy (although chemical conversion of natural uranium, isotopic enrichment and fuel fabrication precede the power plant and waste treatment and storage are required afterwards). Sometimes secondary energy is converted at the point of gathering or extraction of primary energy as is the case with hydroelectric and wind generators and often with coal power plants.

After various energy conversion processes the resulting secondary energy forms are delivered to the consumers as *final energy.* For example, this involves transport, storage and distribution. Final energy forms are fuels, electricity and other energy carriers that are delivered to the point of consumption and subsequently used in various devices such as appliances, machines, and vehicles: gasoline at a service station, electricity in a house or fuelwood in a barn. We have shown in the last chapter that for stationary applications, the trend has been toward energy forms that can be transported and distributed by grids: electricity, natural gas and to a lesser degree district heat. For other applications where storage, portability, transportability and high energy density are the desired qualities, the trend has been toward application of liquid fuels, of which gasoline, diesel and jet fuel are best examples.

The next energy transformation is the conversion of final energy in end use devices to *useful energy* forms such as work and heat. Useful energy is measured at the shaft of an automobile engine or an industrial electric motor, the heat of the household radiators or industrial boiler, or the luminosity of a light bulb. The application of useful energy serves to provide energy services such as a moving vehicle, warm room or process heat.

Energy systems of modern societies can be viewed as complex machines for conversion and transformation of one energy form to another while extracting energy services needed for providing goods and services. It is important to realize that in providing goods and services (say, well-lit room or computer software), energy services are a factor input for the transformation and embodiment of other resources – capital, materials, labor skills and knowhow.

Figure 5-1 illustrates various energy conversion and transformation steps that ultimately result in the provision of goods and services. Figure 5-1 shows that energy is conserved: all of the primary energy is

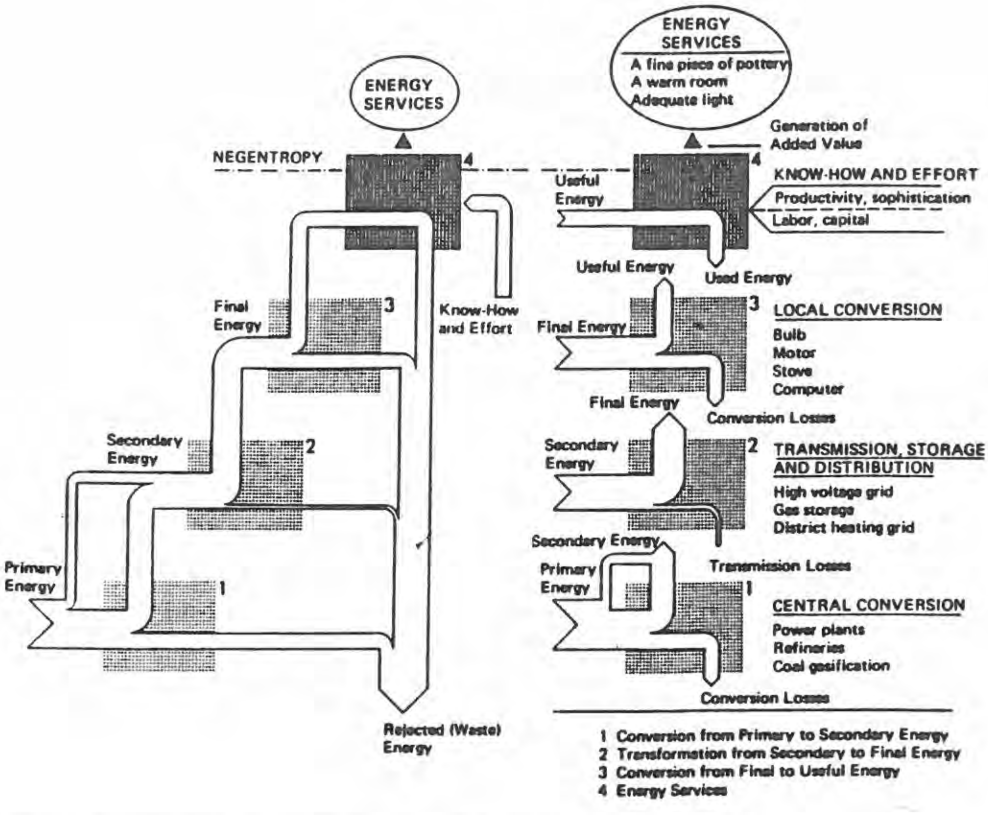

Figure 5-1 Energy Conversion and Use (Häfele, 1981).

ultimately converted into rejected (waste) energy. At each step a part of the energy delivered to the system or device is transferred to the ultimate purpose of the system and part is rejected into the environment (e.g. air and water) as "waste" heat. The figure also lists typical examples of energy conversion facilities and processes at each transformation stage. Primary energy is converted to various secondary energy forms in central power plants (electricity and heat), in refineries (oil products such as gasoline, diesel, jet fuel and heating oil) and coal gasification plants (synthesis gas). Secondary energy is converted into final energy forms in transport systems (high voltage grids), storage facilities (gas storage or hydropower reservoirs) and distribution systems (district heat system or gasoline stations). Final energy is converted into useful energy forms in end use (usually local) conversion devices such as a light bulb (radiant energy), motor (mechanical energy) or stove (heat).

In contrast, it is much more difficult to evaluate the energy services that result from provision of useful energy. Energy services depend on numerous factors that can be characterized as "external" to the energy system such as social behavior (e.g. life-styles) of the consumers or the structure of the economy. For example, the energy services provided by a moving vehicle will depend on how effectively the vehicle is used in transporting goods and people, on its design (e.g. aerodynamics, frictional losses and weight, etc.) and on the typical operational cycles (e.g. traffic conditions etc.). Energy service of heating a room depends on insulation of the house, heating profile, outside temperature, ventilation and many other factors in addition to the characteristics of the heating system. We will return to this question and explicitly estimate the effectiveness in provision of energy and exergy services.

5.1.2. Energy Conservation

In the previous chapter we have outlined some of the more important structural changes in the economy, how they are related to the transformations that have occurred in the energy system and how the efficiency of energy uses has evolved in the context of overall economic and technological development. While the industrial societies consume energy lavishly compared to energy use patterns a century ago or those in the developing countries today, the efficiency of energy use has increased dramatically especially since the beginning of the century and more recently since the so-called energy crisis. Despite these impressive improvements of energy use in modern societies, the energy consumption patterns are very diversified and inhomogeneous even among the industrialized countries.

In some sense, we can almost speak of path dependency: countries or regions that have evolved to have rather high energy intensity experience very disruptive and difficult adjustment periods to lower energy use, apparently no less difficult than the countries or regions with much higher efficiencies in energy use. It is almost as if a paradox governs energy use. The more energy an industrial society uses, the more it wants. The more energy is used, all the more are the life-styles, economic structure, social institutions and settlement-patterns dependent on lavish energy use. We have demonstrated that the efficiency improvement and conservation appear to be rather slow processes by historical standards and that the improvements achieved since 1973 stand out as shorter-term, above average reductions in energy use.

In the past most of the reductions in the specific energy needs and energy intensity have been achieved through improvements in technical efficiency, while today it is often claimed that many of the conversion technologies and energy use patterns appear to be rather efficient so that the question arises whether it will be necessary to place higher emphasis in the future on energy conservation. We will show in the subsequent analysis of exergy efficiency that the current energy systems are in fact rather inefficient compared with minimum exergy requirements for the present patterns and structure of energy needs. Despite the fact that the potential efficiency improvements are indeed very large, conservation can contribute toward substantial reduction of energy use. Unfortunately, conservation and efficiency improvement are frequently used as synonyms for the same concept, namely reduction of energy needs. Since energy is always conserved according to the first law of thermodynamics, we refer to all reductions in specific energy needs for performing a given task as *efficiency* improvement, while we call all reductions of energy needs due to changes in the nature or level of the required task *conservation*. For example, the use of a more fuel efficient automobile for a particular trip would be a question of efficiency improvement, while any reductions in energy needs for this given trip that are related to better demand management such as the improved utilization of the automobile, improved traffic conditions, etc. would be a question of conservation measures. In addition, alternatives to undertaking the given trip would also be conservation measures, such as walking or making a telephone call.

This concept of conservation measures, however can be used in different contexts, sometimes it could refer to what we call service efficiency and sometimes it could refer to actual changes in social behavior (e.g. life-styles). In the sense of the latter definition conservation could indeed also mean being "too cold in winter and too hot in summer"[1] and thus could result in austerity measures. We will discuss only the issues associated with service efficiency, where we assume that the life-styles and tasks to which energy is applied such as the provision of services and products *would not change*. Thus, we will consider conservation measures and their potential improvement only to the extent that they are related to energy services such as better demand management, design and utilization of energy end use devices and systems ranging from vehicles and production processes to transport systems and dwellings.

Thus, our working hypothesis with these considerations will be not to change the actual energy end use patterns in the sense of austerity measures. Any additional conservation measures and changes in consumption patterns toward lower energy needs that go beyond our assumptions about efficiency improvements and improvement of energy services would certainly reduce primary energy use even further. Our objective, however, is not to deal with this aspect of conservation measures, but rather to evaluate how large are the efficiency improvement potentials with current energy services of the OECD countries.

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[1] Statement attributed to President Reagan who characterized energy conservation as a measure of sacrifices (Rosenfeld and Hafemeiser, 1988).

5.1.3. Energy Efficiency

The established definition of energy conversion efficiency (first law efficiency) is the ratio of the amount of energy transferred to the ultimate purpose of the system divided by the actual energy input to the system (see, Olivier, 1983). In this context the term "efficiency" is a physical measure, or a ratio of output to input. In all cases where one energy form is transformed into another one, the overall energy efficiency of the whole system can be evaluated by simply multiplying individual energy efficiencies of each conversion step along the conversion chain. For a particular conversion facility and device energy efficiency will depend primarily on its technical factors, although the load factor and other energy management issues also influence the actual performance. It is a useful measure for comparing the performance of energy conversion facilities and devices of a particular type with each other. For example, it is useful for comparing efficiencies of power stations, of heating boilers, industrial furnaces, refrigerators or light bulbs.

In the previous chapters we have always referred to the first law efficiencies when we illustrated the improvements achieved in a particular type of energy conversion facilities such as for example in electricity generation. This was the area where dramatic increase in fuel-conversion efficiencies were achieved during this century. We mentioned in the previous chapter that the prevailing first law efficiency of electricity generation was about five percent around the turn of the century, i.e. less than five percent of the chemical energy in the fuels was converted to electricity. Today the average efficiency of electricity generation in OECD countries is about 36 percent and the best combined-cycle natural gas power plants can achieve almost a 50 percent efficiency.[2] Thus, a seven fold increase was achieved in electric conversion efficiency over the last 80 years. In terms of the best available technology during this period, the efficiency probably increased even more. In contrast, when wood or coal are burned in an open fireplace, less than 20 percent of the energy is radiated as heat, the rest escapes up the chimney (Summers, 1971). A well-designed home furnace or central heating boiler can transform up to 80 percent of the energy in the fuel to heat (typical household boiler efficiencies are between 70 and 80 percent), which represents quadrupling of conversion efficiency with respect to the open fireplace. This illustrates that the concept of energy efficiency can be used effectively for comparing the effectiveness of facilities and devises of

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[2] According to Lee (1988) conversion efficiencies higher than 50 percent can be achieved with the reheat gas turbine and today's steam turbine technology. A national energy savings project started by the Japanese government is 1978 includes a full-scale research and development effort aimed at building an advanced reheat gas turbine combined cycle, burning LNG, and achieving an efficiency of 55 percent. The test on the first prototype began in 1984. In the meantime, commercial combined-cycle facilities reach operating efficiencies in the same range. A recently opened cogeneration power plant PEGIUS in the Netherlands with a combined-cycle natural gas turbines operates at 52 percent electricity efficiency (ABB, 1989).

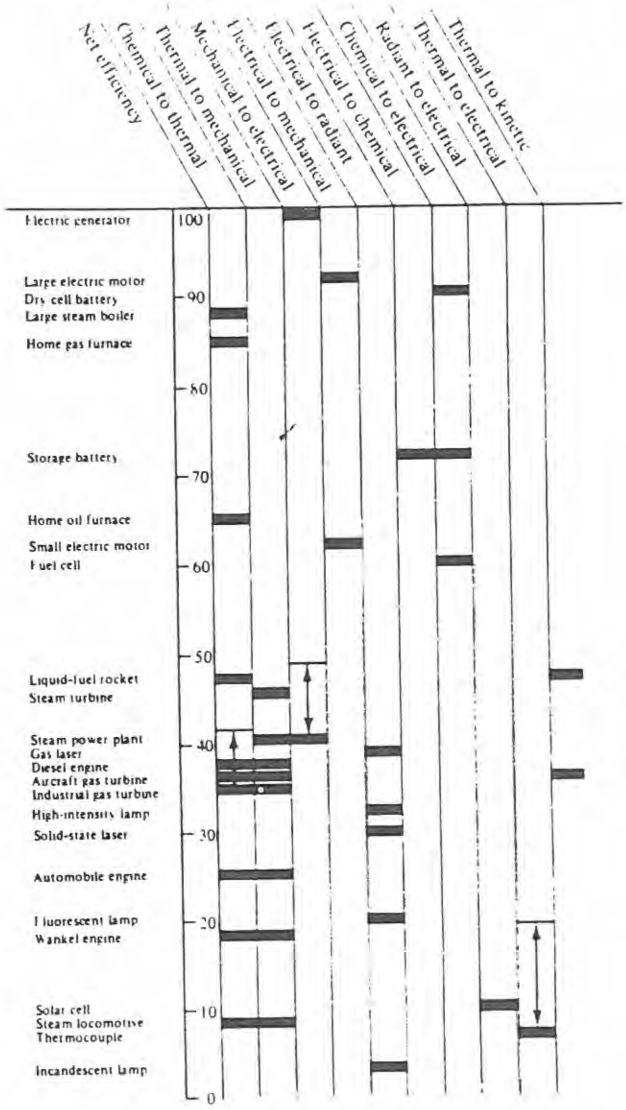
particular type as well as for evaluating improvement of efficiencies over time.

The overall efficiency of the whole energy system is the weighted average of all individual efficiencies along all energy conversion, transport, distribution and end use chains. To obtain the overall efficiency of a given energy chain, the efficiencies of each particular component must be estimated and than multiplied by the efficiency of other components that comprise the energy chain. If a particular energy chain consists of four processes, each with an efficiency of 50 percent, the efficiency of the whole chain would be 6.25 percent. This hypothetical example indicates that every single stage of converting the available to desirable energy forms results in degrading large portions of energy in fuels into waste heat that is released into the environment. This means that we have to evaluate the efficiencies of individual energy conversion devices and systems, than determine the efficiency of different energy chains in transforming primary into useful energy forms and finally estimate the weighted average efficiency of the whole system.

Let us first start with the efficiencies of individual conversion devices and systems. The same procedure applies, since there are usually a number of conversion steps in a particular energy device or facility. For example, electric power plants consist of a number of components. To obtain the overall efficiency of a steam power plant the net efficiencies of all conversions in the chain from fuel to electricity must be multiplied by each other. Power-plant boilers can convert about 90 percent of the chemical energy in the fuel into heat. Modern steam turbines achieve about 48 percent net efficiency in converting the (high-temperature) thermal energy of the steam into mechanical energy. Generators can convert up to 99 percent of the mechanical energy produced by the steam turbine into electricity. Therefore, the efficiency of the whole power plant is about 43 percent (90% times 48% times 99%). In other words, about 43 percent of the chemical energy in the fuel is transferred to the task of the system, namely electricity generation. This means that in the best case almost 60 percent of the energy in the fuel results in waste and frictional heat which is released in to the environment usually either into adjacent body of water or, if cooling towers are used, into the surrounding air (Summers, 1971).

Table 5-1 shows various pathways of energy conversion from one to another form and gives approximate net efficiencies of individual conversion devices and facilities. Most of the primary energy is in the form of chemical energy (e.g. fossil fuels) that is converted into the thermal energy that used for space heating (low-temperature) and industrial processes (high-temperature). Some of the thermal energy is converted into mechanical energy (thermal engines), most of which is in turn converted into electricity (generators), and so on. Chemical energy in the fuels is used directly for

Table 5-1 Efficiency of Energy Conversion.



Source: Summers (1971) and Eden *et al.* (1981).

transportation or mechanical drives in industry or for generating electricity (fuel cells). Electrical energy is used for lighting, heating and mechanical drives. The net efficiencies shown in Table 5-1 were originally estimated by Summers (1971) and later modified by Eden *et al.* (1981) to approximately indicate the representative values attainable with present technology. The bars in the Table 5-1 indicate representative values, and are as such not very precise. There is usually a considerable difference between the best performance and average performance of most of the conversion devices listed. The bars are given for illustrative purposes and are not supposed to be exact. They range from less than 5 percent for the ordinary incandescent lamp to 99 percent for large electric generators.

Table 5-1 indicates that only a part of the energy inputs to a device or a facility is transferred to the desired energy task. Thus every stage of converting the available to desirable energy forms results in some conversion losses that are released into the surrounding environment usually in the form of waste heat. Due to the first law of thermodynamics, energy is always conserved, meaning that energy transferred to the ultimate purpose of the system and energy dissipated in the process always sum to the total energy inputs into the system. Since there are conversion losses associated with each transformation stage, after a number of conversion processes usually most of the primary energy inputs are dissipated into the environment. It was illustrated in Figure 5-1 that after the provision of energy services – work and heat – all of the energy is eventually degraded into waste heat. The question we are asking in this context is how much of the primary energy is converted to the final purposes or tasks of the energy system. This means that we have to first evaluate the aggregate efficiency of energy chains and then determine the weighted average efficiency of the whole system. This we will do more precisely in the following sections. Here we show how the efficiency of energy chains from primary to useful energy could be evaluated for four representative useful energy categories: low-temperature space heat, propulsion of vehicles and illumination.

5.1.3.1. Space Heating

We assume boiler efficiency of about 80 percent for oil or gas central heating system. Since there are energy requirements to transport and distribute energy to final users and to convert primary energy into fuels, the overall primary to useful energy efficiency of central heating system might be on the order of about 60 percent. Thus, about 60 percent of the primary energy inputs result in boiler heat. There are additional conversion losses in going from the boiler heat to radiators and eventually providing the service of a warm room. We will return to this question later, let us for the time being calculate the relative efficiency of other alternatives for space heating.

Resistance heating converts all electricity inputs into heat, but electricity generation is on average about 36 percent efficient, so that the overall efficiency of resistance heating might be on the order of 30 percent after accounting for efficiency of producing fuels used for electricity generation and efficiency of electricity transport and distribution. A heat pump, on the other hand, can provide space heating with a slightly higher efficiency. It works as an inverted refrigerator because it takes heat from a colder to a warmer environment. The difference is that the task for the refrigerator and airconditioning is to cool the colder environment while the task for the heat pump is to heat the warmer environment. In the case of airconditioning, refrigeration and heat pumps, the efficiency can be higher than one and is called the coefficient of performance (COP). For example, electrical heat pumps generate more heat than the electrical (mechanical) energy that is used to power the heat pump, so that the coefficient of performance is higher than one. Coefficient of performance equal to 2 means that a kilowatt of electricity can generate two kilowatts of heat in an electric heat pump. When multiplied with the average primary to final electricity efficiency of about 30 percent, the overall efficiency is about the same as for peace heating with an oil or gas boiler, namely it is about 60 percent. With a higher value for COP in the range of 3 for low-temperature heating applications, the overall efficiency would reach 90 percent. Often, much of the useful energy is not applied directly for the purpose or the task of the system – heated space is often not in use, insulation of many buildings is poor and so on. In fact, a building with a high degree of thermal integrity needs almost no heating since the "waste" heat from cooking, lighting and other energy services often suffices for raising the temperature to comfortable levels. Thus, the actual efficiency is substantially lower and we will discuss this question in further detail under the concept of service efficiency.

5.1.3.2. Cogeneration of Electricity and Heat

The degraded energy need not be always wasted. In fact, cogeneration of electricity and district heat is a typical example of how the overall efficiency of provision of both power and heat can be substantially increased. For example, the power station continues to generate electricity that is distributed through the electric grid and in addition produces low-temperature heat that is piped to the consumers as hot water through the district heating systems. In such cases of combined use of heat and electricity the overall conversion efficiency of a power plant is much higher reaching the level of boiler efficiencies in the range of about 60 to 80 percent. The basic problem in applying these schemes is one of different systems scales and temporal demand profiles of electricity and heat generation. The average kWh of generated electricity travels about 100 km to the point of consumption, while the district heat applications are limited to about a tenth of that distance, meaning that all of the heat generated at a central power plant is difficult to absorb locally. Furthermore, electricity is demanded over the whole year, albeit with daily and some seasonal variations, while the district heat demand is limited to the colder days of the year. Often this kind of enhancement of overall energy efficiencies is hampered by the lack of useful applications of large amounts of low-temperature heat.

For this reason, smaller scale cogeneration is also practiced and ranges all the way to devices that are suitable for production of space heat and electricity with high efficiencies in single households. Fiat has developed a Total Energy Module (totem) during the 1970s that employs a natural gas (or biogas) fueled automobile engine for generating electricity and thermal heat exchangers for space heating and warm water. Totem scheme has not been a great commercial success and is now limited to a small number of applications, but larger diesel and natural gas systems are now on the market. These larger cogeneration systems are however more suitable for consumers with higher demand than a single household. Often these cogeneration units are connected directly to a district heating system instead of serving an isolated group of consumers.

5.1.3.3. Lighting

Incandescent lamp efficiencies are about 4 percent in converting electricity into visible radiant energy, while fluorescent lamps can reach higher efficiencies of up to 35 percent with a typical value of 20 percent. This leads to an average efficiency of electric light of about 10 percent (some estimates for the United States give a lower value of about 7 percent, see Ayres, 1988). Considering the 30 percent efficiency in converting primary energy into final electricity, gives an overall efficiency for lighting of about 3 percent, or at most about 10 percent for the fluorescent lamps. The overall efficiency of light would increase slightly would one consider the "passive" heating of the rooms that is a by-product of generating radiant energy. On the other hand, the overall efficiency would appear to be lower should the "indirectly" wasted light be subtracted. Light is blocked by lighting systems and fixture and by various "filters" that are used to make the light more pleasant. Again, the actual efficiency might be lower.

5.1.3.4. Transportation

Just as in the case of heat and electricity, we will only show for illustrative purposes how the efficiency of a motor vehicle might be calculated as a function of the efficiency of the whole energy chain from primary energy to vehicle propulsion. The actual conversion efficiency of a gasoline engine is in the order of about 33 percent under ideal conditions, but in practice cars operate at changing load profiles in average traffic so that the aggregate conversion efficiency, assuming a mix of urban driving cycle and highway travel, is substantially lower. Additional losses to internal engine friction, cooling exhaust and a number of parasitic loads including the alternator, oil pump, water pump, cooling fan and power steering and power brake reduce the average efficiency to about 20 percent (see Williams, 1987). We assume a higher average efficiency for diesel engines of about 30 percent compared with 20 for gasoline engine because of the higher compression ratio (leading to better fuel efficiency) and because most of the commercial vehicles such as trucks and buses have turbo-compressors that recover some of the energy from the exhaust gases and also because they usually operate much closer to optimal engine performance profile than do automobiles. Thus, our average final to useful conversion rate for automotive gasoline and diesel engines is estimated to be at best 30 percent. Considering refinery, transport and distribution losses for automotive fuels to be abut 10 percent, the overall primary to useful efficiency is probably closer to 20 rather than to 30 percent.

The transformation of mechanical to kinetic energy results in additional losses in the power train, rolling friction and aerodynamic drag. We estimate these losses at about 30 percent for automobiles and at 40 percent for trucks and buses due to the higher aerodynamic drag, rolling resistance, frictional losses and more parasitic loads (e.g. refrigeration, air conditioning, hydraulic and compressed air drives, etc.). Parasitic loads such as air conditioning, automatic transmission, power windows and power steering decrease the automobile efficiencies as well. This all means that the net conversion of useful mechanical energy to vehicle-kilometers is less than 55 percent efficient for the average fleet (efficiency of 60 percent for automobiles and 50 percent for commercial vehicles). This results in the overall final to kinetic energy (or available vehicle-kilometers) efficiency of about 14 percent.

5.1.3.5. First-Law (Energy) Efficiency

These illustrative examples have shown that the overall efficiency of current energy systems in transforming primary energy to useful energy forms is somewhere in the range of at most 30 percent and at least 3 percent. This is of course a rather wide range spanning an order of magnitude between the lower bound for energy chains ending in radiant energy and the upper bound for energy chains ending in mechanical energy (heat engines) and thermal energy (heat pumps). The basic problem with this measure, however, is not the wide range of prevailing energy conversion efficiencies, but rather the fact that it is not clear how much these efficiencies could be improved. For example, the measure can be misleading because it could be misinterpreted to imply that the improvement potential might be almost 97 percent in the case of the low figure of 3 percent for energy efficiency of chains ending in radiant energy. In fact, the improvement potential for the efficiency of any conversion system is not a function of the current efficiency levels – the improvement potential for lighting systems is not necessarily larger or smaller than that for space heating because the current efficiency is lower or higher. This apparent contradiction is due to the fact that energy is always conserved according to the first law of thermodynamics which simply translates into an observation than some conversion efficiencies are inherently lower than other form the point of view of energy balances.

The question we are interested in is what are the absolute theoretical limits in improving conversion efficiencies. The above logic could be incorrectly taken to imply that the theoretical limit might be one, or 100 percent efficiency. As we will see later, the theoretical limits are in many cases substantially lower then 100 percent. The second problem is associated with the coefficients of performance. They can be higher than one, or higher than 100 percent, thus implying that efficiencies could be improved by simply replacing furnaces and boilers by heat pumps. There are many practical, economic and technical reasons why this is not possible for the time being. Many heat pumps are installed worldwide, however their market is still limited. More importantly, however, the basic problem is that when heat pumps are viewed as a link in the overall energy chain, the efficiency of the overall chain need not be higher just because it contains a heat pump, as was shown above for the case of space heating. Furthermore, the COP of the heat pump drops as the temperature gradient increases between the colder environment and the warmer one that is to be heated (as will be shown in the next section). At temperatures approaching industrial process heat applications, the heat pump efficiency decreases compared to industrial boilers and furnaces even as a stand-alone system.

We have defined the energy or the first law efficiency as the ratio of energy transferred to the ultimate purpose of the system divided by the actual energy input to the system, let us denote this measure by ϵ. As we have seen from the illustrative examples, when the theoretical maximum value of ϵ is greater than one, it is called the coefficient of performance (COP), otherwise it is called efficiency. Heat pumps and refrigerators have values of ϵ that can be larger than unity (for heat pumps usually larger than 2 and for refrigerators larger than 1).

Table 5-2 shows numerators and denominations that define ϵ for various classes of devices and facilities and also gives maximal theoretical values (ϵ_{max}) and standard nomenclature (name used). The table is based on AIP (1975) and defines ϵ_{max} in terms of absolute temperatures. These temperatures are expressed in degrees Kelvin (equal to degrees Celsius plus 273, which is the difference between the absolute zero and zero degrees Celsius). Four different environments (reservoirs) are assumed with different temperatures: T_1(hot)$>T_2$(warm)$>T_0$(ambient)$>T_3$(cool). W and Q refer to work and heat, respectively. In some of these conversion processes it is assumed that a unit of heat Q is transferred from lower to higher temperature reservoir by expenditure of work such as mechanical or electrical energy (e.g. in a heat pump) or that a unit of heat is transferred from a higher to lower temperature reservoir to generate work (e.g. in a heat engine). Maximal efficiency $\epsilon_{\max}$ is one, or 100 percent, when one form of work is transformed into another, e.g. conversion of mechanical energy into electricity.[3]

Table 5-2 First-Law or Energy Efficiency.

Note: $T_1(\text{hot}) > T_2(\text{warm}) > T_0(\text{ambient}) > T_3(\text{cool})$.

Type of device or system[a]	Numerator in ratio defining ϵ	Denominator ratio defining ϵ	$\epsilon_{\max}$	Standard nomenclature
Electric motor (W/W)	Mechanical work output	Electric work input	1	Efficiency
Electric generator (W/W)	Electric work output	Mechanical work input	1	Efficiency
Heat pump, electric (Q/W)	Heat Q_2 added to warm reservoir at T_2	Electric work input	$\frac{1}{1-(T_0/T_2)} > 1$	Coefficient of performance (COP)
Air conditioner or refrigerator, electric (Q/W)	Heat Q_3 remove from cool reservoir at T_3	Electric work input	$\frac{1}{(T_0/T_3)-1}$	Coefficient of performance (COP)[b]
Heat engine (W/Q)	Mechanical or electric work output	Heat Q_1 from hot reservoir at T_1	$0 \le 1-\frac{T_0}{T_1} < 1$	Efficiency (thermal efficiency)
Heat-powered heating device[c] (Q/Q)	Heat Q_2 added to warm reservoir at T_2	Heat Q_1 from hot reservoir at T_1	$\frac{1-(T_0/T_1)}{1-(T_0/T_2)} > 1$	Coefficient of performance or efficiency
Absorption refrigerator[d] (Q/Q)	Heat Q_3 removed from cool reservoir at T_3	Heat Q_1 from hot reservoir at T_1	$\frac{1-(T_0/T_1)}{(T_0/T_3)-1}$	Coefficient of performance (COP)[b]

a Symbols W and Q refer to work and heat, respectively.

b Can take any positive value, it is not restricted.

c A furnace is a special case; for it, $\epsilon_{\max}=1$. More generally, the device could include a heat engine and heat pump; then $\epsilon_{\max}>1$.

d "Absorption refrigerator" means any heat-powered device for cooling.

Source: AIP (1975).

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[3] Although ϵ is defined by AIP (1975) without the explicit reference to the second law of thermodynamics, its ideal maximum value is – for all but work-in work-out devices, such as electric motors – limited by the second law, as we will show in the next section.

Table 5-2 illustrates the basic drawbacks of the energy or first-law efficiencies: Their maximum value is a function of temperatures, but it is also specific to a particular device or conversion system. The values may be greater than, less than or equal to one depending on the particular device or system. Thus, the measure emphasizes the maximum conversion for devices of a particular type rather than the minimum heat or work requirements for a particular task. Furthermore, it cannot readily be generalized to complex systems in which the desired output is some combination of work and heat. This was vividly illustrated with the case of cogeneration, where the total efficiency was simply calculated as the sum of heat and electricity. This is not satisfactory because the measure does not adequately emphasize the central role of the second law of thermodynamics in governing the maximum efficiencies of energy use. For example, the electric heat pump illustrates that a unit of electricity can be used in principle to produce almost three times as much low-temperature heat (almost two units of heat and one unit of electricity inputs dissipated into heat implying a COP of almost three), whereas on average more than three times as much high-temperature heat is required to generate one unit of electricity in a power plant. This clearly illustrates that electricity or mechanical energy has a higher quality form than thermal energy and low-temperature heat in particular. This is reflected in the concept of *available work* which is an entity that is consumed whereas energy is conserved. Using both the first and second law of thermodynamics a superior measure of efficiency can be formulated. This alternative efficiency measure defines the minimum *task* requirements of available work and is device or system independent but it can be employed to assess prevailing efficiency in a realistic energy system.

We have shown that the first law efficiency can be used effectively for comparison of conversion facilities and devises of a particular type as well as for evaluating improvement of efficiencies over time for different technologies and energy forms. We have also demonstrated that it has severe limitations. Basically it cannot be used to determine the theoretical minimum energy requirements for provision of goods and services. The use of the first law of thermodynamics, the conservation of energy, is inadequate for considering minimum task energy, since energy is not consumed, energy cannot be lost but only inefficiently used. Thus, it is necessary to define the theoretical minimum energy required to perform a specified task that could serve as the measure of effective energy use. Such a measure could be used as a yardstick to judge how "inefficient" is a particular energy system compared with the minimum theoretical energy needed to perform the function of the system.

5.1.4. Exergy Efficiency

An appropriate measure for theoretical minimum energy requirement for a given task can be defined in conjunction with the second law of thermodynamics. According to the second law, any process involving heat leads to inexorable increase of entropy which means that not all of the energy can be made available in useful form. In other words, the second law of thermodynamics dictates that, although the amount of energy in the universe is constant, in all real processes energy is degraded with the passage of time. In most general terms, there is a relentless tendency for the extent of disorder in the universe, or entropy, to increase. In fact, Hawking (1988) argues in his best-selling book *A Brief History of Time* that the tendency toward entropy underlies the psychological experience that we know as time, otherwise most physical laws would allow the universe to run equally well forward or backward. The second law makes it fruitful to define a quantity that has the dimension of energy, yet is actually consumed in a energy conversion process as disorder increases with a rising tide of entropy. This quantity is *available work* or ordered work energy. Thus, according to Hawking, it is the decrease of available work, or entropy increase, that actually defines the psychological arrow of time and distinguishes between the past and the future. The increase of entropy that is associated with the *consumption* of available work is the central pivot of the second-law or exergy efficiency. Thus, the consumption of available work is resource limited, while energy is always conserved in the universe. Every energy conversion system that transforms one energy form into another increases disorder or entropy.

There is a theoretical upper limit to the amount of available work that can be produced from *thermal energy* at a temperature T_1 in a setting of lower ambient temperature T_0. This upper limit is, roughly speaking, the available work, the maximum work that can be provided by a system as it proceeds to its final state in equilibrium with the ambient environment, usually the atmosphere.

The method of computing the maximum theoretical efficiency of a *heat engine* such as steam turbine was enunciated by Nicolas Léonard Sadi Carnot in 1824 and is thus often called *Carnot efficiency*. The maximum achievable thermal efficiency is expressed by t' fraction $(T_1 - T_2)/T_1$, where T_1 is the absolute temperature of the working fluid entering the heat engine and T_2 is the temperature of the fluid leaving the engine.[4]

In a modern steam turbine T_1 is typically more than 800°K and T_2 is about 300°K or about 27°C (Summers, 1971). ΔT or the difference between T_1 and T_2 is about 500°. Therefore, according to Carnot law, the maximum

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[4] The thermal efficiency ν of the Carnot cycle is often rewritten as $(T_1 - T_2)/T_1 = 1 - T_2/T_1$. Here we assume that T_1(hot)> T_2(warm)> T_0(ambient). These temperatures are expressed in degrees Kelvin (equal to degrees Celsius plus 273, which is the difference between the absolute zero and zero degrees Celsius).

theoretical efficiency is slightly more than 62 percent. Because the inherent properties of a steam cycle do not allow the heat to be introduced at a constant upper temperature, and because of the numerous losses in the intermediary processes, the maximum theoretical efficiency of steam turbine cycle is less than 60 percent in the order of about 53 percent. Modern steam turbines achieve about 90 percent of that value or 48 percent net efficiency. As we have seen in the previous section, to obtain the overall efficiency of the steam power plant this value has to be multiplied by the net efficiencies of the other energy conversion steps in the chain from fuel to electricity. The resulting efficiency turned out to be 43 percent.

There are two extreme values associated with the Carnot efficiency, one where ΔT approaches zero and one where it tends toward infinity; in these cases the maximum theoretical efficiency approaches zero and one, respectively. This reflects the fact that the available work increases with the temperature, approaching one as temperature increases to infinity. We have mentioned that the Carnot efficiency is a theoretical maximum for a "reversible" heat engine, a hypothetical device device that is capable of operating in both directions. It can produce work by transferring heat form the higher to the lower temperature reservoir, which are assumed to be at constant temperature. In this case it would operate with energy efficiency $\epsilon_{\max}$ (see Table 5-1). This ideal reversible machine could also operate backwards by absorbing mechanical work. By doing so it would "pump" heat from a cooler to a warmer reservoir with the same efficiency as it produced work by operating in the opposite direction. In this case it would operate with COP of $1/\epsilon_{\max}$. Such an ideal machine would need ideal working fluids, it would need to have absolutely no pressure, heat or mechanical losses and so on. These conditions cannot be fulfilled for a practical machine. The degree of irreversibility in the real world of practical machines is illustrated by the difference between the ideal Carnot efficiency and the actually observed efficiency of heat engines and heat pumps.[5] This illustrates that there is a certain symmetry between the heat engines and heat pumps. One produces work by transferring heat form a warmer to a colder reservoir, while the other uses work to transfer heat from a colder to a warmer reservoir.

We have up to now defined the available work or exergy efficiency of a heat engine with the reference to temperature T_2 that is lower than the temperature T_1 from which the heat is transferred, both temperatures were assumed to be higher than the temperature T_0 of the ambient environment (thus, it was assumed that $T_1 > T_2 > T_0$). It is possible to generalize the process to a "heat pump" that can transfer a unit of heat from a cold reservoir T_4 to the cool reservoir at temperature T_3 that is still cooler than the reference ambient environment (i.e., $T_4 < T_3 < T_0$). The maximum achievable Carnot efficiency is $(T_4 - T_3)/T_3$. The exergy approaches zero as the

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[5] We have shown that a modern steam turbine achieves almost 90 percent of the efficiency of an ideal, reversible heat engine.

temperature gradient diminishes, is one when $T_4=T_3/2$ and becomes infinite as T_4 approaches the absolute zero (degrees Kelvin).

Figure 5-2 shows the exergy ν of a thermal Carnot process by assuming the reference temperatures T_2 and T_3 to be equal to $T_0=294°K$ (=21°C). In other words, the heat engine operates between T_1 and T_0 while the heat pump operates between T_4 and T_0. Note, that defined this way available work or exergy of any thermal process is inherent in departure form the equilibrium state defined by a reference temperature of the ambient environment. The curve given in Figure 5-2 would change with different choice of T_0. For example, T_0 could be 3°K of the outer space outside the earth's atmosphere. A hypothetical heat engine could use this temperature gradient between the earth's surface and outerspace, after all most of the solar heat that is absorbed by the earth also leaves the earth as infrared radiation (see the discussion in the next chapter about the "greenhouse effect").

Work is the highest quality (lowest entropy or highest order) form of energy, and consequently the most valuable. Mechanical and electric energy has the highest order and equivalent to available work, while the available work of thermal energy increases with temperature gradient with reference to the lower ambient temperature ($\Delta T=T_1-T_0$). Energy in the form of mechanical work or electricity is the highest grade, approximately equal to the chemical energy in the fossil fuels, whose quality is in turn superior to high-temperature heat. They are all much higher grade energy than the form to which they are ultimately degraded, low-temperature heat (Olivier, 1983). Consequently, the second law imposes upper limits on the conversion efficiencies with a given temperature gradient (ΔT).

5.1.4.1. Available Work or Exergy

In order to understand and calculate the second-law efficiencies, we now give a more general definition of exergy and available work (B):

> "It is the maximum work that can be provided by a system (or by fuel) as it proceeds (by any path) to a specified final state in thermodynamic equilibrium with the atmosphere; interaction with the atmosphere is permitted but work done on the atmosphere is not counted" (AIP, 1975), although in some cases, a base reservoir other than the atmosphere or some other reference (equilibrium) ambient conditions might be appropriate (e.g., ground water, deep ocean, outer space).

The reference is to work and not heat because (as we have argued above) work is the highest "quality" form of energy, equivalent to heat at infinite temperature. More importantly, work is the best overall measure of capacity for doing *any task*. AIP (1975) gives the examples for potential, thermal and chemical energy. For a raised weight (to take an elementary example), the available work is simply *mgh*, the work that can be done by

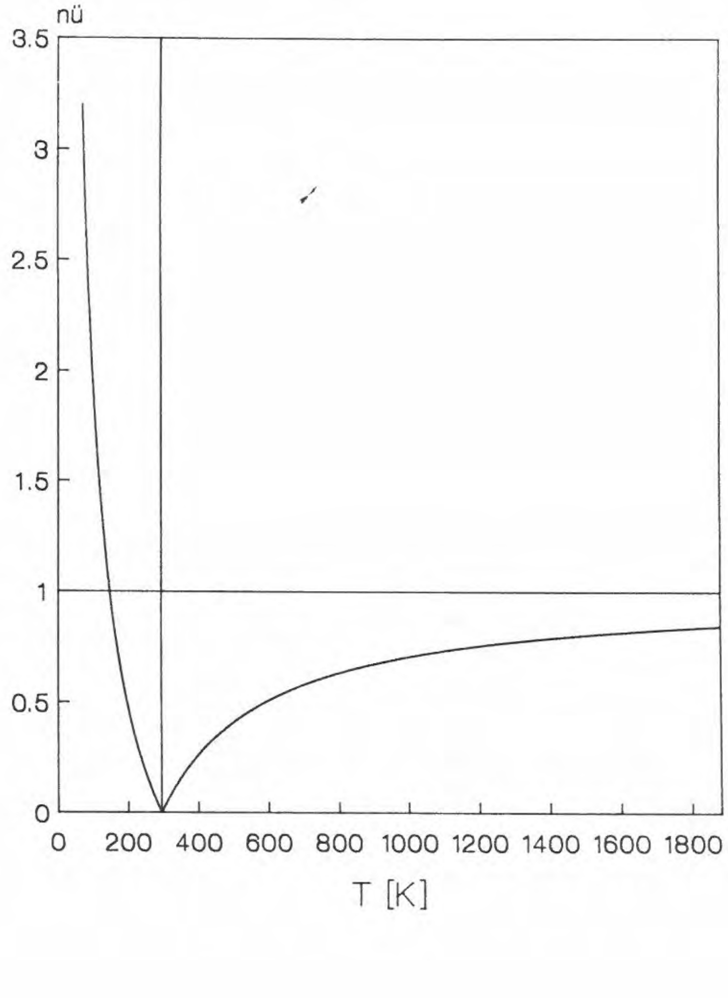

Figure 5-2 Exergy or Available Work (ν) of a Thermal Carnot Process as a Function of Temperature T, for T_0=294°K (=21°C).

lowering the weight to the ground level (equilibrium ambient conditions). For heat Q_1 extracted from a hot reservoir at temperature T_1, the available work (exergy) is $B=Q_1[1-(T_0/T_1)]$. For fuel with heat of combustion $|\Delta H|$, B is roughly equal to $|\Delta H|$ usually to within 10 percent. For a chemical cell, the available work is $B=-\Delta G_0$, the change of Gibbs free energy in the reaction carried out at ambient temperature and pressure (ignoring the contribution of the diffusion of reaction products into the atmosphere).

A more general definition of available work or exergy refers to a system that interacts with its surrounding environment that might include other systems and the atmosphere. We define such a system by five characteristics, its energy E, entropy S, volume V, pressure P and (absolute) temperature T. For example, energy could include the internal energy, gravitational potential energy, kinetic energy of motion and so on. Assume that a given system, through changes in these five characteristics comes to the thermodynamic equilibrium with the surrounding environment, e.g. the atmosphere. The reference temperature and pressure of the surrounding environment are assumed to be T_0 and P_0. Upon reaching the equilibrium, the system has energy E_0, entropy S_0 and volume V_0. In proceeding to the equilibrium state, the system can exchange heat and work, but not matter with the surrounding environment. It can also do work on other systems. The maximum useful work that can be transferred to other systems by the time the equilibrium state is reached is called *available work* or *exergy B* and it is given by:

$$B = (E-E_0)+P_0(V-V_0)-T_0(S-S_0).$$

The Gibbs concept of available work includes an additional term associated with the entropy of mixing of components of the system in the surrounding environment. For example, this could include the diffusion of combustion products into the atmosphere.

The concept of *available work* or *exergy* makes possible a simpler and, for our purposes more useful, general definition of efficiency, which we call *second-law efficiency* (AIP, 1975):

$$\nu = \frac{B_{\min}}{B_{actual}}$$

It states that for any energy task, the second-law or exergy efficiency can be defined as the ratio of the *theoretical minimum amount of available work or exergy* needed to perform a particular function to *actual available work or exergy consumed* by a particular device or a system to perform the same function.

This efficiency measure can of course be applied also to any energy device or facility, but its true value is that it is task oriented and specifies the theoretical minimum amount of available work required *independently* of employed device or conversion facility. The second-law efficiency whose maximum is always one by definition, provides rapid insight into the performance of a specific device executing a specified task in terms of how efficiently that task might be performed where an ideal device available. It shows the maximal, theoretical potential for improvement of any given energy system. Theoretical maximum means maximum permitted by the first and second laws of thermodynamics. It also indicates the level of "convertibility" of one energy form to another.

Consequently, the second law efficiencies impose an upper limit on the maximum theoretical efficiencies that can be achieved with a given conversion technology. Moreover, since practical thermodynamic and mechanical machines can only be made of real materials, with finite heat conductivities, mechanical properties and other physical properties. However, current power plants, engines and process designs are often closer to achievable limits than is sometimes realized.[6] In the case of modern steam turbines we have illustrated that the current net efficiencies of about 48 percent are relatively close to the maximum theoretical efficiency of about 60 percent for heat engines (working with a ΔT of about 500°C). This leaves an impression that the improvement potential is not very large. Some marginal improvement is obviously still possible between 48 and 60 percent, but is constrained by the theoretical limit of the Carnot cycle for heat engines operating with a given temperature gradient. However, our more general formulation of the second-law efficiency is not limited to the theoretical maximum given for the heat engines by the Carnot cycle. Although the Carnot cycle is more efficient than any other heat and power cycle (e.g. Brayton, Rankine, Otto, Diesel and Stirling cycles), the specified task of the power plant is to convert the chemical energy of the fossil fuels into electricity. For this task, an ideal fuel cell would be the more efficient alternative than an ideal thermal engine. Thus, for the given task, the more efficient process would involve the fuel cell, despite the fact that the the Carnot cycle gives the maximum efficiency achievable by a heat engine. In the case of the fuel cell, the potential improvement is larger than the increase form 48 to 60 percent. While it is true that the theoretical maximum value for Carnot efficiency is about 60 percent for a peak stem temperatures of about 500°C (as was explained above), it is almost 87 percent for a flame temperature of about 2000°C. What the second law helps to emphasize is that for the task of converting chemical energy to electricity, there are other processes that are more efficient than a thermal conversion in a heat engine. While the Carnot efficiency *is* an upper limit for a heat engine, the salient point is that a thermal process is not necessarily the only alternative for the given task. The ideal fuel cell is a realization of a device that does not suffer the irreversibility of combustion and therefore has the upper limit $\epsilon_{\max}$ is close to one

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[6] Weinberg (1977, 1978), Ayres (1988) and others emphasize that the thermodynamic theory is gradually recognizing this reality and that new research fields are emerging such as "thermodynamics of finite time". They point out, for example, that the notion of thermodynamic availability has been extended to "finite time availability" and that completely new tools for thermodynamic analysis are being developed. Basically, this means that often power is required rather than available work, say in motor racing.

(AIP, 1975).

Let us briefly consider another example where the difference with the respect to the energy efficiency is even larger. For example, household central heating using oil furnaces achieve average efficiencies in the range of 60 to 80 percent in converting chemical energy in the fuel to useful heat in the boiler (a value of 75 percent is given in Table 5-2, implying that on the average of a year about 75 percent of the heating oil energy is transferred from fuel to hot water in the boiler.) This is often incorrectly taken to mean that a more efficient household heating furnace would be the best possible way to provide space heating.

There are two fallacies in this erroneous statement: First, the task of the oil furnace is to convert the chemical energy in the fuel oil to thermal energy in the hot water; second, the task of the whole heating system is to provide the service of a warm room. For the task set for the oil furnace, more efficient systems are available. For instance a Totem can be used (see the description in the previous section) to power a heat pump or possibly the heat pump could be powered with the intermediary of electricity. Both of these alternatives would be more efficient than an oil furnace. But the actual second law efficiency of the whole heating system is dramatically lower than the foregoing discussion might indicate.

Olivier (1983) points out that the task set for domestic space heating might be, given the specific heat losses from a dwelling, to provide heat in order to maintain rooms on a particular temperature schedule over a whole season. Since the ΔT for this task is on average not larger than 20^{o}C, the maximal efficiency is determined by the Carnot cycle and is about 7 percent! In this case the energy and exergy efficiencies differ dramatically (by a factor of 10 between 75 percent energy efficiency of an oil furnace and 7 percent exergy efficiency of the space heating system). For a power plant, on the other hand, the difference between the energy and exergy efficiencies was less dramatic.

Table 5-3 gives the first-law and second-law (e.g. energy ϵ and exergy ν efficiency) for heat engines and pumps assuming single-source and single-output tasks. Next we will consider a few examples that illustrate how to evaluate the second-law efficiency for a few representative heat engines and heat pumps, but first we will briefly analyze the second-law efficiencies for transformation of work to work (W_{in} to W_{out}). Square 1. in Table 5-3 shows that the energy and exergy efficiencies are equal in transforming one form of work to another. The reason for this has already been given. Work is the highest quality energy form and since exergy is equal to work so that the transformation process can achieve efficiency of one ($\epsilon_{\mathrm{max}}=1$), or 100 percent. Typical examples are transformation of mechanical energy to electricity in a generator or the reverse process in an electric motor. The best generators are very close to this ideal with efficiencies close to 99 percent. For obvious reasons, the exergy efficiency cannot be higher than the energy efficiency for a practical machine, but since work and exergy are the same it

Table 5-3 First-Law and Second-Law Efficiency[a].

Note: T_1(hot)$>T_2$(warm)$>T_0$(ambient)$>T_3$(cool).

	Work: W_{in}	Fuel: Combustion heat $\lvert\Delta H\rvert$ Available Work B	Heat Q_1 from hot reservoir at T_1
Work: W_{out}	1. $\epsilon = W_{out}/W_{in}$ $\nu=\epsilon$ (electric motor)	2. $\epsilon = W_{out}/\lvert\Delta H\rvert$ $\nu=\frac{W_{out}}{B}\ (\approx\epsilon)$ (power plant)	3. $\epsilon = W_{out}/Q_1$ $\nu=\frac{\epsilon}{1-(T_0/T_1)}$ (geothermal plant)
Heat Q_2 added to warm reservoir at T_2	4. $\epsilon(COP)=Q_2/W_{in}$ $\nu=\epsilon(1-\frac{T_0}{T_2})$ (electric heat pump)	5. $\epsilon(COP)=Q_2/\lvert\Delta H\rvert$ $\nu=\frac{Q_2}{B}(1-\frac{T_0}{T_2})$ (engine heat pump[b])	6. $\epsilon(COP)=Q_2/Q_1$ $\nu=\epsilon\frac{1-(T_0/T_2)}{1-(T_0/T_1)}$ (district heat[c])
Heat Q_3 added to cool reservoir at T_3	7. $\epsilon(COP)=Q_3/W_{in}$ $\nu=\epsilon(\frac{T_0}{T_3}-1)$ (electric refrigerator)	8. $\epsilon(COP)=Q_3/\lvert\Delta H\rvert$ $\nu=\frac{Q_3}{B}(\frac{T_0}{T_3}-1)$ (gas air conditioner)	9. $\epsilon(COP)=Q_3/Q_1$ $\nu=\epsilon\frac{(T_0/T_3)-1}{1-(T_0/T_1)}$ (absorb. refrigerator[d])

a For single-source single-output tasks.
b Engine driven heat pump (usually natural gas).
c Any heat-to-heat device such as district heat or solar hot water heater.
d "Absorption refrigerator" means any heat-powered device for cooling.
Source: AIP (1975).

is identical and lower than one only to the extent that actual losses of exergy occur in the machine due to internal friction, air or hydraulic drag, etc. For our purposes, it is just important to note that the theoretical maximum is one for exergy efficiency of transforming one form of work into another. This is not the case with transformation on one form of heat into another or into work. These processes are usually less efficient, because the exergy is a function of absolute temperature and the temperature gradient over which the machine operates. Bellow we will give a few examples of how the exergy efficiency is calculated for a few types of heat engines and heat pumps.

5.1.4.2. Combustion of Fossil Fuels

We have mentioned before that the available work or exergy of fossil fuels is about equal to the heat of their combustion. This is the reason for approximate equality of the energy and exergy efficiency ($\nu \approx \epsilon$) in square 2. of Table 5-3. For most fuels, exergy (or available work) B is slightly higher than the heat of combustion $|\Delta H|$. We denote this difference by $h=B/|\Delta H|$. The heat of combustion consists of two major components, the internal-energy and the non-useful work (change in volume at given pressure). For example, for methane (natural gas) the heat of combustion is 192 kcal/mole, if it is burned in air and all combustion products are in gaseous state (including water vapor); this is the "low heating value". The heat of combustion is slightly higher with 212 kcal/mole, if it is burned in air and the resulting water vapor is condensed into a liquid; this is the "high heating value". The exergy (without accounting for the entropy change due to the diffusion of combustion products) is 193 and 194 kcal/mole for the low and the high heating values, respectively. Thus, exergy is higher than the heat of combustion for the low heating value and smaller for the high heating value. This is the case for most fossil fuels. If we account for the exergy of the diffusion of the combustion products of burning methane in air, the exergy is even higher by another three percent. The values of h are higher, and are above one, for the low heating value when the exergy of diffusion of combustion products is included; they are lower, and bellow one, for the high heating value, ignoring the exergy of the diffusion products.

We have made a simplifying assumption to calculate the exergy of fuel combustion by taking the higher values of h and thus the "low heating" value as the reference point (see Baehr, 1979). This results in the following ratios of exergy to heat of combustion for the three most important commercial fuel types: For coal (assuming an average of brown coal, anthracite and coke) $h=1.06$; for oil products $h=1.06$; for natural gas (mostly methane) $h=1.04$. Thus, our assumption implies $\nu \geq \epsilon$ in the case of the heat of combustion, although the difference is usually less than a few percent.

Due to the small difference between ν and ϵ we simply observe that energy and exergy is approximately the same for combustion of most widely used fuels. The difference becomes more apparent for energy forms such as hydrogen or some types of biomass. For most of the energy conversion devices using heat of combustion the effect of this difference is small, because coal, oil and natural gas provide virtually all of the combustion heat in the industrialized economies. Thus, the power plant efficiencies are approximately the same in exergy and energy terms. They range between 30 and 40 percent for most of the conventional power plants, the OECD average is 35 percent.

The general definition of the second-law efficiency states that minimum exergy for the task is an essential ingredient of an efficiency calculation. In the particular case where the task is electricity generation, the efficiency would be limited by the Carnot efficiency only if we assume that the electricity would be generated by a heat engine. As we have mentioned above, the energy efficiency of a heat engine would be almost 90 percent at flame temperatures exceeding 2000°C, but is as low as a maximum of 60 percent for peak steam temperature of 500°C. According to AIP (1975), the exergy efficiency helps to emphasize that for conversion of chemical energy to electricity, the Carnot efficiency is not the upper limit. The ideal fuel cell, instead of an ideal heat engine, is a device with an exergy efficiency of one. Thus, the second-law consideration of conversion of heat of fuel combustion into electricity indicates that the process is between 30 and 40 percent efficient both in energy and exergy terms, although according to the Carnot efficiency the modern power plants achieve almost 90 percent of the theoretical maximum for steam cycle.

5.1.4.3. Space Heating

The Carnot efficiency gives the theoretical minimum exergy requirements for transferring heat Q_2 to warm reservoir at temperature T_2 for heating (and process heat in industrial applications) and for extracting heat Q_3 from a cool reservoir at temperature T_3. Since the minimum task exergy is given by the Carnot cycle, it is used to calculate the exergy efficiency.

Let us first consider space heating consisting of a furnace and hot water radiators that add heat Q_2 at temperature T_2 to warm air for space heating. The energy and exergy efficiencies of the system are given in square 5. of Table 5-3. We assume a mean ambient temperature of $T_0=274°K$ ($=1°C$) and the mean temperature of the heated air $T_2=294°K$ ($=21°C$). The ratio Q_2/B is slightly lower than one in the best case because, as was shown above, exergy is higher than the heat of combustion for most fossil fuels. For natural gas exergy is about 4 percent higher than the heat of combustion (low heating value). This gives the second law efficiency of 6.5 percent: $\nu=(1/1.04)(1-274/294)=0.065$. Assuming a smaller temperature gradient ΔT reduces the overall efficiency. For example decreasing the mean temperature of the heated air to 284°K air with the same ambient reference temperature would decrease the efficiency to about a half, or 3 percent. In general, the lower is the application temperature of useful heat with a given ambient reference temperature the lower is the exergy. Note that instead of assuming a decrease in the mean temperature of the heated air, efficiency also decreases if we assume a slightly higher ambient reference temperature of say 284°K which is often the case throughout the heating season and especially during the fall and spring.

We obtain the same result by considering the efficiency of this heating system more explicitly. The overall conversion chain from final exergy (of natural gas) to useful exergy of heated air consists of a number of components. Let us consider two distinct steps in the chain – a furnace that adds heat Q_1 to the hot water at temperature T_1 and hot water radiators (heat exchangers) that add heat Q_2 to warm air at temperature T_2. The overall second law efficiency ν is a product of the furnace efficiency ν_1 and the radiator efficiency ν_2. The later is given in square 6. of Table 5-3. Assuming the mean temperature of hot water $T_1=313^o$K (=40^{o}C) and the same warm air and ambient temperatures, as above, the exergy efficiency of the hot water heating is 12 percent and the exergy efficiency of the warm air heating with hot water is 41 percent which results again in the overall final to useful exergy efficiency of 6.5 percent:

$$\nu=\nu_1\nu_2=[(1/104)(1-274/313)][(1-274/294)/(1-274/313)]=0.065.$$

Let us now consider a heat pump for the same task of adding heat Q_2 to warm air at temperature $T_2=294^o$K and the same ambient reference temperature of $T_0=274^o$K. Furthermore, we assume two conversion steps in the chain of final to useful exergy – electricity powers the heat pump which heats hot water and hot water (e.g. floor heating or radiators) heats warm air. Heat pump adds Q_1 to hot water at temperature $T_1=313^o$K (=40^{o}C) from a cool reservoir at temperature $T_3=285^o$K (=12^{o}C), e.g. ground water. Typical exergy efficiency ν_1 of a heat pump operating at these conditions is about 30 percent. From square 4. in Table 5-3, this implies an energy coefficient of performance of about 3.35:

$$\epsilon_1(COP)=\nu_1/(1-T_3/T_1)=0.3/(1-285/313)=3.354.$$

Note that the coefficient of performance depends on the temperature gradient for a given exergy efficiency. A heat pump is most effective over small temperature steps; at temperature ratios $T_3/T_1>1.43$ it looses its "magnification" as ϵ_1 decreases bellow one. Thus, the heat pumps become unaffective when the absolute temperature step exceeds 43 percent. This means that for all high temperature applications direct heating is much more effective than the application of (electric or engine powered) heat pump.

The exergy efficiency of hot water to warm air heating, ν_2, is given in square 6. of Table 5-3 and is 76 percent:

$$\nu_2=(1-T_0/T_2)/(1-T_3/T_1)=(1-274/294)(1-285/313)=0.76.$$

The overall final electricity to useful heat exergy efficiency is 22 percent: $\nu=\nu_1\nu_2=(0.3)(0.76)=0.22$. To illustrate the point that the overall efficiency of the system decreases for a higher temperature step-up for the heat pump, we keep all the assumptions the same including the heat pump exergy efficiency (of 30 percent), but assume that the cool reservoir is the ambient air at temperature $T_3=T_0$. This increases the net temperature gradient from from cool reservoir to room temperature from 9^{o}C to 20^{o}C. Simple calculation shows that the overall exergy efficiency of the system decreases to 16 percent. To derive the exergy efficiency of the whole chain from fossil fuel to space heat with the heat pump, there are in principle two routes.

Either the heat pump is powered by electricity from a power plant or by an engine (say natural gas) either directly or via intermediate electricity conversion (boxes 4. and 5. in Table 5-3, respectively). In the first case the overall exergy efficiency is about 8 percent (with 22 exergy efficiency of the heating system and 35 percent exergy efficiency of electricity generation). The overall efficiency in the second case is probably lower because smaller heat engines (such as small diesel or otto motors) are less efficient than for instance the large combined-cycle gas-turbines under equivalent operating conditions.

5.1.4.4. First and Second Law (Exergy) Efficiency

In the previous section on energy efficiency, we have also briefly analyzed the typical conversion processes for transportation and illumination. In these two cases, the exergy and energy efficiencies are about the same, since we are dealing with conversion of mechanical energy to kinetic energy for vehicles and conversion of electrical energy to radiant energy. If we consider the more general formulation of the second law efficiency, as we have applied to estimate the efficiency of thermal conversion processes, then exergy efficiency could be indeed much lower for the two given tasks, moving goods and people from one to another location and illuminating needed areas. The function set for a motor vehicle could be, given its engine and drive train efficiencies, its aerodynamic drag, tire resistance and other losses, to provide mechanical work to move it at a particular speed for a given distance in order to transport people and goods. The function of artificial lighting could be, given physical characteristics such as the construction of the luminaries, such as the nature of the control system, the size and orientation of windows or the color and reflectiveness of the wall surfaces, to provide light to maintain a certain illumination level throughout a day.

In all such cases, it is by no means trivial to calculate the least available work or exergy that would be needed to fulfill the energy task. For example, a hypothetical vehicle could be powered by an ideal fuel cell and an electric motor. The fuel to mechanical exergy efficiency would be 100 percent. Furthermore, the vehicle could move in an vacuum tunnel by magnetic levitation and thus avoid all frictional losses. Some minimal exergy would be required for overcoming elevation between two destinations (potential energy), but that is "recyclable" so that in the long run the minimum exergy requirements would be nil. In comparison with such a hypothetical vehicle, the current exergy efficiency of transport is by comparison infinitesimal. All such considerations, are interesting if one wishes to identify absolute theoretical limits in "anything goes future". Our objective in assessing the prevailing exergy efficiencies is to determine improvement potentials, rather than to venture in the realm of the science fiction. Thus, we have attempted not to alter the "life-styles" or energy use patterns, when we discussed exergy efficiencies in the foregoing sections. In the spirit of this maxim, we will assume here the same exergy and energy efficiency for transportation and illumination, and for all conversion processes from work to work.

Given these assumptions, it is apparent that the calculated efficiencies of most conversion chains primary to useful exergy are rather low compared with their energy efficiencies. This shows how much room there is for improvement in principle (without changing energy use patterns). Exergy efficiency therefore indicates "waste" of fuels and other sources of "exergy" (ordered states). For any specified energy task requiring work and/or heat, maximizing exergy efficiency is equivalent to minimizing fuel consumption, although some waste is inevitable in practice. We have shown that the calculated exergy efficiencies were between a few percent and less than 15 percent for the useful energy applications discussed so far.

In fact, the overall efficiencies for the given examples are quite low for the whole chain, but appear to incur most of the conversion "losses" in going from final to useful exergy. Let us briefly summarize the approximate range of calculated efficiencies for the three examples of space heating, vehicle transport and illumination:

1. Space heating – the idealized thermodynamic function could be conceived as the transfer of heat from an ambient heat reservoir, at the temperature of the outside air, to a reservoir at the temperature of the interior of the heated area assumed to be 21°C (AIP, 1975). The weighted ambient temperature during the heating season is not lower than say 1°C in the middle latitudes, meaning that ΔT is about 20° and the lower reference temperature is 1°C resulting in the "second law" or intermediate efficiency of about 7 percent. Multiplying with the efficiency of the boiler, refinery and other components of the energy system that precede the space heating devices, results in the overall efficiency of typical space heating system of about 5 percent. Slightly higher overall efficiencies of about 8 percent were shown to be possible by deploying heat pumps instead of conventional heaters. Allowing for the frequent practice of off-season heating when the ambient temperature is much higher, the actual efficiency of final energy to space heating is is in extreme cases significantly lower due to much lower temperature gradient. Other estimates of the heating efficiency are in the same range, between 3 and 6 percent. (e.g. see Schipper, 1976; Sorenson, 1987; and AIP, 1975).

2. Transportation – the idealized transport function can be characterized to be the provision of kinetic energy for the vehicle to cover a certain distance at a given speed. The actual conversion efficiency of a gasoline engine is in the order of about 33 percent under ideal conditions, but in practice cars operate at changing load profiles in average traffic so that the aggregate conversion efficiency, assuming 50 percent urban driving cycle and 50 percent highway, is substantially lower. Additional losses to internal engine friction, cooling exhaust and a number of parasitic

loads including the alternator, oil pump, water pump and cooling fan reduce the average efficiency to about 20 percent (18 to 22 percent, see Williams, 1987). We have assumed a higher average efficiency for diesel engines (of 32 percent compared with 14 for gasoline engine) because of the higher compression ratio (leading to better fuel efficiency) and because most of the commercial vehicles such as trucks and buses have turbo-compressors that recovers some of the energy from the exhaust gases and also because they usually operate much closer to optimal engine performance profile than do automobiles. Thus, our average final to useful conversion rate is estimated at about 20 percent. The transformation of mechanical to kinetic energy results in additional losses in the power train, rolling friction and aerodynamic drag. We estimate these losses at about 30 percent for automobiles and at 40 percent for trucks and buses due to the higher aerodynamic drag, rolling resistance, frictional losses and more parasitic loads (e.g. refrigeration, air conditioning, hydraulic and compressed air drives, etc.). Parasitic loads such as air conditioning, automatic transmission, power windows and power steering decrease the automobile efficiencies as well. This all means that the conversion of mechanical work to vehicle-kilometers is less than 55 percent efficient for the average fleet (60 percent automobiles and 50 percent commercial vehicles).[7] This results in the overall conversion of final energy in the fuels (exergy of combustion heat) to performed vehicle-kilometers is about 14 percent. The efficiency of the whole chain is about 12 percent including the refinery and other conversions of primary crude oil to motor fuels. Other estimates are lower ranging from 3 percent (Rossi, 1984), between 8 and 9 percent (Ayres, 1988), 10 percent (Schipper, 1976) and 12 to 15 percent (Olivier, 1983). Thus, our figure is probably optimistic, but it refers to the whole OECD region, while most of the other estimates are based on the situation in the United States with less efficient motor vehicles.

3. Lighting – the function of artificial lighting could be characterized to be the provision of light in order to maintain a certain illumination level throughout a day. We have already mentioned that the incandescent lamp efficiencies are about 4 percent in converting electricity into visible radiant energy. Fluorescent lamps can reach higher efficiencies of up to [illegible] percent with a typical value of 20 percent. This leads to an average efficiency of electric light of about 10 percent (some estimates

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[7] The second law efficiency of useful to mechanical energy conversion in an internal combustion engine is strictly speaking one, since there is no degradation in energy form. However, this ignores the losses and other functions of an automobile that go beyond the provision of vehicle-kilometers: When we account for all "parasitic" functions and conditions of practical design of vehicles and driving conditions the resultant intermediate conversion is lower as given above on the order of 55 percent. This is true for all vehicles in general. Exergy is one and the theoretical minimum is required only to overcome the height from going from one place to another. Thus, a Maglev vehicle in and vacuum pipe (or better a permanent magnet levitation) would need only this minimal energy. However, this is an unrealistic example, because what really matters is of course the *speed* and acceleration so that they must be accounted for.

for the United States give a lower value of about 7 percent, see Ayres, 1988). The efficiency would be much lower if factors were considered that would affect the "quality" of light. For example better reflectiveness of the lamp (through reflectors and focusing) would increase the direct light yield, better reflectiveness of the walls would increase the indirect light and so on. However, all such measures tend to change the nature of overall artificial lighting and would thus affect the service aspect. Thus, we estimate the average conversion efficiency of final electricity to useful radiant energy to about 10 percent and the overall efficiency of the chain at 3 percent (including the electricity generation efficiency). Ayres (1988) argues that another 25 percent of electricity consumption should be added due to indirect loads associated with lighting because radiant energy produces heat that must be removed especially in hot weather. This would ultimately reduce the overall efficiency further to slightly more than 2 percent. Sorensen (1982) and Olivier (1983) give even a lower overall efficiency estimates of 2 percent. Here again, our estimate would tend to represent an upper value.

These three illustrative examples show that the second law or the actual intermediate conversion efficiencies result in a rather low range of transformation effectiveness of converting final energy into space heating, kinetic energy of vehicles and lighted areas. The overall average is somewhere between 2 or 3 percent and 15 percent. These are indicative numbers and not representative averages. However, they clearly indicate that the largest improvement potentials are certainly to be found at the level of end use applications. The indicative efficiency of around 10 percent at the end use level is in a sharp contrast to the primary to final efficiency in the OECD countries of 70 percent.

In the following sections, we will attempt to calculate the energy and exergy efficiency of the primary to useful energy conversion in the OECD countries. It will be shown that the representative figure of about 15 percent is a good indicator of the exergy efficiency while energy efficiency is higher with about 40 percent. Before we do that, however, let us briefly consider the most elusive part of the energy system, the conversion of useful energy and exergy to energy services. This is a territory of energy and exergy analysis that has been very sparsely explored. Consequently there are only a few sporadic estimates that could be used to assess current service efficiencies.

5.1.5. Service Efficiency

The comparison of final to useful energy and exergy conversion leads to a rather low overall efficiency compared with primary to final conversion. Especially the relatively low efficiency in exergetic terms questions the overall effectiveness of energy use in modern societies. In other words, the relatively low exergetic conversion values indicate that often higher quality energy forms are applied to provide low quality services. A good example is the use work (mechanical energy) to provide (low-temperature) heat. If the objective is to maximize the efficiency of the energy system, it makes no sense to use an energy form with exergy of one to provide heat with a low temperature gradient compared to the surrounding environment. In thermodynamic terms this would mean to waste most of the available work (most of exergy). Instead, the overall efficiency can be improved by a better match between the thermodynamic quality of an energy carrier and the quality required for a particular energy service. For example, electricity and fuels should be used for provision of mechanical energy while low-temperature waste heat should be used for space heating. Despite the fact that usage of electric resistance heating or natural gas for space heating appears to be wasteful with exergy, there are other reasons for such applications. Examples include real-time-control or availability of power. Nonetheless, compared with lavish consumption of exergy in end-use applications, the actual energy services that are derived appear to be even less efficient and perhaps the weakest link in the efficiency of the whole energy system.

There are many vivid examples for the notorious inefficiency of energy services. Typical examples include the "control" of room temperature by widely open windows while the radiators are on full blast, or an automobile occupied only by a driver, that has not been tuned for a long-time, idling in bumper-to-bumper standing traffic. In both cases the primary to useful energy conversion chains might be very efficient, but the ridiculously low efficiency of the last link in the chain, namely the provision of energy services, reduces the overall efficiency drastically. Major improvements in oil refining, power plants, automobiles and household heating systems can be diluted to insignificance by wasteful services.

We will try to give indicative estimates of efficiency of energy service despite the obvious caveats, the most serious being the genuine lack of data. Thus, our quantitative assessment should be taken for what it actually is – an attempt to estimate approximate energy service factors. It is not a comprehensive assessment that could be used instead of real data in further analysis. Table 5-4 shows that this last step in assessing the relative efficiency of energy and exergy services is the most uncertain and rather judgmental in nature. It includes factors such as the thermal integrity of buildings, the needed space heating area; load factor of vehicles and required transport services; and provision of exactly needed light without waste. The judgmental part is especially critical when it concerns the life-style aspects of energy services, e.g. heating living areas that are not used, driving alone in a car, or lighting an empty room. It should be mentioned that service efficiencies are probably different for energy and exergy calculation schemes. We did not want to define different figures because of their rough nature it makes no sense to distinguish them due to the low significance of estimated numbers. In principle, however, the exergetic service factors should represent theoretical maximum efficiency for a given end-use task, while energetic service factors could be limited to estimates of best efficiencies for particular end-use devices.

Table 5-4 Conversion Steps in Energy and Exergy End Use and Services.

Conversion	Technology	Examples	Efficiency
Primary to Final	Conversion, Distribution Technologies	Power Plants, Refineries Grids	First and Second Law Efficiencies
Final to Useful	End Use Technologies	Boilers, Vehicle-engines Light-bulbs	First and Second Law Efficiencies
Useful to Services	End Use Services	Heated, Passenger-km, Lighted Area	Service Factors or Efficiencies

Source: After Olivier, 1983.

In an attempt to reduce the uncertainties we have made a working assumption *not to change the function or task of current energy services* when assessing the relative service efficiencies. For example, the relative energy and exergy services in transport are derived as the ratio of the least possible useful energy requirements for a given transport function divided by the actual amount of energy consumed *without* changing the nature of the transport function. We assume similar modal categories such as automobiles, trucks and jet aircraft (Ayres, 1988), similar living patterns and energy uses in households and services, and similar industrial productions profiles such as steel and cement. In order to assess the service factors we do change the capacity utilization of vehicles and possible improvements in logistics, the thermal integrity of buildings and usage, and industrial production utilization of energy in provision of services such as idle time and losses. All of these service factors are naturally very difficult to estimate with any precision and they are highly judgmental. However, we are here primarily interested in approximate figures of relative magnitude and not in the absolute values. The sole purpose is to estimate how large are the conservation and efficiency potentials that do not change life-styles, and the structure of provided services and products. Given these basic assumptions, we will now illustrate approximate magnitude of the representative service factors for three typical energy uses: process heat, space heating and transport.

5.1.5.1. Process Heat

Most of the industrial furnaces provide heat for chemical, mineral and metallurgical processes. In general, some process heat is delivered in the form of steam however at temperatures that vary with the application from temperatures of about 200°C to about 300°C, but there are also important applications at much lower temperatures. These circumstances make it quite difficult to assess the service factors with any degree of precision. Robinson (1987) and Olivier (1983) give the relative service efficiencies of process heat at about 60 percent. Other estimates are much lower. For example, much of the process heat needs in the paper and pulp industry could be eliminated altogether through its own energy production from wastes (Ayres, 1988). In this case, the service efficiency would be minimal or zero. However, this is an extreme example, and in practice the service efficiencies can be relatively high. This illustrates that there is a substantial "waste" of fuels used for process heat either through repeated heating steps or through waste (idle, start-up and shut-down time). In other words, a service factor of 60 percent implies that the energy requirements for process heat would be halved under optimal conditions, production organization and planing. This would include enhanced recycling of materials and elimination of wastes in production thus reducing the overall processing requirements.

As we will show in the following sections, the final to useful process heat conversion is 70 percent efficient in the OECD countries, while the exergy final to useful efficiency could be taken to be at least 25 percent. Together with the aggregate primary to final conversion efficiency of about 70 percent, this results in the energy efficiency of the whole chain of about 50 percent and an exergy efficiency of about 12 percent. Taking the approximate service factor of 60 percent would reduce the overall primary to energy and exergy services efficiency to figures as low as 30 and 12 percent, respectively. Compared to the efficiencies given in the literature, the figure for exergy efficiency is very likely an over-estimate of the actual overall efficiency of process heat applications. Olivier (1983) estimates only one percent overall efficiency while Ayres (1988) gives a figure of about 2.5 percent for all industrial energy uses. This brief example illustrates vividly that the overall efficiency of provision of energy services is indeed very low compared with the prevailing efficiencies of converting primary to final energy forms.

5.1.5.2. Space Heating

The relative service efficiency of space heating systems is notoriously difficult to assess, because it is based to an extent on arbitrary assumptions. Compared to the least conceivable heating requirements the current service efficiencies of space heating are certainly very low. A building which is sufficiently well insulated, uses low heat loss windows and is designed for low cold air infiltration through heat recovery ventilation, requires no heat input from and artificial space heating system. Passive heating measures such as waste heat from refrigeration, cooking and solar heat are usually sufficient to maintain comfortable room temperatures. Since both in very temperate climatic conditions as well in the extremely cold climates and bad weather some space conditioning is required we have assumed a that it would be possible to reduce heating requirements for the same comfort by a factor of 8 though better dwelling design and insulation, thus the service efficiency might be in the neighborhood of 15 percent, take or give 10 percentage points. Ayres (1988) estimates service efficiency of space heating at about 10 to 15 percent, Sorensen (1982) and Robinson (1987) give 16 percent, while Krause (1981) assumes 10 percent; our assumption of 15 percent appears to be reasonable because it represents an average of the estimates from the literature.

The energy efficiency of the overall energy chain for space heating might be on average about 8 percent, if we take the overall primary to final energy conversion of 70 percent, the average heating system efficiency of about 70 percent and the service factor of 15 percent. The exergy efficiency would be much lower due to the low temperature gradient of about 20°C for most applications. The exergetic overall primary to service efficiency is about 0.6 percent with the same assumptions. This corresponds again with the estimates in the literature: for example, Olivier (1983) gives one percent and Ayres (1988) about 0.4 percent. At the same time, this extremely low aggregate efficiency indicates that it is the heating applications where the improvement potential is indeed very large by all standards of measurement.

The actual service efficiency is probably even lower compared with an ideal standard. For example, well insulated dwellings tend to "float" above the ambient temperature, reducing the actual heating load factor averaged over a year. In fact, the dwellings with the best conceivable thermal insulation do not need any heating or cooling *at all* (Ayres, 1988; or Olivier, 1983), thus in the very extreme case the service efficiency of the current heating systems is strictly speaking close to zero. However, as long as there are any heating requirements at all, the efficiency of the best current heating system designs can be very high and in conjunction with the high degree of insulation would also lead to high service efficiency.

5.1.5.3. Transport

Most of the transport services in the industrialized countries are provided by motor vehicles, trains and aircraft. Merchant vessels are not important anymore in terms of the overall passenger traffic while they still carry a substantial share of international freight transport volume. In terms of the average modal split, automobiles have the highest share in passenger traffic in most of the developed countries. The overall service factor for transport activities depends, therefore, to a large degree on the efficiency with which the motor vehicles are used on average.

For example, there are 4.5 available seats per automobile in the FRG. The automobiles traveled in 1985 about 314×10^9 vehicle-km and provided about 484×10^9 passenger-km (Verkehr in Zahlen, 1985). Thus, the average load factor was 1.5. This leads to an average capacity utilization of 33 percent. We have further reduced this number to 20 percent due to the idle time, waiting in congested areas and urban traffic. In some cities, more than half of the vehicle-km are devoted to waiting and idle driving in search of a parking spot. For commercial vehicles, the service factor is likely to be higher than form automobiles, say on the order of 50 percent. The load factor for trains is probably lower than for buses and trucks. For example, in Austria 60 percent of all freight cars are utilized while the other 40 percent travel empty. The utilized cars have an average capacity utilization of about 50 to 60 percent, giving the overall freight utilization of 30 to 36 percent. In intercity passenger travel the ratio of passenger-km to available seat-km is about 35 percent. This leads to a rough estimate of 35 percent for all operations. Aircraft probably have a higher load factor. According to IATA (1987), it is 67 percent for passenger operations, 64 percent for international freight and 60 for domestic. The average is about 65 percent.

For all transport modes taken together in the OECD countries, these rough assumptions result in an aggregate lead factor for all transport operations of about 34 percent. Soreson (1982) gives the following estimates: Automobiles 16 percent; Buses and trucks 25 percent; aircraft 16 percent; trains 24 percent. (for the US). Krause (1981) assumes the same service factor for all vehicles of 50 percent (for FRG) and Olivier (1983) nearly the same factors (for the UK), while Robinson (1987) assumes a factor of 40 percent for all vehicles (Canada).

In the previous sections, we have estimated the representative useful energy and exergy efficiency of automobiles at about 15 percent. The aggregate average for all means of transportation in the OECD countries is somewhat higher with about 20 percent according to our estimates. Given these assumptions, the overall conversion of final energy and exergy to transport services is thus about 5 percent. This compares with Olivier (1983) estimate 8 percent. Ayres (1988) estimates the overall service efficiency of automobiles (in the US) at 4 percent; trucks at 12 to 15 percent; freight (diesel) trains at 25 percent; and aircraft at 5.5 percent. Thus, the relative efficiency is the highest for electric trains and lowest for the automobile. Individual transportation has its energy price and it is clear that due to the relatively low service factors that the automobile cannot reach the energy efficiency of mass transportation. At the same time, it is precisely the individual character of the automobile that is both the reason for its low efficiency and very high quality of service (e.g. convenience and comfort).

5.1.5.4. Overall Service Efficiency

These three important applications of final energy and exergy for space heating, process heat and transport result in energy services. The efficiency of providing energy services with useful energy or exergy is estimated to be about 40 percent. Exergetic final to service efficiency is about 8 percent, while the energetic final to service efficiency is about 20 percent. Considering the average conversion rate of primary to final energy of about 70 percent in the OECD countries, the overall efficiency of providing energy and exergy services is indeed very low (between 5 and 15 percent for energy and exergy efficiency, respectively, see the following sections), despite the very uncertain and rough nature of our numerical calculations. However, we did indicate that these rough estimates, and in particular the exergy efficiency of about 5 percent, are in a good agreement with figures quoted in the literature. Ayres (1988) estimates the overall efficiency in the United States at about 2.8 percent. Olivier (1983) estimates 3 percent efficiency for the United Kingdom, and Marchetti (1980) estimates the overall efficiency at less than 5 percent.

At face value, these low figures suggest that enormous improvements should be possible. Yet everybody knows from personal experience how difficult it has been to conserve energy and improve the end use efficiencies even during the periods of very high energy prices of the 1970s. Nevertheless, it is clear that we are still very far from any physical or theoretical limits in improving efficiencies. The primary to final energy conversion is in comparison rather high, and the efficiency of industrial and commercial applications of final energy is in general much higher than in the households and other individual end use applications. At the same time, this fact also illustrates the difficulties embedded in the attempts to improve the energy service efficiencies. The largest gain potentials are available at the point of consumption. Since we have not made any attempts to change the patterns of energy use or life-styles in our assumptions, most of the potential improvements could in principle be of technological and institutional nature without directly affecting the consumers. However, this implies that much of the capital stock invested in machines, devices, appliances, buildings and vehicles would have to be replaced with more energy efficient ones and this takes time. The improvement potential of energy, exergy and service efficiencies will depend on the likely timing of the replacement of existing capital stocks with more efficient ones and will thus depend on the duration of these processes.

5.1.6. Diffusion and Substitution Processes

The speed at which new efficient systems can be introduced depends to a large extent on the rate of replacement of the older generations. Thus, the vintage structure plays an important role. This is more so the case when the rates of growth are relatively low as is currently the situation in most of the industrialized countries. The replacement speed, or the rate of structural change is different throughout the economy. The studies of innovation diffusion indicate that larger systems such as infrastructures tend to be replaced by the new ones at relatively slow rates. For example, the replacement of older energy sources by new ones lasted on the order of 80 to 90 years. Crude oil was first introduced almost 100 years ago and it is only during the last decades that its market share started declining in most countries. The use of crude oil as an important energy source is basically a question of development of whole infrastructures. Oil pipelines and tankers are needed, refineries and a host of end use technologies.

The duration of the replacement of old transport infrastructures by new ones is equally long process. The development of railroads lasted about 100 years from the first applications in 1830s until they reached the climax of their importance in the 1920s. With the advent of road transport and motor vehicles their relative importance started to decline. There are many examples that show that the development of new infrastructures are processes that last many decades. In Chapter 2 we have addressed some of these questions when we discussed social and economic changes.

The efficiency improvements that we considered in this chapter, however do not only refer to large complex systems but also to energy end use and conversion technologies. Technologies that are closer to the ultimate consumer have shorter life-spans than infrastructures so that the replacement processes tend to be faster. The aging of older vintages is much quicker for vehicles than power plants or for the housing stock. This to a large extent determines the rates of replacement. Vehicle fleets can be replaced in about three decades. This is also the case with the rolling stock of locomotives and cars for railroads. The aircraft on the other hand have a somewhat longer service life. In any case, it could last up to 30 years before most currently used vehicles could be replaced by more efficient ones. Another extreme example are the light bulbs, they could be replaced within comparatively very short time span of a few years if not less.

Table 5-5 compares the rates of replacement of old by new technologies in the United States and Soviet Union. We denote the replacement time by Δt; it stands for the elapsed time between the introduction of a new technology and the 50 percent mark in the substitution of the old one. Twice the replacement time gives the duration of the complete substitution of the old by the new. As can be seen in Table 5-5, the replacement time for many technologies has been surprisingly similar in the two countries. This indicates to some extent the inertia of the system as it is embodied in the vintage structures.

Another salient point is that these replacement processes lead to inhomogeneous nature of technological and structural change. The replacement rates will vary from one sector to another and from one energy application task to another. The mean duration for the replacement of most of the systems is likely to be on the order of about 30 to 40 years. If we assume that

Table 5-5 Diffusion Time of New Technologies, US and USSR.

	USA		USSR	
	t_0	$\Delta t(years)$	t_0	Δt (years)
primary energy				
wood	1883	65	1919	77
coal	1885	66	1926	76
oil	1956	79	1985	120
gas	1990	112	1983	47
energy technologies				
surface coal	1975	70	1986	59
infrastructure				
canals	1840	48	1843	113
railways	1913	90	1941	101
roads	1916	92	1941	101
passenger transport				
rail	1920	51	1971	57
car/bus	n.a.	50	1976	53
air	2004	67	2006	80
transport technologies				
steam/motor ships	1886	75	1900	66
diesel/electric locomotives	1951	13	1961	14
labor force				
agriculture	1893	115		
manufacturing	1930	120		
service	1975	224		
education				
literacy rate	1822	160	1923	38

Source: Grübler and Nakićenović (1988).

the new systems that are being introduced now are twice as energy efficient as the ones they will be replacing, than in about 30 years the overall efficiency could be twice as high as today. This implies an annual efficiency improvement rate of more than 2.3 percent. Should in addition demand grow so that the new systems are introduced faster than the replacement needs, than the improvement rates can be higher. In any case this illustrates that it will be difficult to achieve higher overall improvement rates than a few percent per year. The achievement of higher efficiency improvement rates will require vigorous incentives and active efforts. In the longer term such improvements appear to be necessary mainly in view of adverse environmental impacts of anthropogenic activities and especially of carbon-based fuels. More efficient systems must be introduced now to have impacts on the overall efficiency improvement during the next decades. The improvement potential is indeed high, but time will be needed to exploit it.

For every given energy service task there are two basic processes that influence the overall demand. There is the replacement of older by new and more efficient technologies that reduces the overall energy requirements, and at the same time, there is the diffusion of new applications of energy, or more widespread use of a particular energy service task. Thus, the color television sets are becoming more efficient and require less energy for a particular task, but at the same time, more consumers own the TVs and their performance increases (both factors off-setting to a degree the efficiency improvements). Often the diffusion, or the increase in ownership, is easier to asses than the improvements in performance that results from replacement of old by new vintages.

5.1.7. Improvement of Energy and Exergy Efficiencies

In fact, the assessment of potential improvements is the main reason behind this exercise in estimating the actual efficiency of energy use. It is only in this context that the current overall efficiency of the energy system has any relevance. An efficiency of 5 or 15 percent by itself is just a fact. As Ayres (1988) observed, it is not immediately obvious whether low efficiency of energy use is anything to worry about. After all, efficiency is just one factor in judging the performance of energy services. Time and quality of provision of services are very important and so are the economic costs. With increases in mobility, speed and just-in-time provision of energy services might be sometimes even more important than the efficiency measures. Higher speed of vehicles has a high energy price and decreases the efficiency per passenger and ton-kilometer. Provision of heat where and when it is needed means that higher quality forms of useful energy have to be applied, the required conversions have again usually some efficiency penalty.

Another important caveat is that the efficiencies are not the only or even the predominant indicator of *quality* for useful energy forms. As we have observed above, part of the energy is degraded in order to produce energy services, so that there is an implicit trade-off between conversion *efficiency* and required energy *quality form*. Furthermore, according to Ayres (1988) *time* has a value in the real world, which is another way of saying that the *rate* of output on an energy conversion device (i.e. generation of electricity when it is needed, or power of an automobile engine) is likely to be as important for a particular function and often more important than the actual conversion efficiency. Thus, there is a second important trade-off between time and energy. The design point for optimal power output is not the same as the design point for optimal efficiency (Ayres, 1988) and, by the same token, the design point for appropriate form quality of energy provided for a particular purpose is not necessarily the same as the design point for optimal efficiency.

All told, the efficiency estimates were given in order to evaluate and identify possible improvements, and were not intended to leave an erroneous impression that apparently inefficient conversions should be replaced by more efficient ones at the expense of time and form quality of current patterns of providing useful energy. In a modern society power is provided where and when it is needed (in order to use capital, materials, labor skills and knowhow effectively), so that it would be very misleading to conjecture that the efficiency could be improved by, for example, harnessing hydraulic power directly at the point of gathering instead by conversion to electricity that is delivered to the consumer, although at face value one conversion step would be eliminated thus increasing the efficiency.

Thus, the structure of the energy system and the patterns of energy use are the result of complex and intricate trade-offs between efficiency, resource availability, cost of capital, time and environmental impacts. Unfortunately, not all social and environmental costs are internalized in the current configuration of the energy system and end use. And this is an area where the efficiency improvements are beneficial. If we do not alter the nature of the current social choice, but analyze only the potential improvements with a given static structure of energy system, we *de facto* also assume a homeostatic development of the energy services. This would mean that service factors that go along with the given conversion efficiency would perhaps change, but not the services themselves. This means keeping the modal split in transport about the same, the requirements for given temperature in dwellings and temperatures of process heat in industry, etc. This is certainly unrealistic, since these parameters will most likely also change in the future with the introduction of new technologies, human activities and different environmental, social and economic considerations concerning the energy provision. However, this kind of static view of future energy demand allows to compare the net effect on efficiency if the currently most advanced systems are employed throughout the economy and energy system. Here, we ignore the question of costs and how long it might take before these new technologies and required institutional and social changes could be implemented. We merely focus on the effects on energy efficiency of the currently best performing systems.

Before trying to give a rough estimate of the potential improvements that could result from replacement of the current energy system by the best available system, let us briefly consider what the theoretically best system could do were it possible. With the same unrealistic assumptions, namely keeping the structure and efficiency of energy services the same, the best possible system would be one with the exergy efficiency equal to 100 percent!

This simply means that the current energy system achieves only a tiny fraction of the best possible efficiency of the ideal system. We have estimated the overall exergy efficiency at somewhere between 5 and 15 percent with the lowest relative efficiency in end use conversion. The primary to final conversion efficiency is in comparison high with 70 percent. This high improvement potential is simply the result of the definition of second law efficiency as a ratio of theoretical minimum amount of exergy needed to perform a particular function to actual exergy requirements of a particular (i.e. current) systems. In the following sections that give a more detailed evaluation of the actual energy and exergy efficiency of the current energy system in the OECD countries, we will show that the actual exergy efficiency is about 15 percent without accounting for the relatively low efficiency of energy services. Should this be a representative case, than the efficiency of current energy systems could be improved by about a factor of 7 without improving energy services. By accounting for service efficiency of about 40 percent, the factor improvement could be as large a 10.

Let us now briefly consider the possible exergy efficiency improvements that could be achieved by replacing the estimates of current efficiencies in the OECD countries by the best now available with the same primary energy sources and end use applications. This again must be viewed only as an approximate indication of the improvement potential since we are assuming invariant structure of the energy system and end use. We realize that this is a very unrealistic assumption, in view of the changes in the patterns of energy provision and consumption since the early 1970s (that was described in Chapter 4). In fact, it is notoriously difficult if not impossible to actually de-couple the effects of efficiency improvements, structural change in the economy such as the possibility of materials disintensification, the substitution of old by new technologies, and increases in actual energy services (e.g. in the developing countries). Nevertheless, we will attempt to keep the structure and intensity of energy demand constant, while merely changing the efficiencies with which a given final energy form is applied to end use. This we will only do anecdotally, by giving a few illustrative examples of how the heating and transport efficiencies could be increased by deploying some of the best, current practices. Unfortunately, due to the complexity of the assumptions and lack of actual data, it is not possible to make a more consistent approach by simply replacing the current by the best possible efficiencies.

5.1.7.1. Process and Space Heat

The overall efficiency of cement and steel is estimated to improve by about a factor of two. The temperature required for the most efficient, dry cement production process is about 650°C implying a theoretical second law efficiency of at most 65 percent. McCarl and Preda (1980) give the minimal energy inputs for production of one ton of cement at 24 Watt-years. The actual current efficiency in producing a ton of cement is about 14 percent, or 87 percent worse than the theoretical minimum. Fifteen years ago it was about 7 percent (Fortune, 1974). This suggests an annual improvement rate of about 4 percent. We estimate the best efficiency at 17 percent or about 20 percent higher than the current average.

The minimal theoretical efficiency for producing a ton of steel from iron ore is about 93 Watt-years and ten times less if recycled steel is used. We estimate that the best current practice could increase the overall efficiency by about a third mainly through higher share of recycled steel and iron instead of iron ores as converter input. A small part of these gains will result in the second law increases, most will be due to the higher efficiency of the converters. This is in agreement with the estimate of most efficient iron and steel making processes by Ayres (1988) of about 23 percent.

For process heat we can assume the best furnace conversion rate in excess of 90 percent (Williams, Dutt and Geller, 1983). Thus, we estimate the best conversion efficiency of industrial boilers and furnaces to be about 20 percent higher than the current average. Due to the somewhat higher application of steam in industrial processes the second law efficiency is also higher. Service factors are likely to be higher than for similar current uses due to the much better real-time control of boilers and furnaces. Together, these assumptions almost double the efficiency of providing industrial process heat.

The estimation of possible space heating efficiency improvements is almost as difficult as determining the service factor. Large improvements could certainly result from improved thermal insulation, passive heating systems and much better space heat control possibilities. All of these measures would reduce the exergetic needs, although they would not necessarily increase the second-law efficiency. We have mentioned in the context of service efficiency of space heating that a well insulated house or office building will "float" higher above the ambient temperature reducing the heating requirements. The temperature rise of a superinsulated house without any heating can be up to 17°C higher in the winter than that of an ordinary house. This means that the superinsulated house will not need any heating at all during most of the year even in rather harsh climatic conditions. Such a house stores the "free" heat from people, lighting, appliances and passive solar heating through windows (Rosenfeld and Hafemeister, 1988). Thus, the best house needs almost no space heating at all.

The other space heating uses are in the service sector and industry. Rosenfeld and Hafemeister (1988) give an example of a commercial building that employs advanced energy-efficient design – the Albany County Airport Terminal in the United States. The terminal has been built and performs better than the design originally indicates. Its space heat requirements are less than 18 percent of a conventional design. Similar designs can be achieved in other commercial buildings. This is an improvement of more than a factor of five. However, most of these advanced space and water heating and cooling and ventilation systems employ computers for managing sophisticated control mechanisms. This means that additional electricity requirements will be needed, but on the other hand energy-efficient buildings also have lower specific electricity requirements for lighting and other uses (e.g. air conditioning) so that this omission probably does not affect much of our overall estimates. A higher share of heat pumps and cogeneration for space heating would also increase the efficiency. Together, these assumptions hold the potential of more than tripling the efficiency of space heating.

5.1.7.2. Transport

The best of the new transport aircraft consume about 15 percent less fuel per passenger-kilometer than their model predecessors. For example, the new Airbus 320 and Boeing 757-200 consume at least 15 percent less fuel than similar aircraft of only ten years ago (e.g. Boeing 737-400 needs about 20 percent less fuel than the older version Boeing 737-200). However, these latest-generation aircraft are not representative of the whole fleet. On the other hand, since with most of the upgrading in the design also performance (such as range and payload) are also improved, the overall net improvement for a given "unit" of service is larger than the savings in fuel would indicate by themselves. Thus, the resulting improvement could easily be larger than 20 to 30 percent. It goes without saying that the average service factor of passenger and freight aircraft could be expected to increase to at least 70 or 80 percent.

The most fuel efficient automobiles require less than half of the current design. A number of small Japanese cars such as Daihatsu Charade, Subaru Justy or Toyota Starlet have an average fuel consumption of about 4 l/100 km. In addition there are a number of diesel passenger cars with lower fuel consumption. Although all of them have a seating capacity for four persons, they usually are equipped with small engines and do not provide the performance of the current average fleets. Most of the manufacturers have prototypes of the same size with even lower fuel consumption. Here, we assume less modest improvements of about 70 percent with respect to the current average fuel consumption because even the most efficient fleet will include specialized vehicles such as off-road cars, sports cars and luxury sedans. However, it is likely that the service factor for automobiles could increase substantially assuming that much of the urban driving efficiency will increase through less idle time and more parking opportunities outside the city centers. In addition, the average number of passengers can be expected to increase as well, either because people will use smaller cars when traveling alone, or will use alternative means of transport when traveling alone (e.g. commuting and business trips).

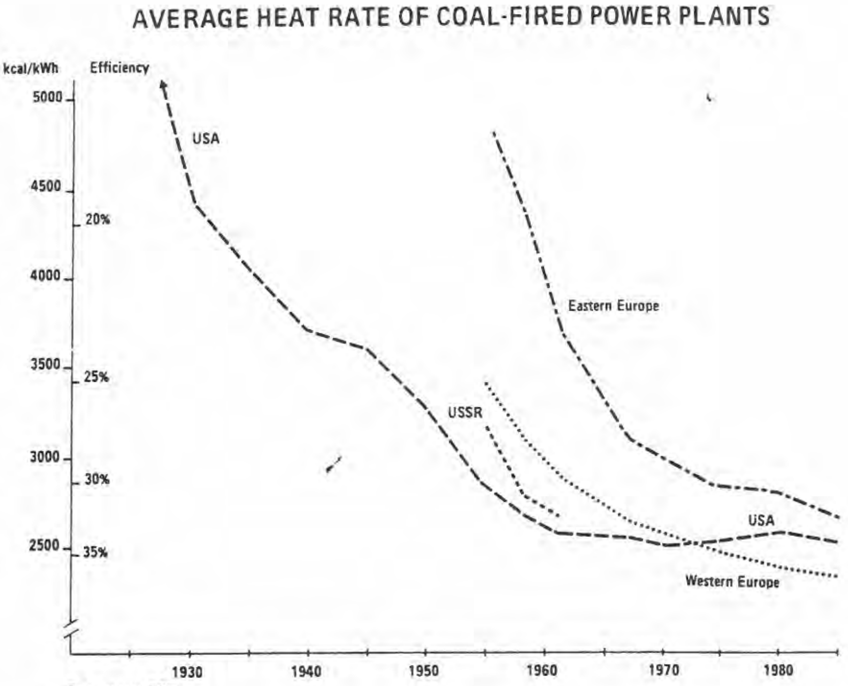
For commercial vehicles we assume a similar development. Higher capacity utilization would be mostly due to better logistics leading to less "empty" trips. The efficiency of vehicles themselves can be expected to correspond to the best current designs such as the Neoplan composite-materials bus or the new SAAB-SCANA turbo-compound diesel engine for trucks and buses with higher overall efficiency. The resulting overall fuel efficiency of commercial vehicles could be almost 40 percent higher than the current fleet. The application of electronic management systems will help improve the efficiency of all road vehicles. The vehicle management systems (engine, transmission, etc.) are already available on many passenger and commercial vehicles, but the road navigation and routing systems will certainly have at least equal effect in reducing idle fuel consumption.

Together all these improvements imply more than a two-fold increase in the overall efficiency of primary energy to transport service efficiency.

5.1.7.3. Overall Efficiency Improvement Potential

These illustrative examples indicate that if through some miracle the current practice of energy conversion and use were replaced by the best available practice, the resulting overall efficiency could increase twofold. This assumed increase was derived without speculation about changes in the patterns and structure of energy services. However, in the spirit of the assumptions concerning the improvements in end-use conversion efficiencies, the primary to final conversion would also improve and thus make a contribution toward increases in the overall efficiency, though perhaps not so large as the improvements in end use. For example, the transport and distribution losses of natural gas could be and should be reduced both because that increases efficiency and because it is desirable from the environmental point of view (see Chapter 6). Technological measures could include first of all reduction of flaring and venting of natural gas to the absolute minimum, but they could also include better efficiencies of LNG transport and more methane-tight distribution grids.

This all illustrates the fact that technological change has been and will be in the future an important determinant in reducing the energy requirements and improving the efficiency of many human activities. The discussion suggests that with basically already available technologies, only about a half of the current energy consumption would be required in the hypothetical "best-technology" energy system. We have shown in the previous chapter (Chapter 4) that such reductions in specific energy needs have been an important feature of the evolution of energy use patterns and energy inputs to the economy ever since the beginning of the so-called Industrial Revolution. The average energy intensity (energy-GNP ratio) has declined at a rate of about one percent per year. At this rate, it would take more than 70 years to decrease the average energy intensity to one half. This illustrates the magnitude of our high-efficiency assumptions: it implies that the energy intensity would decrease to a half since we assumed the level of end use services not to change. Using this analogy, it could take up to the year 2050 before our postulated energy efficiency improvements could be realized.



Data source: ECE

Figure 5-3 Improvements in Power Plant Efficiencies.

Fortunately, this historical analogy is not entirely appropriate because the end use patterns were not constant during the last two centuries. In fact, one of the great achievements of the industrialization process and technological advance was that the animal and human toil were replaced by inanimate sources of work. The end-use demand increased enormously the whole period and especially during the last 80 years. We have already mentioned that the efficiency of electricity generation increased by a factor of eight during the last 80 years, from about 5 percent around the beginning of the century to about 40 percent today some natural gas power plants. Figure 5-3 shows the improvement in power plant efficiencies that have led to the current conversion rates.

Were this a representative number for the likely efficiency improvement rates for the whole energy system (including end use), our postulated "high-efficiency world" could be achieved by the end of the century. Unfortunately, not all energy conversion and end-use efficiencies increased so rapidly as in electricity generation. Other improvements were more modest but are still impressive. We have given the example of space heating where the typical efficiency probably improved by a factor of four in 80 years (comparing the open fireplace with a modern heating boiler). The efficiency of industrial drives and prime movers increased even faster during the last 80 to 100 years. The steam engine had a typical efficiency of only a few percent at the end of the last century, while the overall conversion efficiency of electric drives today is almost 10 times higher. In all of these examples the service factor increased even more: modern heating systems are easy to control and much easier to use than the open fireplace; electric industrial drives can be as small as the task requires, while steam engines had to be on the site and required elaborate transmission systems for delivering power where it was needed on the shop floor. All of these factors would tend to indicate that the appropriate historical analogy would suggest that the required time to double the efficiency of energy system and end use might be somewhere between 30 and 40 years.

5.2. International Energy and Exergy Efficiency

In Chapter 3 (Table 3-9 and Figure 3-16) we have given the energy balance in the OECD countries and important energy flows from total primary energy requirements, conversion to fuels and electricity, storage, transport and distribution to final energy consumption by energy form observing that the overall efficiency of primary to final energy transformation is about 70 percent. In Table 5-6, the OECD energy balance is reproduced together with the transformation efficiencies at each of the two stages of energy conversion: primary to secondary and secondary to final. All of the estimated efficiencies are based on the ratios of the energy transferred to the given purpose or function divided by the actual input of energy. They represent the official statistics of the prevailing first law efficiencies in the OECD countries.

First we will briefly summarize the discussion from Chapter 3 as to how the average efficiencies of conversion of primary to final energy forms have been derived, and then show how the useful energy and exergy conversion ratios have been assessed. Table 5-6 does not show the efficiency estimates for this third conversion stage from final to useful energy and exergy. Final energy is converted to useful energy forms in appliances, machines, vehicles and various other devices that provide energy services. In the following two sections we will give rough estimates of useful energy by demand category and final energy carriers. We will give both the energy and exergy efficiency estimates.

It should be stressed, however, that these conversion efficiencies are not based on actual measurements but rather on estimates of typical final energy applications, and as such only represent rough indicators rather than precise numerical values implied by significance of the given numbers. It would have been more appropriate to express the estimated efficiencies in terms of a numerical ranges or in terms of medians. Despite this deficiency,

Table 5-6 Energy Balance in the OECD Countries for 1986, Energy Flows in GWyears and Conversion Efficiencies in Percent.

	Coal	Solids	Oil	Nat.Gas	Nuclear	Hydro	Electr.	Heat	Total
Production (I)	1118.6	157.8	1148.9	883.6	421.5	364.9			4095.3
Trade (T)	9.2		1162.1	106.0			1.2		1278.6
Primary (P)	1127.8	157.8	2311.1	989.7	421.5	364.9	1.2		5373.9
To Fuels (P_1)	292.4	150.4	2140.1	813.5			1977.5		5373.9
To Electr. (P_2)	835.4	7.4	171.0	176.2	421.5	364.9	(1976.3)		
Sec. Fuels (S_1)	283.3	149.3	2031.0	775.6			683.0	13.6	3935.8
Sec. Electr. (S_2)	(275.8)	(2.7)	(59.5)	(61.1)	(149.9)	(134.0)	683.0	(13.6)	
Final (F)	268.3	149.2	2023.7	701.4			621.4	12.3	3776.4
S_1/P_1 (%)	96.9	99.3	94.9	95.3			34.5	100.0	73.2
F/S_1 (%)	94.7	100.0	99.6	90.4			91.0	90.4	96.0
F/P_1 (%)	91.8	99.2	94.6	86.2			31.4	90.4	70.3

Source: Primary to final energy balances based on OECD, 1988.

the estimates are useful for comparing relative magnitudes. Giving a range , however, would increase the complexity of the tables and thus in the interest of giving a simple representation only point estimates are given. Instead, we have performed sensitivity analysis by changing the values of the estimated efficiencies in order to evaluate the resulting variation in the overall efficiency of the whole energy system.

Table 5-6 shows that in 1986 the OECD countries consumed 5.4 TWyears of primary energy. The total amount of secondary fuels produced from primary energy sources was 4.0 TWyears and resulted in 3.8 TWyears of final energy delivered to use. This means that the overall efficiency of energy conversion, transport and distribution is roughly 70 percent, 73 percent from primary to secondary and 96 percent from secondary to final. This overall conversion efficiency to final energy forms includes own energy use by the energy system, and all losses in transmission and distribution and of course all energy needs of conversion processes such as the refineries and power plants. In addition, there are some statistical discrepancies that cannot be separated from the actual losses and energy needs of the energy sector so that they are also included in the implied conversion efficiencies.

The prevailing efficiency of conversion of primary energy sources to secondary electricity is about 35 percent (whereas secondary fuels to secondary electricity efficiency is somewhat higher than 36 percent). The efficiency of going from primary energy to final electricity is about 31 percent. In comparison, the other direct final uses of primary energy have higher efficiencies. About 97 percent of all coal, that is not used to generate electricity, is delivered (mostly) to industrial uses. Crude oil refining, transport and distribution system is almost 95 percent efficient. The natural gas is delivered to end use with lower efficiency of about 86 percent, but part of the implied "losses" could easily be due to relatively uncertain accounting and measurement errors. The other source of apparently low efficiency could be due to some deliveries as LNG, but that cannot explain the relatively large discrepancy. Thus, the low conversion efficiency of 86 percent is most likely due to measurement "discrepancies" rather than to actual physical losses that go beyond a few percent energy requirements for transport and storage of natural gas.

In the next two sections we will assess the average end use efficiencies for the OECD countries by final demand category and by delivered final fuel. We will try to give indicative rates of prevailing conversion of final to useful energy and exergy. These useful energy conversions represent estimates rather than actual observations. They are based on conversion efficiencies of end-use devices, machines, appliances and vehicles in the European Communities and the United States, which together represent most of the energy consumption of the OECD countries (together they represent 76 percent of primary energy consumption of the OECD region). Where appropriate we will also illustrate the typical service efficiencies discussed in the literature of the various useful energy and exergy applications.

It will be shown that there is a considerable difference of end-use efficiencies in energy and exergy terms. The largest discrepancy between energy and exergy methods of estimating the efficiency of energy end use is in those categories where heat is required and especially where low-temperature heat is demanded. In this context it should be recalled that the available work or exergy of heat is a function of absolute temperatures. The higher the thermal gradient with respect to the reference temperature, the higher is the exergy of the process. Work is the highest quality of all energy forms and equivalent to heat at infinite temperature. Thus, the exergetic efficiency is a function of the assumed application temperatures for various energy end uses. These assumptions are especially critical since they are not a linear function of temperatures, so that small differences could be amplified into large efficiency changes at an aggregate level. Furthermore, they are critical since they represent the major difference between the energy and exergy analysis of conversion efficiencies. Thus, for clarity, we summarize our major assumptions concerning various end-use applications of heat in Table 5-7. These assumptions have been used to derive second-law efficiencies (ν) for space heating, process heat and cooking by various final fuels. Given these assumptions, the following three tables show the overall final to energy services efficiencies of different final energy forms in the four typical energy uses in the OECD countries: process heat, space

Table 5-7 Assumed Exergy Efficiencies for Heat with Given Application Temperatures.

Heat	T_0	T	ΔT $=T-T_0$	T_0 $=T_0+273$	T $=T+273$	ν $=\Delta T/T$
	°C	°C	°K	°K	°K	
Space Heat	1	21	20	274	294	0.07
District Heat[1]	1	80	79	274	353	0.22
Warm Water	12	45	33	285	318	0.1
Cooking	21	165	144	294	438	0.33
Process Heat[2]	12	110	98	285	383	0.26
Air Condition	28	21	✓ 7	301	294	0.02
Refrigerator[3]	21	-10	31	294	263	0.12

[1] Refers to power plant to district heat exergy efficiency. District heat to space heat exergy efficiency is 32 percent, giving the overall efficiency of 7 percent.

[2] For electricity we assume higher application temperature leading to exergy efficiency of 30 percent.

[3] Freezers have higher efficiencies due to higher temperature gradient.

heating, cooking and transport.

5.2.1. Efficiency by Demand Category in OECD Countries

Table 5-8 shows that oil products and especially fuel oil is still the major final energy form for industrial process heat with a 45 percent share, while the other 55 percent are shared (unequally) by coal, natural gas and electricity. Fossil fuel furnaces and industrial boilers transform chemical energy to heat inside the furnace to produce useful energy. For coal we have assumed an average efficiency of 65 percent and higher efficiencies for fuel oil 75 percent. The average useful energy efficiencies for natural gas and electric furnaces and boilers are assumed to be slightly higher with about 80 percent. This leads to an average final to useful energy conversion of about 74 percent. The prevailing final to useful energy efficiencies were estimated to be slightly lower in the European Communities: 61 percent for coal, 73 for oil and 75 percent for natural gas (Eurosat, 1988).

Most of the industrial boilers and furnaces provide heat for chemical, mineral and metallurgical processes. In general, process heat is delivered in the form of steam however at temperatures that vary with the application. At temperatures of about 200°C the Carnot efficiency would be about 40 percent, while at 300°C it would be about 60 percent. In practice, however

Table 5-8 Estimated Industrial Process-Heat Efficiencies in the OECD Countries, in Percent.

	Final Energy Shares (%)	Useful Energy Efficiency (ϵ)	Final Exergy Shares (%)	Second Law Efficiency (ν)	Useful Exergy Efficiency ($\nu\epsilon/h$)
Solids[1]	9.8	55.0	10.9	23.0	10.7
Coal	7.4	65.0	7.2	26.0	16.3
Oil Products	45.0	75.0	45.0	26.0	18.4
Natural Gas	30.8	80.0	30.2	26.0	20.0
Electricity	7.0	80.0	6.6	30.0	24.0
Total	100.0	74.2	100.0	25.9	18.3

1 Solid fuels includes peat, fuelwood, wood waste, back liquor, industrial waste and garbage.
Note: We have assumed following values for the ratio of exergy to heat of combustion: for biomass h=1.18; for coal (assuming an average of brown coal, anthracite and coke) h=1.06; for oil products h=1.06; for natural gas (mostly methane) h=1.04. Otherwise, h=1.

there are distribution losses and some applications at much lower temperatures. AIP (1975) and Schipper (1976) assume second law efficiencies of about 25 percent. We assume an average Carnot efficiency of about 26 percent for fossil and 30 for electric process heat due to slightly higher application temperatures. This results in an overall average final to useful exergy efficiency of 26 percent (corresponding to an aggregate application temperature of 110°C). These assumptions lead to an overall final to useful energy and exergy efficiencies of 74 and 18 percent, respectively. The exergy efficiency is very likely an over-estimate of the actual overall efficiency of process heat applications. Olivier (1983) and Ayres (1988) estimate the efficiency at about 14 percent. However, their estimates also include a service factor. Robinson (1987) and Olivier (1983) give the relative service efficiencies of process heat at about 60 percent, meaning that their estimate is *de facto* much lower. Our estimates are also lower: accounting for the primary to final conversion efficiency of 70 percent, gives the overall efficiencies of 52 and 13 percent for energy and exergy respectively. The exergy efficiency could be as low as 7 to 8 percent, assuming the service factor of about 60 percent: Olivier (1983) estimates only one percent overall efficiency while Ayres (1988) gives a figure of about 2.5 percent for all industrial energy uses.

Again, the absolute values are here only of theoretical importance and have little practical meaning since the assumptions are debatable. What is important, however, are the relative differences in the efficiencies stemming primarily from the variation in the process heat temperature and boiler and furnace efficiencies. The overall efficiency increases with the quality form of the delivered final energy and is highest for electricity and lowest for coal and this is reflected in the exergy efficiency. Thus, the quality form is reflected in relative application effectiveness. These assumptions result in an overall final to useful energy and exergy efficiencies of 74 and 18 percent, respectively.

Table 5-9 Estimated Space Heating Efficiencies in the OECD Countries, in Percent.

	Final Energy Shares (%)	Useful Energy Efficiency (ϵ)	Final Exergy Shares (%)	Second Law Efficiency (ν)	Useful Exergy Efficiency ($\nu\epsilon/h$)
Coal	6.4	55.0	6.4	7.0	3.7
Oil Products	42.8	70.0	43.4	7.0	4.6
Natural Gas	43.0	70.0	42.8	7.0	4.7
Electricity	6.6	100.0	6.3	7.0	7.0
Heat	1.2	90.0	1.1	32.0	28.8
Total	100.0	71.2	100	7.3	5.0

Note: We have assumed following values for the ratio of exergy to heat of combustion: for coal (assuming an average of brown coal, anthracite and coke) h=1.06; for oil products h=1.06; for natural gas (mostly methane) h=1.04. Otherwise, h=1.

In heating and other low-temperature applications coal and electricity play only a secondary role with about slightly more than 6 percent share each (electricity provides another 1.2 percent of cogeneration heat), while fuel oil and natural gas provide about equal shares of 43 percent. Most of the coal is used in larger industrial or district heating systems. The average coal efficiencies for heating are assumed to be about 55 percent which roughly corresponds to the average value in the European Community countries in 1986 (Eurostat, 1988). Fuel oil and natural gas usually achieve higher energy conversion efficiencies of about 70 percent. This is again about the same conversion efficiency as prevailed in the European Community countries (Eurostat, 1988). Resistance heating is 100 percent energy efficient since there are no boiler losses (provided of course that the heater is installed inside the heated area), all of the electricity is dissipated into heat. Energy conversion efficiency is assumed to be 90 percent for heat that is cogenerated with the electricity, since there are some heat losses in the distribution system and the heat exchangers.

The second law efficiency is calculated assuming the heating temperature of 21°C and lower reference temperature of about 1°C. This results in a conversion rate of 7 percent. The same is assumed for cogeneration of heat, where we have a heat to heat conversion. We assume district heat temperature of 80°C and the same heating temperature of 21°C. This gives the Carnot final to useful efficiency of 32 percent. The resulting overall final to useful exergy efficiency is about 5 percent. The exergetic heating efficiencies are to an extent based on arbitrary assumptions. In practice the lowest conceivable exergy needs for space heating is negligibly low if not zero. A building which is sufficiently well insulated, uses low heat loss windows and is designed for low air infiltration, requires no heat input from and artificial space heating system. Passive heating measures such as waste heat from refrigeration, cooking and solar heat are usually sufficient to maintain comfortable room temperatures. Since both in very temperate climatic conditions as well in the extremely cold climates and bad weather some space conditioning is required some exergy needs will always exist, but they could be reduced for the same comfort by a large factor.

Ayres (1988) estimates service efficiency of space heating at about 10 to 15 percent, Sorensen (1982) and Robinson (1987) give 16 percent, while Krause (1981) assumes 10 percent. Assuming a service factor of 15 percent and given the primary to final efficiency of 70 percent, our overall estimate of energy efficiency of the space heating is about 10 percent and only 0.5 for exergy efficiency. This corresponds to the estimates in the literature for overall exergy efficiency: for example, Olivier (1983) gives one percent and Ayres (1988) about 0.4 percent. Similar assumptions apply for hot water use although the efficiencies might be slightly higher due to the higher application temperatures.

Conventional cooking over a gas burner or an electric range is notoriously inefficient in comparison with other final energy uses. Most of the heat is lost either directly in the combustion process or indirectly by radiation or convection (Ayres, 1988). For oil cookers we have given energy conversion efficiency of about 35 percent and for natural gas burners and stoves of about 55 because of easier control of the temperature and heating cycle. Electricity is assumed to have the highest efficiency of about 100 percent because of complete dissipation of resistance heat through radiation and convection.

Table 5-10 Estimated Cooking Efficiencies in the OECD Countries, in Percent.

	Final Energy Shares (%)	Useful Energy Efficiency (ϵ)	Final Exergy Shares (%)	Second Law Efficiency (ν)	Useful Exergy Efficiency $(\nu\epsilon/h)$
Coal	2.5	31.0	2.6	33.0	9.8
Oil Products	10.9	35.0	11.3	33.0	10.9
Natural Gas	28.8	55.0	29.4	33.0	17.5
Electricity	57.8	100.0	56.7	33.0	33.0
Total	100.0	78.2	100.0	33.0	25.3

Note: We have assumed following values for the ratio of exergy to heat of combustion: for coal (assuming an average of brown coal, anthracite and coke) $h=1.06$; for oil products $h=1.06$; for natural gas (mostly methane) $h=1.04$. Otherwise, $h=1$.

The Carnot efficiency is assumed to be 33 percent for all cooking applications assuming a heating temperature of 165°C with "in-doors" reference temperature of about 21°C. From one side this could be an underestimate since ovens and pressure cookers achieve much higher temperature and thus have higher efficiencies, but on the other hand cookers are often over-sized for a particular application so that these two factors are assumed to cancel one another on the average. The actual theoretical minimum for providing cooked food could be much lower. It is the energy required to transform the raw chemical form of food into digestible state and the exergy would be much lower because the heat from the process could be recovered.

The service efficiency is again the most difficult component to estimate. Considering the fact that a typical microwave oven consumes less than a third of power in comparison to a typical electric heating plate, thus the efficiency of the same service is reduced to a third. Modern induction stoves consume about 60 percent of the electricity of a comparable electric range stove. Furthermore, food is often over-cooked which also reduces the service efficiency. Better temperature and heating control mechanisms are assumed to further reduce the final energy requirements, thus we estimate the service conversion efficiency at 20 percent. Olivier (1983) assumes a 100 percent service factor in cooking (but a much lower second law efficiency of about one percent), while other estimates correspond more closely to our assumptions: Sorensen (1982) gives 20 percent. Together these assumptions result in very low exergetic efficiencies: Olivier (1983) estimates the overall efficiency at about 1 to 2 percent and Ayres (1988) at about 3 percent. If we assume a service factor of 20 percent, and given the primary to final conversion of 70 percent, the resulting overall cooking exergy efficiency is about 4 percent.

Table 5-11 Estimated Transport Efficiencies in the OECD Countries, in Percent.

	Final Energy Shares (%)	Useful Energy Efficiency (ϵ)	Final Exergy Shares (%)	Second Law Efficiency (ν)	Useful Exergy Efficiency ($\nu\epsilon/h$)
Jet Aircraft	9.6	25.0	9.6	100.0	23.6
Otto Cars	48.7	15.0	48.7	100.0	14.2
Diesel Trucks	41.0	25.0	41.0	100.0	23.6
Oil Products	99.3	19.6	99.3	100.0	18.5
Electricity	0.7	85.0	0.7	100.0	85.0
Total	100.0	20.0	100.0	100.0	18.9

Note: We have assumed following value for the ratio of exergy to heat of combustion for all oil products $h=1.06$, for electricity $h=1$.

Most of the final energy used to provide transport services in the OECD countries consists of oil products: jet fuel, diesel and gasoline. Only about 0.7 percent of all final transport energy is electricity for trains, streetcars and subways. Electricity consumption for elevators and escalators is not included in our estimate, but is probably negligible. The average final to useful conversion efficiency of engines and gas turbines is assumed to be about 20 percent (15 for gasoline engines, 25 for truck diesel and 25 for jet engines). For example, in the case of the automobile, engine efficiency together with the aerodynamic and other frictional losses result in an average conversion of mechanical to kinetic energy of about 15. There are prime movers including gas turbines, otto and diesel engines on the market can achieve higher final fuel to useful mechanical energy efficiencies. For example, aircraft turbo-fan and unducted-fan engines can reach 35 percent efficiency, fuel-injected lean-burning gasoline engines also can achieve up to 35 percent efficiency, while the diesels with turbo-charging can achieve 42 percent efficiency.

Electric trains are more efficient with the assumed average electricity to useful efficiency of about 85 percent. This illustrates that the modern trains are much more energy efficient than automobiles, commercial vehicles and aircraft. In comparison the steam trains achieve lower efficiencies on the order of less than a percent. However, in contrast to other fuels than have primary to final conversion efficiencies of about 90 percent, final electricity is about 30 percent efficient in terms of primary energy inputs, so that the overall electric train efficiency reduces to about 25 percent, but is still slightly higher than other modes.

The second law efficiency is 100 percent for all four modes of transport, since they all involve conversion of one form of work to another. The apparent difference between the energy and exergy efficiencies is due to variation in the heat of combustion with respect to energy among different fuels (h).

The service efficiency of passenger and goods transport is very difficult to estimate with any degree of certainty. In order to give approximate values we have attempted to derive rough estimates. For aircraft we assume a load factor of 65 percent. IATA (1987) gives the load factor of 67 percent for all passenger operations and 64 percent for international freight and 60 for domestic. We have further reduced the service efficiency to 60 percent due to inefficiencies in air control, traffic congestion and flight pattern regulations. For instance, Lufthansa reports that 10 percent of consumed fuel is due to congestion and waiting times in landing, takeoff and taxing. Other large savings that are service oriented are also possible through better air control and more optimal route regulations. For example, the regulations specify that the twin-engine jets must stay within an hour of the closest airport in the trans-Atlantic operations and would save about 8 percent of the fuel if they could chose the same routes as three and four-engine aircraft. Thus, we assume a 60 percent service efficiency for all commercial aircraft.

Automobiles have the average seating capacity of 4.5, but the actual utilization is about 1.5 persons per vehicle.[8] This leads to an average capacity utilization of 33 percent. We have further reduced this number to 20 percent due to the idle time, waiting in congested areas and urban traffic. In some cities, more than half of the vehicle-km are devoted to waiting and idle driving in search of a parking spot. For commercial vehicles we have assumed a 50 percent service factors. This is a representative number and indicates that more than half of the time the vehicles carry loads, but that they are often less than full. For trains we assume a lower load factor of 35 percent. For example, in Austria 60 percent of all freight cars are utilized while the other 40 percent travel empty. The utilized cars have an average capacity utilization of about 50 to 60 percent, giving the overall freight utilization of 30 to 36 percent. In intercity passenger travel the ratio of

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[8] For example, there are 4.5 available seats per automobile in the FRG. The automobiles traveled in 1985 about 314×10^9 vehicle-km and provided about 484×10^9 passenger-km (Verkehr in Zahlen, 1985). Thus, the average utilization is 1.5.

passenger-km to available seat-km is about 35 percent. This leads to our average figure of 35 percent for all operations.

The aggregate average of these rough assumptions is about 34 percent for aircraft and motor vehicles and about 35 percent for train transport. Soreson (1982) gives the following estimates: Automobiles 16 percent; Buses and trucks 25 percent; aircraft 16 percent; trains 24 percent. (for the US). Krause (1981) assumes the same service factor for all vehicles of 50 percent (for FRG) and Olivier (1983) nearly the same factors (for the UK), while Robinson (1987) assumes a factor of 40 percent for all vehicles (Canada). The estimated transport efficiencies are about 20 percent, which is reduced to about 8 percent assuming a service factor of 40 percent. Thus,the overall primary to useful transport conversion efficiency might be as low as 5 percent, accounting for 70 percent primary to final efficiency.

These four important applications of final energy for space heating, process heat, cooking and transport result in energy efficiencies of between 70 and 20 percent, while the exergy efficiencies ranged between 25 and 5 percent. The actual efficiencies might be up to 40 percent lower if average service efficiencies are accounted for. Considering the average conversion rate of primary to final energy of about 70 percent in the OECD countries, the overall efficiency of providing energy services is somewhere between 15 percent and up to at most 40 percent in energy terms. Overall exergy efficiency is much lower; it is at most 15 percent and more likely on the order of about 6 percent. Despite the very uncertain and rough nature of our numerical calculations we will see that this range is in a good agreement with other estimates in the literature.

5.2.2. Efficiency by Energy Form in OECD Countries

In order to evaluate the overall energy efficiencies in the OECD countries, it is necessary to estimate the aggregate efficiency for final to useful conversion for each of the five final energy forms and multiply with the efficiencies of primary to final energy conversions given in Table 5-6. For this reason the following five tables, just as the last four, illustrate the assumptions we have made for deriving useful efficiencies for the five major final energy carriers in the OECD countries: coal, biomass (other solid), oil products, natural gas and electricity.

Table 5-12 shows that most of the final coal is consumed by large (industrial) consumers. About 26 percent is still used for heating while the rest goes into cement and steel production and for industrial process heat. Large commercial boilers and furnaces are most efficient with 65 percent conversion of final to useful energy. Together the overall final to useful

Table 5-12 Estimated Coal Efficiencies in the OECD Countries, in Percent.

	Final Energy Shares (%)	Useful Energy Efficiency (ϵ)	Final Exergy Shares (%)	Second Law Efficiency (ν)	Useful Exergy Efficiency ($\nu\epsilon/h$)
Cement	11.1	50.0	11.1	26.0	12.5
Steel	41.7	50.0	41.7	29.0	13.9
Process Heat	21.6	65.0	21.6	26.0	16.3
Space Heat	25.6	55.0	25.6	7.0	3.7
Total	100.0	54.5	100.0	22.4	11.7

Note: We have assumed following value for the ratio of exergy to heat of combustion for coal (assuming an average of brown coal, anthracite and coke) h=1.06.

conversion rate for all coal uses is about 55 percent. We have already explained our assumptions leading to the efficiency estimates for space and process heat. Here we will document the estimates of steel and cement efficiencies.

For steel production we assume the second law efficiency of 29 percent. Fredriksson (1983) gives an estimate of 24 percent, Krause (1981) of 26 percent and Olivier (1983) gives 21 percent for iron making. The conversion efficiency is about 50 percent. Most of the losses occur in the coke ovens and are estimated at about 17 percent. Other losses are due to the converters. In 1986, the average energy requirements for a ton of steel were about 450 GWyears in the OECD countries; 153 GWyears of energy were consumed to produce 342 million tons of steel. The theoretical minimum energy content of coal required to produce a ton of steel varies between 23 Wyr/ton for recycled iron and steel and about 10 times as much for iron ore. Based on the average share of 65 percent scrap and 35 ore, the minimal requirements in the OECD countries are about 92 Wyr/ton. Thus, the overall efficiency is about 20 percent. Table 5-12 gives an overall exergy efficiency for iron and steel produced by coal as 14 percent, because processes used operate with a higher share of iron ore than the average steel production (electric arc furnace uses very little iron ore, reducing the share of recycled scrap for coal processes).

Our second law efficiency for cement is about 26 percent and the same for industrial process heat because of similar ΔT. The conversion efficiency is estimated at 50 percent in going from the chemical energy of coal to thermal useful energy resulting in the exergy efficiency of about 13 percent.

Again the estimates in the literature are comparable: Krause (1981) gives 19 percent; Fredriksson (1983) 22 percent; and Olivier (1983) only 10 percent. In 1986, the average efficiency for producing a ton of cement was about 13.5 percent in the OECD countries and thus corresponds to our estimate of the overall efficiency.

Together these assumptions result in an overall final to useful energy efficiency for coal of 55 percent and in exergy efficiency of 12 percent. Considering that the primary to final conversion efficiency of coal is fairly high at about 92 percent, coal is used with an overall exergy efficiently compared with the rough overall energy system efficiency of about 6 percent.

Table 5-13 Estimated Other Solid Fuels[1] Efficiencies in the OECD Countries, in Percent.

	Final Energy Shares (%)	Useful Energy Efficiency (ϵ)	Final Exergy Shares (%)	Second Law Efficiency (ν)	Useful Exergy Efficiency ($\nu\epsilon/h$)
Process Heat	51.7	55.0	51.7	23.0	10.7
Space Heat	48.3	50.0	48.3	7.0	3.0
Total	100.0	52.6	100.0	15.3	7.0

1 Other solid fuels includes peat, fuelwood, wood waste, back liquor, industrial waste and garbage.

Note: We have assumed the same value for the ratio of exergy to heat of combustion for all solid fuels as for biomass h=1.18.

Table 5-13 gives the useful conversion efficiencies of biomass, wood, wastes and other solid fuels. About a half of these solid fuels are used mostly for heating in rural areas, while the other half is used for industrial process heat. The average conversion rate is about 55 percent. This number results from slightly lower efficiencies than those calculated for coal applications in industrial furnaces and large heating boilers, because most of the biomass applications tend to be of a smaller scale especially in the rural areas. The second law efficiency for space heating is given by 7 percent and for process heat it is again slightly lower than coal due to somewhat lower ΔT for representative applications. The overall efficiency of final to useful energy is thus about 53 percent, while the exergy efficiency is about 7 percent.

Table 5-14 Estimated Oil Products Efficiencies in the OECD Countries, in Percent.

	Final Energy Shares (%)	Useful Energy Efficiency (ϵ)	Final Exergy Shares (%)	Second Law Efficiency (ν)	Useful Exergy Efficiency ($\nu\epsilon/h$)
Jet Aircraft	5.8	25.0	5.8	100.0	23.6
Otto Cars	29.4	15.0	29.4	100.0	14.2
Diesel Trucks	24.7	25.0	24.7	100.0	23.6
Process Heat	17.5	75.0	17.5	26.0	18.4
Space Heat	22.6	70.0	22.6	7.0	4.6
Total	100.0	41.0	100.0	66.0	15.6

Note: We have assumed following value for the ratio of exergy to heat of combustion for all oil products h=1.06.

Table 5-14 shows that approximately 60 percent of all oil products are used in the transportation sector. Roughly 30 percent as gasoline, 25 as diesel fuels and 6 percent in form of jet fuel in aviation. We have discussed all of the pertaining efficiency and conversion estimates of oil products uses in the previous section under transport, space and process heating. Let us only briefly summarize these estimates: Jet and diesel engines are assumed to be 25 percent efficient, followed by gasoline engines with about 15 percent efficiency. These conversion efficiencies refer only to the conversion of final energy of oil products to motive power and not to the actual service such as vehicle or ton-kilometers. Further conversion of kinetic energy to to available vehicle or ton-kilometers is a function of actual service utilization. We have already mentioned before that the service factors are very difficult to estimate with any degree of certainty since almost no data are collected systematically. For transport services we have assumed the following service factors: aircraft 65 percent, cars 33 percent and commercial vehicles 50 percent.

The other 40 percent of the final oil products are used for space heating and in industrial process heat. We have neglected here some of the use of oil products and natural gas in iron and steel industry; however, the average efficiencies are not much higher than for coal fueled process so that the overall picture for steel production is not affected by this omission. The representative boiler and furnace efficiencies are assumed to be much higher than for coal at 70 and 75 percent, respectively, largely due to economies of scale and higher fuel quality form. The second law efficiencies of utilizing boiler and furnace heat are assumed to be the same as for all fossil fuels, at 7 and 26 percent, respectively.

The aggregate final to useful energy conversion rate is about 41 percent and higher than crude oil to electricity conversion of about 35 percent. The second law efficiency is 66 percent. The estimated final to useful exergy efficiency is about 16 percent. Given the primary to final conversion efficiency of about 95 percent, the overall exergy efficiency reduces somewhat to about 15 percent, but may be as low as 6 percent, assuming an average service factor of 40 percent.

Table 5-15 Estimated Natural Gas Efficiencies in the OECD Countries, in Percent.

	Final Energy Shares (%)	Useful Energy Efficiency (ϵ)	Final Exergy Shares (%)	Second Law Efficiency (ν)	Useful Exergy Efficiency ($\nu\epsilon/h$)
Process Heat	34.6	80.0	34.6	26.0	20.0
Space Heat	65.4	70.0	65.4	7.0	4.7
Total	100.0	73.5	100.0	13.6	10.0

Note: We have assumed following value for the ratio of exergy to heat of combustion for natural gas (mostly methane) $h=1.04$.

Table 5-15 shows that about 65 percent of natural gas is used for heating and the other 35 percent for process heat. As discussed in the previous section, the overall efficiencies of both of these applications are rather high with an average of about 74 percent. Natural gas furnaces and boiler achieve very high efficiencies due to rather clean and almost complete burning as well because of better temperature profile control. The second law efficiency of furnace and boiler heat to provision of services is assumed to be the same as for fuel oil and coal since basically the same application temperatures are involved. This results in final to useful exergy conversion efficiency of 10 percent. Since the primary to final natural gas conversion is in principle very efficient, the actual, overall efficiency should not be much lower than 10 percent. However, the OECD energy balances include considerable losses of natural gas that are most likely due more to measurement "discrepancies" than to actual physical losses beyond a few percent energy requirements for transport, storage and distribution. The statistical efficiency of primary to final conversion is about 86 percent and with that lower than for any other final fuel.

The overall final to useful exergy efficiency of natural gas is much lower than that of oil, but it is also lower than that of coal. This is of course a rather counter-intuitive result since natural gas has a high quality and is often characterized as premium fuel. However, both in Europe and the US there are many regulations governing the natural gas applications. Most of it is used in relatively inefficient conversion processes that "waste" some of the quality (exergy) of natural gas. For example, natural gas is one of the most efficient fuels for electricity generation and certainly leads to lowest environmental burdens in all possible uses due to high ratio of hydrogen to carbon and low sulfur content compared with other fuels. All of these advantages are not reflected in the efficiency estimates, because more than 80 percent of natural gas is used for providing heat, and as we can see from Table 5-15 more than 65 percent of than amount goes to low-temperature applications with an overall exergetic efficiency of only a few percent. Thus, more than a half of all natural gas is used space heating.

This all illustrates once again that the efficiency is not the only parameter that is important concerning the issues of appropriate energy use. On the other hand, natural gas can be more efficient than coal in most of these applications, and thus the replacement of coal is desirable from the environmental point of view although the current natural gas applications are not more efficient than those of coal. The salient point is that natural gas is the cleanest of all fossil fuels and that it holds the promise of much higher conversion and second law efficiencies for the future. Thus, the current low efficiencies of natural gas end use only reflect the fact that it is used mostly for space heating, so that the efficiency improvement potentials are indeed very large.

Table 5-16 shows a number of categories of electricity end-use with representative conversion efficiencies. In contrast to other final energy forms, electricity uses are rather diversified and thus difficult to aggregate in a smaller number of different classes. The highest efficiency is achieved in resistance heating and cooking, all of the electricity is converted into heat. Refrigerators are a special case since they convert final electricity to more useful heat, in energy terms, so that their useful energy efficiency or COP is about 140 percent. This is due to the fact that a refrigerator works as an inverted heat pump using electricity to "pump" heat form a colder reservoir (inside the refrigerator) to a warmer reservoir (inside the room). Trains are about 85 percent efficient in converting electricity in mechanical energy. Household appliances and drives are much less efficient. This is the function of the design and smaller scale, reflecting the trade-offs between cost and efficiency. During the last ten years the efficiencies of appliances have increased substantially, but they are still far away from the best practices in

Table 5-16 Estimated Electricity Efficiencies in the OECD Countries, in Percent.

	Final Energy Shares (%)	Useful Energy Efficiency (ϵ)	Final Exergy Shares (%)	Second Law Efficiency (ν)	Useful Exergy Efficiency ($\nu\epsilon$)
Lighting	9.4	10.0	9.4	90.0	9.0
Hhld Drives	9.1	50.0	9.1	60.0	30.0
Hhld Frigs	17.0	140.0	17.0	12.0	16.8
Hhld Washers	10.5	50.0	10.5	20.0	10.0
Hhld Cookers	4.7	100.0	4.7	33.0	33.0
Res. Heat	11.1	100.0	11.1	7.0	7.0
Rail Trspt	1.3	85.0	1.3	100.0	85.0
Electrolysis	5.5	30.0	5.5	100.0	30.0
Steel	4.3	80.0	4.3	30.0	24.0
Furnace	8.9	80.0	8.9	30.0	24.0
Ind. Drives	16.3	60.0	16.3	70.0	42.0
Cog. Heat	1.9	90.0	1.9	32.0	28.8
Total	100.0	74.9	100.0	43.4	32.5

industrial applications. The lighting is on average about 10 percent efficient in the OECD countries because it includes a mixture of incandescent, fluorescent and some high intensity discharge electric lighting. Electrolysis is on average about 30 percent efficient. This results in the average efficiency of electricity for all useful energy applications is about 75 percent.

The second law efficiency is difficult to assess with high precision for most of the applications. We have already discussed in the previous section the estimates for space heating, process heat, cooking and electric trains. Here, we will deal with the estimates of appliance efficiencies. Household appliances include a variety of functions converting electricity both into heat and mechanical energy. The conversion of electricity to mechanical energy is 100 percent, but most of these appliances have much higher heating requirements than those for mechanical work. The household drives include appliances such as vacuum cleaners, blenders, mixers and ventilation equipment. The aggregate second law efficiency is 43 percent, which leads to overall exergetic efficiency of 23 percent. This efficiency is quite high compared with other final energy forms, but it would be even higher where the electricity applied entirely to provide end-uses that require mechanical and kinetic energy or other forms of work. Much of electricity is used to produce low-temperature heat, and in these applications there is a large "loss" of exergy. This is analogous to the uses of natural gas for low-temperature heating that leads to low exergy efficiency. We have also included cogenerated heat into the electricity category, since it is a by-product of electricity generation. We assume the second law efficiency of about 32 percent due to the temperature "step-down" of about 60°C form the hot water in the district heating system to the warm air in a room.

As a rule the service factor is quite high for these appliances since they are used only when needed: Sorenson (1982) gives a value of 50 percent for the US; Olivier (1983) and Robinson (1987) give 40 percent for the UK and Canada. The service factor for the refrigerators , however, is estimated to be lower: Sorensen (1982) assumes 17 percent for the US; and Olivier (1983) 20 percent for the UK. The reason is that it is assumed that they are often over-sized and seldom used to the full capacity.

These assumptions and estimates result in a comparatively high overall exergy efficiency of 32 percent, the highest of any other final energy form illustrating the high quality form of electricity. The low primary to final conversion brings the overall efficiency down to about 10 percent.

5.2.3. Energy and Exergy Efficiency in OECD Countries

It is now relatively simple to estimate overall efficiencies of the whole energy system in the OECD countries. We have given the conversion efficiencies of primary to final energy forms in Table 5-6. Now all we have to do is add the end use efficiencies given for each of the five major final energy forms in previous five tables (coal, other solids, oil products, natural gas and electricity from Tables 5-12 through 5-16) to Table 5-6 by multiplying the efficiencies of primary to final conversion by efficiencies of final to useful conversion stages in each energy chain. The result is shown in Table 5-17.

The useful energy conversions given in Table 5-17 (from Tables 5-12 through 5-16) represent estimates rather than actual observations. They are based on conversion efficiencies of end-use devices, machines, appliances and vehicles in the European Community countries and the United States, which together represent most of the energy consumption of the OECD countries (76 percent of primary energy consumption). Despite the fact that these estimates are to a degree uncertain, they illustrate that the closer we get to the user or consumer, the lower are the efficiencies because of the compounding of conversions along various energy flows from primary sources to useful energy forms resulting in an overall energy and exergy

Table 5-17 Energy Efficiency in the OECD Countries for 1986, Energy in GWyears and Conversion Efficiencies in Percent.

	Coal	Solids	Oil	Nat.Gas	Nuclear	Hydro	Electr.	Heat	Total
Production (I)	1118.6	157.8	1148.9	883.6	421.5	364.9			4095.3
Trade (T)	9.2		1162.1	106.0			1.2		1278.6
Primary (P)	1127.8	157.8	2311.1	989.7	421.5	364.9	1.2		5373.9
To Fuels (P_1)	292.4	150.4	2140.1	813.5			1977.5		5373.9
To Electr. (P_2)	835.4	7.4	171.0	176.2	421.5	364.9	(1976.3)		
Sec. Fuels (S_1)	283.3	149.3	2031.0	775.6			683.0	13.6	3935.8
Sec. Electr. (S_2)	(275.8)	(2.7)	(59.5)	(61.1)	(149.9)	(134.0)	683.0	(13.6)	
Final (F)	268.3	149.2	2023.7	701.4			621.4	12.3	3776.4
Useful (U)	146.3	78.5	829.3	515.3			465.2	11.1	2045.6
S_1/P_1 (%)	96.9	99.3	94.9	95.3			34.6	100.0	73.2
F/S_1 (%)	94.7	100.0	99.6	90.4			91.0	90.4	96.0
F/P_1 (%)	91.8	99.2	94.6	86.2			31.4	90.4	70.3
U/F (%)	54.5	52.6	41.0	73.5			74.9	90.0	54.2
U/P_1 (%)	50.0	52.2	38.8	63.3			23.5	81.4	38.1

Note: $U=\epsilon F$, the individual estimates for ϵ are given in Tables 5-12 to 5-16.

efficiencies of about 38. Thus, the closer we get to the user or consumer, there appear to be large opportunities to improve the efficiency. The overall efficiency of converting final to useful energy is about 54 percent compared to the much higher efficiency of primary to final energy conversion of about 70 percent.

This means that vehicles, heating systems, lighting and industrial uses have much lower effectiveness in transforming fuels and electricity into heat and work (54%) than the facilities for conversion of primary energy to fuels and electricity (70%). Together they give (by multiplication) the overall ratio for primary to useful energy transformation for the OECD countries of about 38 percent. Compared to last century when the overall energy efficiency was probably on the order of a few percent, this is represents an enormous improvement. However, an efficiency of less than 40 percent also means that more than 60 percent of primary energy is degraded into waste heat in order to power prime movers and to heat boilers and furnaces. The overall efficiency is even lower if energy services are considered as well. We have given a rough estimate of about 40 percent for the energy services at the aggregate level. This results in primary energy to services efficiency of about 15 percent.

It should be noted, however, that the form qualities are quite different for the various final energy carriers that is to some extent reflected in the energy efficiency estimates. Electricity, natural gas and district heat are grid oriented, can be used rather efficiently and have relatively low adverse environmental impacts. Oil products on the other hand are still the best energy forms in the transport sector because they are very portable due to their liquid form and rather high energy density per unit volume. Coal is from this point of view the least desirable energy carrier, so that more than 74 percent is used for electricity generation while the rest is delivered as final energy to mostly large users. As such natural gas and electricity have about the highest final to useful energy efficiencies of about 74 and 75 percent, respectively. Natural gas has the highest overall efficiency of primary to useful energy of about 63 percent and electricity the lowest with about 24 percent. To some extent this is misleading in view of the foregoing discussion so that there is the need to differentiate the qualities of different final energy carriers. We have defined and estimated the second-law efficiencies of various categories of energy end-use in the previous section. Here, we will attempt to reflect these "quality" differences of various final energy carriers by estimating the overall exergy efficiency of the current OECD energy system.

Table 5-18 gives the exergy efficiency and illustrates that the primary to final exergy conversion efficiency is about the same as the energy efficiency (with the exception of factor *h*, the heat of combustion). The exergetic efficiency is, however, quite different the closer we get to the end use. The reason is of course the relatively low exergetic efficiency of thermal conversion processes with relatively small temperature gradients. As we have shown in the previous section, the exergetic efficiency is quite low for most end uses where low temperature heat is required such as space heating.

In exergetic terms, the overall primary to useful conversion efficiency is even lower than the overall energy efficiency. Table 5-18 shows that the overall exergy efficiency is about 15 percent in conversion primary into useful exergy. Due to the definition of exergy efficiency (as the ratio of least theoretical exergy requirements for a given task divided by the actual exergy consumption), this low efficiency implies that at least in principle and under ideal conditions the improvement potential is almost 85 percentage points or almost a factor of seven. This means that in an ideal energy system, 85 percent of the current primary energy inputs would not be required with the same structure of energy services. If we, in addition, account for the relative service efficiency of about 40 percent, the overall exergy efficiency is reduced to 6 percent.

The difference between the primary to final compared to final to useful exergy is higher than for the energy efficiency given in Table 5-17. The final

Table 5-18 Exergy Balance in the OECD Countries for 1986, in GWyears and %.

	Coal	Solids	Oil	Nat.Gas	Nuclear	Hydro	Electr.	Heat	Total
Production (I)	1163.3	186.2	1217.9	919.0	421.5	364.9			4272.7
Trade (T)	9.6		1231.9	110.3			1.2		1352.9
Primary (P)	1172.9	186.2	2449.7	1029.3	421.5	364.9	1.2		5625.6
To Fuels (P_1)	304.1	177.5	2268.5	846.0			2029.5		5625.6
To Electr. (P_2)	868.8	8.7	181.3	183.2	421.5	364.9	2028.4		
Sec. Fuels (S_1)	294.6	176.2	2152.9	806.6			683.0	3.0	4116.2
Sec. Electr. (S_2)	(275.8)	(2.7)	(59.5)	(61.1)	(149.9)	(134.0)	683.0	(3.0)	
Final (F)	279.0	176.1	2145.1	729.5			621.4	2.7	3953.9
Useful (U)	32.7	12.0	547.6	69.9			201.8	0.8	864.9
S_1/P_1 (%)	96.9	99.3	94.9	95.3			33.7	100.0	73.2
F/S_1 (%)	94.7	100.0	99.6	90.4			91.0	90.4	96.1
F/P_1 (%)	91.8	99.2	94.6	86.2			30.6	90.4	70.3
U/F (%)	11.7	6.8	25.5	9.6			32.5	28.8	21.9
U/P_1 (%)	10.8	6.8	24.1	8.3			9.9	26.0	15.4

Note: $P_{exe}=hP_{ene}$, $F_{exe}\approx hF_{ene}$ (the main difference is basically in cogenerated heat for district heating) and $U_{exe}=(\epsilon\nu/h)F_{exe}$. The individual estimates for ϵ and ν are given in Tables 5-12 to 5-16. We have assumed following values for the ratio of exergy to heat of combustion: for biomass h=1.18; for coal (assuming an average of brown coal, anthracite and coke) h=1.06; for oil products h=1.06; for natural gas (mostly methane) h=1.04. Otherwise, h=1.

to useful exergy efficiency is about 22 percent while the primary to final exergy efficiency is almost unchanged with 70 percent. Further differences become obvious by comparing the overall efficiency of the energy carriers given in Tables 5-17 and 5-18. For example, the highest useful efficiencies are achieved with applications of natural gas with an average of about 63 percent. These relatively high conversion rate in energetic terms of natural gas and solids (other than coal) is due to the fact that they are not converted to secondary fuels in contrast to crude oil and electricity. In fact, most of natural gas and solids are used for process heat and space heating. The useful energy efficiency of these conversion processes is relatively high, but due to the relatively low average temperature of these applications, the exergetic efficiency of final to useful natural gas and solids conversion is rather low with less than 10 percent. Thus, it is interesting to note this apparent discrepancy: In energy terms gas appears to be the most efficient in end-use applications, while in exergy terms it is almost the least efficient. The situation with electricity is almost complete opposite compared with natural gas: It has a high average final to useful conversion efficiency in energy terms and the highest in exergy terms. However, if the conversion efficiency in going from primary to final energy is considered, than the overall efficiency of electricity from primary to useful is certainly the lowest in energy terms, but quite high in exergy terms. In some sense the relatively low primary to final conversion efficiency is returned in form of quality and convenience and results in relatively high useful exergy efficiency. This is also the case with for oil products but less so for natural gas, coal and other solids.

Despite the fact that all these estimates are at least to a degree uncertain, they illustrate that the closer we get to the user, the lower are the efficiencies because of the compounding of conversions along various energy flows from primary sources to useful energy forms resulting in an overall energy and exergy efficiencies of about 38 and 15 percent, respectively. These approximate figures probably overestimate the actual services provided by energy (e.g. warm room or transport by motor vehicles) since we have not accounted for the efficiencies in provision of energy services. In the foregoing discussion we have noted, however, that the service efficiencies might not be higher than about 40 percent on the aggregate level for all energy end-uses. We have already noted that compared to last century when the overall efficiency was probably on the order of one percent and at most a few percent, the individual conversion rates and the overall energy efficiency of 38 percent are indeed a great improvement. At the same time, however, exergy efficiency of 15 percent and overall service efficiency of 6 percent are indeed rather low figures and they are indicative of improvement possibilities in the decades to come. While the numbers are rather uncertain, it is clear that any conversion improvements will reduce the direct energy costs, the indirect social costs and perhaps most importantly the environmental costs of provision of sufficient energy services. Any improvements, especially at the level of end use, will therefore result in positive impacts. At the same time, we have argued in the foregoing section (on efficiency improvement potential) that significant efficiency improvements will necessitate related changes in the technological vintage structure, employment and required skills, and since they are most likely to take place close to end use, and that they will tend to increase the labor and information intensity of energy services and end use.

Thus, the current exergy efficiency of the energy system is somewhere between about 5 and 15 percent, depending on whether the service factors are included or not, but it is probably closer to the lower values. Despite the uncertainty of various efficiency estimates this result is in a good agreement with other estimates in the literature. Ayres (1988) estimates the overall efficiency in the United States at about 2.8 percent. Olivier (1983) estimates 3 percent efficiency for the United Kingdom, and Marchetti (1980) estimates the overall efficiency at less than 5 percent. Due to the fact that the estimates are indeed uncertain, we have analyzed the sensitivity of these results by changing the assumptions. We have varied the estimates of both end-use levels, final to useful conversion and service factors. It turns out that the aggregate values are quite robust also when the rough estimates of service efficiencies are included. The variation was between 3 and 6 percent. Table 5-18 and all previous Tables (5-12 trough 5-16) gave an estimate with overall efficiency of 6 percent. It is probably an upper estimate, but for the benefit of the doubt we have taken a conservative estimate at the risk of overstating the actual value. The important conclusion, however is that the actual efficiency is certainly not much higher than 10 percent when the service factors are included.

Three to six percent is at a face value a very low efficiency. One of the the reasons why it probably appears to be low is that usually primary to final energy conversion of 70 percent is quoted as the overall efficiency of the whole energy system. The reason is that in most of the studies the efficiency in actually delivering energy services is not accounted for. Our estimates show that the aggregate efficiency is about 6 percent in transforming delivered final energy forms to energy services. Thus, this last transformation step appears to be most critical since it has low low efficiencies. Conversely, many of the improvements in conversion of gathered primary energy to delivered final energy are diluted by the low end-use efficiencies of 6 percent. The average final to useful exergy efficiency is about 22 percent. Thus, the conversion of fuels and electricity to heat and work is achieved with one-third of the primary to final conversion efficiency. The next step, services, are assumed to be more efficient efficient with 40 percent. Therefore, any improvements at these levels with aggregate efficiency of 9 percent, would have very large impacts on increasing the overall energy efficiency, on average more than 7 times larger contribution compared to the improvements in going form primary to final energy forms (i.e., 70/9). Figures 5-4.A and B show the relative energy and exergy efficiencies, respectively, for the five energy carriers for primary to final, useful and service conversion levels. They clearly illustrate the relatively low efficiency of end use compared with primary to final conversion.

We have shown in Tables 5-12 through that the industrial uses of final energy in process heat were almost twice as efficient (with over 9 percent of final energy resulting in services) compared with private and other commercial uses of energy such as transport, space heating and cooking. Ayres (1981) estimates that the industrial uses are very close to the highest economically viable efficiencies and identifies the improvement potential at perhaps 20 percent. In private residential and individual transport applications of energy, the improvement potentials are substantially larger because of low average efficiency of between 0.6 and 5 percent. The space heating is one of the least efficient energy uses with less than one percent of final

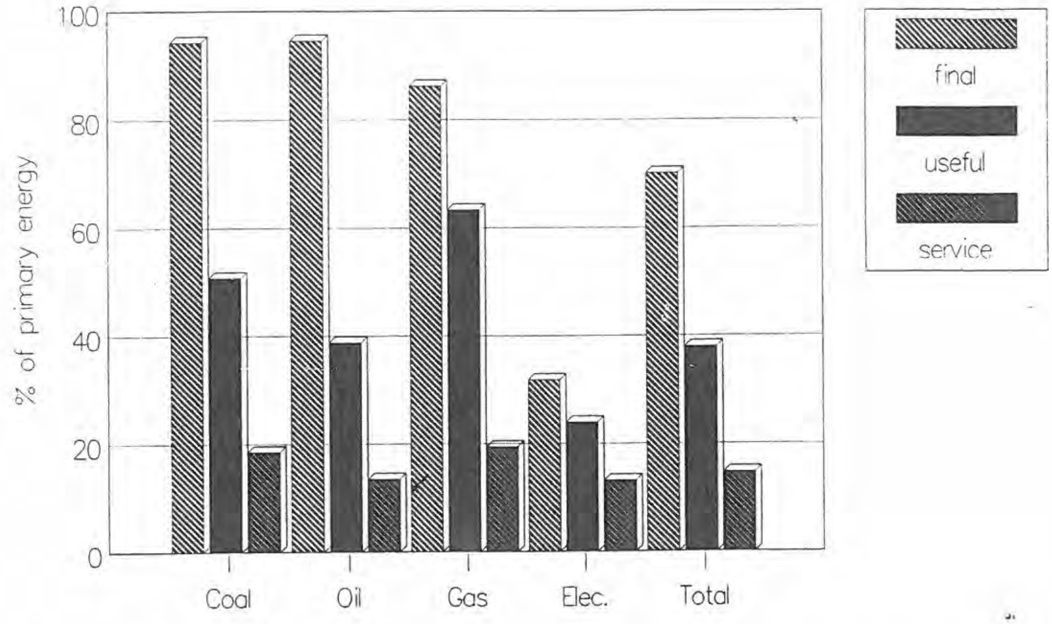


Figure 5-4.A Energy Efficiency in the OECD Countries for 1986, Primary to Final, Useful and Services, in Percent.

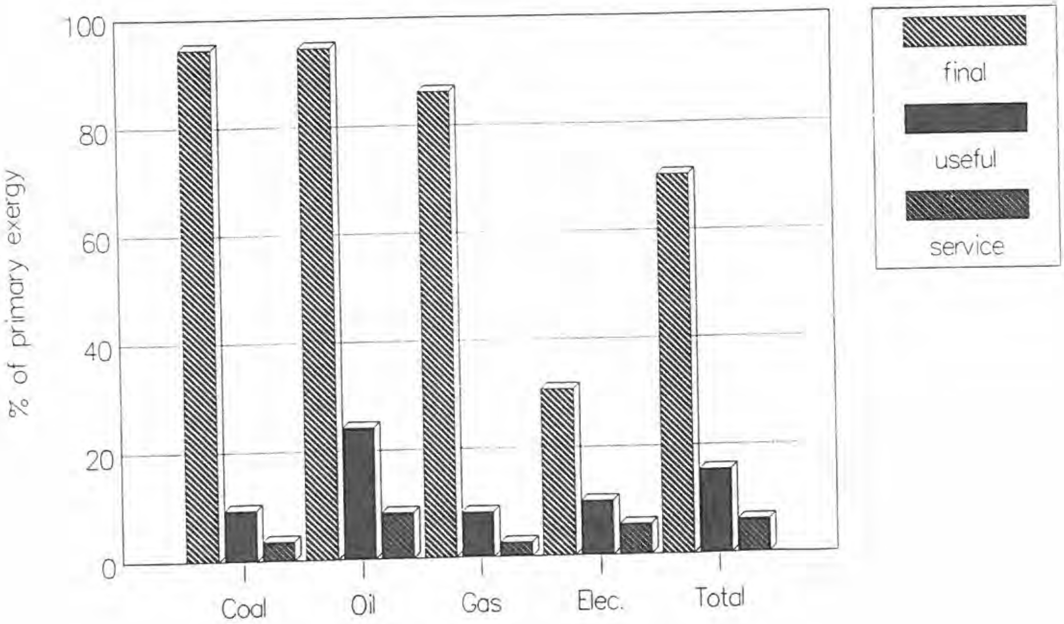


Figure 5-4.B Exergy Efficiency in the OECD Countries for 1986, Primary to Final, Useful and Services, in Percent.

energy resulting in a service. With a 30 percent share in final energy consumption, the doubling of this efficiency would bring more to the overall efficiency improvements than a 13 percentage points improvement in primary to final energy conversion (from current 70 to about 85 percent; an unlikely possibility even under optimistic conditions). This illustrates that end-use efficiency improvements and conservation can have much larger impacts on increasing the effectiveness of energy flow in the OECD countries than equivalent investments in upstream conversion facilities such as power plants and distribution systems.

We have already run down another striking disparity in average efficiencies is among the various final energy forms. It is counter intuitive that natural gas as one of the cleanest and most efficient fossil fuels has the lowest efficiency in provision of energy services. A premium fuel portrays the worst performance. The explanation for this apparent discrepancy is that natural gas is applied to most inefficient end uses such as space heating and process heat. To some degree this is the function of regulatory measures that have limited natural gas use for electricity generation in many OECD countries and it is also the function of convenience of using natural gas for space heating where ever there is an access to the distribution grid. The same is true for electricity uses, although the average efficiencies are among the highest currently achievable due to its quality form. Thus, the conversion losses of transforming primary energy to electricity are compensated to a degree by the relatively high end-use efficiencies.

Another apparent anomaly is the relatively high overall efficiency of coal uses despite its relatively low quality form and rather difficult and cumbersome application to end use especially when compared to other final energy carriers such as electricity and natural gas. The reason is that coal is the oldest energy source. In the previous chapters we have demonstrated that most of the energy needs up to the 1920s were provided by coal. Coal replaced draft animals in transport, whale oils in lighting (by its products such as coal oil), fuelwood in space heating and most of the other traditional energy sources. With the advent of oil era, many coal uses were replaced by crude oil and its products such as kerosene (lighting), gasoline (transport) and fuel oil. Oil products were more versatile and could provide better energy services in most applications. That meant that coal uses became more restricted to those applications where coal was difficult to replace and where coal achieved relatively high conversion efficiencies even when compared with oil products. Examples include steel furnaces, process heat and to some degree electricity generation. Still coal is somewhat more difficult to use due to its larger environmental impacts when compared with its alternatives and due to its solid form (making it more difficult to transport and store). Thus, the relatively high efficiency of coal applications is due to the fact that it survived exactly there where it could provide relatively high efficiency and quality services, and was replaced in all other uses by other, more advanced final energy forms. Almost 75 percent of all final coal goes to industrial uses that are rather efficient compared to the transport, households and services. In contrast, natural gas is providing mostly those energy services where the end-use efficiencies are relatively low such as precess and space heat.

Thus, the aggregate differences in overall efficiencies of the five final energy forms are due to different structure of end uses for each of them. Coal as the oldest final energy form has survived in the most efficient end use categories, while natural gas as the youngest energy carrier has entered mostly inefficient end uses. Less than a fifth of oil products is used in industry, the rest goes mostly to transport services and the remainder for space heat. Again, with the exception of industrial uses, all other use categories are rather inefficient. This all illustrates that the introduction of oil and later natural gas greatly improved the overall efficiency of energy conversion and end use. In these relatively inefficient end use categories, coal requirements would be substantially higher even with new technologies.

This indicates that the overall efficiencies of the energy system must be differentiated since the averages mask many driving forces behind the numerical values. The efficiencies are path-dependent, namely they are the result of the historical development of the whole system and do not necessarily indicate the best allocation of individual energy sources and conversion processes for achieving the highest effectiveness in energy use. They also depend on the structure of the system in the sense that fuel substitution would tend to change the overall efficiency. More natural gas and electricity would increase the aggregate efficiency while more coal would tend to decrease it.

6. GLOBAL AND REGIONAL ENVIRONMENTAL CHANGES

6.1. General

Environmental impacts and developments have always been important in determining the structure of energy consumption. An early example of this is the widespread public opposition to the introduction of coal more than two centuries ago because it released unpleasant (and unhealthy) pollutants when burned in traditional wood stoves or open fireplaces (Brimblecombe, 1987). This opposition persisted despite fuelwood scarcity and very high wood prices. This impasse was alleviated later (also only temporarily) through the development of better coal stoves. The combustion pollutants were now released through the chimney. Decades later, environmental hazards associated with widespread coal use for heating became a serious problem in many cities. London "fog" is a well-known example.

Similarly, the introduction of the automobile solved the nuisance of the environmental pollution associated with horse manure in the urban areas. For example, thousands of so-called "crossing sweepers" were employed in London, who would clean horse manure in front of anyone crossing the street (at the rate of a halfpenny per crossing). Indeed, the environmental pollution problems of urban areas were urgent around the turn of the century. Acid rain "fog", horse manure on the streets, and industrial wastes and pollution abounded in most of the large cities. The replacement of horses by motor vehicles was a welcome change that virtually eliminated at least one of the problems by the 1930s.

The fleet of about 30 million motor vehicles worldwide at that time did not pose any substantial environmental problems, but today this situation is different with almost 400 million motor vehicles in the world. The environmental problems of vehicle use are not global in nature but they universally affect most large urban areas and transit routes. The introduction of the automobile solved notorious environmental problems in cities associated with a horse economy, but eventually generated new and significantly more difficult environmental problems. Today, the modern road transport system is inconceivable without the automobile, ironically also from the environmental point of view. A horse produces about 1,000 grams of excrement per mile traveled. This compares with the 1980 piston engine standards in the US of around 5 grams (CO, NO_x and hydrocarbons) per mile.

This example illustrates that a new technology or, more generally, whole new techno-economic systems, often bring decisive environmental benefits when they replace systems of older vintages. But in the long run they often tend to create new hazards and adverse impacts. Their solution in turn depends on the introduction of a newer and better system (Ausubel, 1989).

Negative environmental effects are associated with the use of almost all energy forms and conversion systems. Some environmental problems have short range effects both in space and time (e.g. waste heat release). On the other extreme, the potential effects are global in nature and may not even be felt for decades (e.g. increase in atmospheric CO_2 concentration and stratospheric ozone depletion).

The objective of this chapter is not to give an exhaustive treatment of environmental constraints, but rather to outline some of those in which the scientific knowledge is rather well established and also indicate areas of large uncertainty. This is done on the basis of some selected examples and where possible we also give an indication of the complex issues involved in dealing with these problems. Some of them could perhaps again be resolved by the introduction of new systems in the future. What is fundamentally new, however, is the global nature of environmental problems and that the response time of global environmental change is usually much longer than our planning periods. It might be too late to act by the time it becomes certain that the anthropogenic activities have created irreversible and worldwide environmental changes endangering life on earth. It is, in this context, that the efficiency improvements in energy use gain fundamental importance, as they can lead to a reduction of potential impacts.

6.2. Global Impacts

6.2.1. Climatic Change

Earth's climate always changes (Schneider, 1987). It is vastly different now from what it was a hundred million years ago when dinosaurs dominated the planet and tropical plants thrived at high latitudes. It is different from what it was even 20 thousand years ago, when ice sheets covered much of the Northern Hemisphere. In the future it will surely continue to evolve. Schneider (1987) further argues that in addition to the natural causes driving climatic evolution, such as fluctuations in the earth's orbit, future change will probably be influenced by human activities. It is often claimed that we may be already experiencing the climatic effects of increased concentrations of "greenhouse" gases in the atmosphere. A considerable part of these gases was emitted by the burning of fossil fuels.

We have shown in Chapter 3 that over the last two centuries most of the energy consumed worldwide consisted of fossil fuels and fuelwood. When these fuels are burned, carbon is oxidized and the resulting carbon dioxide (CO_2) is released into the atmosphere. As a result, the composition of the atmosphere is changing. Detailed atmospheric measurements since 1957 show an increase in CO_2 concentrations from 315 to 350 parts per million (ppm) by volume, as shown in Figure 6-1.A. Atmospheric carbon dioxide concentrations portray pronounced annual fluctuations, but on the average an increasing trend is apparent. These concentrations were measured at Mauna Loa Observatory in Hawaii (Bacastow and Keeling, 1981), but they are representative for the general increase. Bolin, Döös, Jäger and Warrick (1986) report that the Hawaii measurements, together with the record from the South Pole, reveal several important features of the carbon cycle. These, together with a number of other measurements, all confirm the annual cycle and an increasing trend in atmospheric CO_2 concentration. The current rate of increase is estimated at about 0.4 percent (1.4 ppm) per year.

Earlier measurements of atmospheric carbon dioxide (since the middle of the last century) were usually rather inaccurate (Bolin, Döös, Jäger and Warrick, 1986). Wigley (1983) has concluded that the most likely value around 1870 was about 270 ppm. Thus, there is no doubt that the concentrations of carbon dioxide in the atmosphere have been rising during the last hundred years, despite the fact that the estimates for the concentrations during the last century are uncertain. As shown in Figure 6-1.B, it is now roughly one third higher than it was before the advent of the Industrial Revolution. These estimates are based on the analysis of air trapped in glacier ice. They indicate relatively constant mean concentrations up to 1800 and a steady increase thereafter.

Carbon dioxide is called a greenhouse gas because it lets short wave radiant energy from the sun into the atmosphere more freely than it lets long-wave radiation emitted by the earth out. At the beginning of Chapter 2 we showed a schematic view of the energy flow in nature, where it was illustrated that 178,000 TWyr/yr of solar energy intersected by the earth (which results in $340 W/m^2$ solar insulation at the earth's surface) are eventually emitted by the earth as infrared radiant energy. Carbon dioxide, water vapor and some other atmospheric trace gases are relatively transparent to visible sunlight, but are more efficient at absorbing the longer infrared radiation emitted by the earth. As the carbon dioxide concentrations increase in the atmosphere this can alter the earth's energy balance in the same way

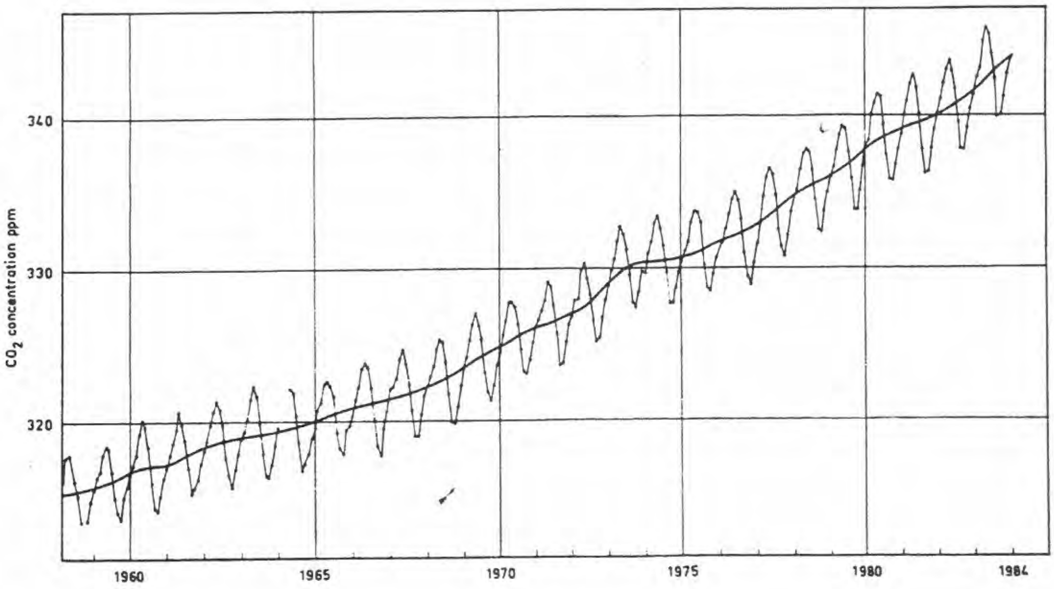


Figure 6-1.A Atmospheric Carbon Dioxide Concentrations, Hawaii (Bolin, Döös, Jäger and Warrick, 1986).

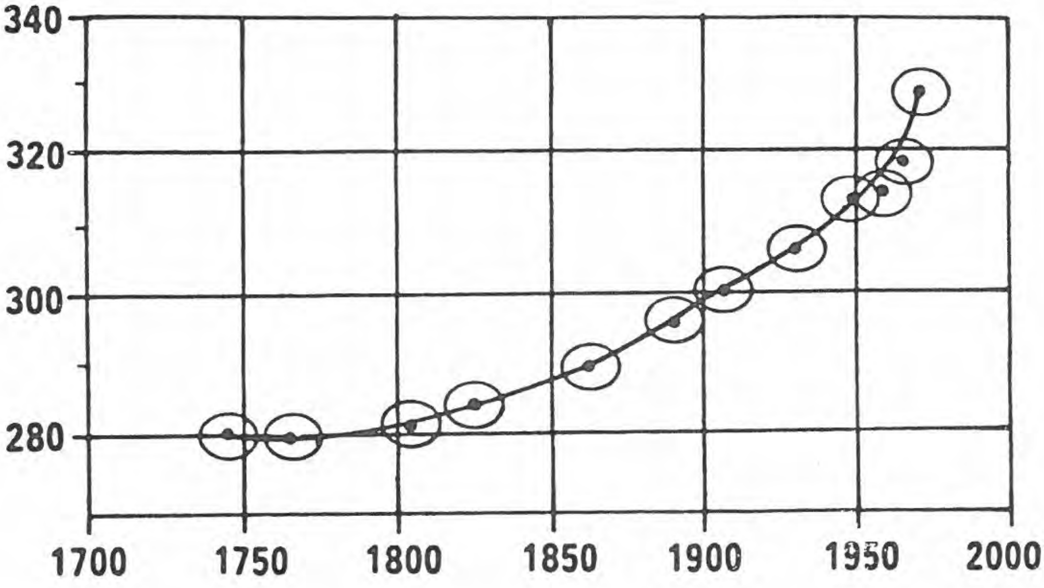


Figure 6-1.B Historical Carbon Dioxide Concentrations obtained from Glacier Ice (Neftel *et al.*, 1985).

as the air in a greenhouse warms because the radiation is retained. Thus, it is broadly accepted that when the carbon dioxide concentration rises, the temperature at the earth's surface must rise as well (Schneider, 1987). That is the so-called greenhouse effect and its existence is not questioned. It explains, for example, the very hot temperatures on Venus (with thick atmosphere mostly consisting of carbon dioxide) and cold conditions on Mars (with very thin atmosphere and low carbon dioxide concentrations).

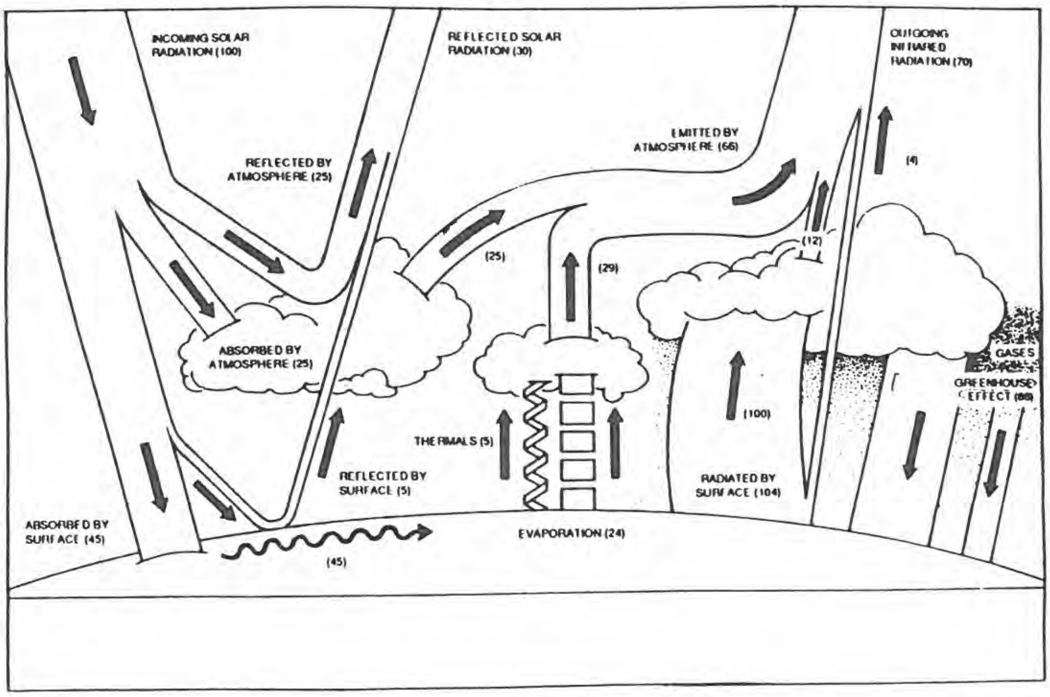


Figure 6-2 The Greenhouse Effect (Schneider, 1989).

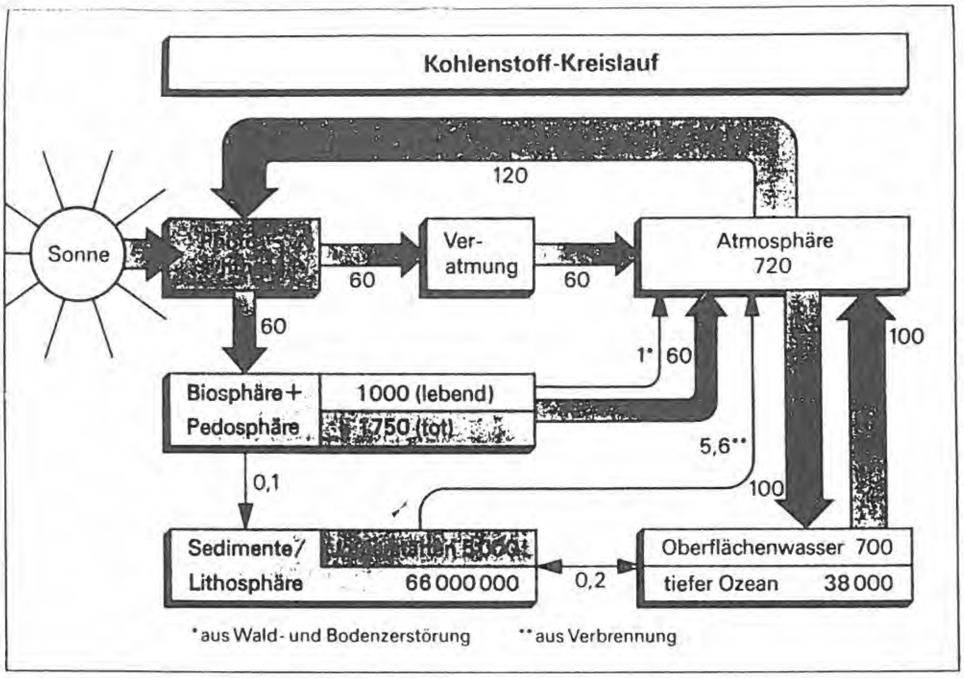
The flow and storage of energy among the various climatic subsystems is exceedingly complex and not sufficiently understood. Figure 6-2 shows a highly simplified illustration of these flows. The greenhouse effect arises as the earth's atmosphere tends to trap heat near the surface (Schneider, 1987 and 1989) because trace greenhouse gases absorb infrared radiation emitted by the earth. Hence, the increase in the atmospheric concentration of greenhouse gases tends to warm the earth's surface and the lower atmosphere (by downward infrared reradiations, as shown in Figure 6-2). The arrows represent energy flows relative to the earth-averaged solar constant of about 340W/m^2 (given in percent).

Therefore, the earth's atmosphere acts as a thermal blanket, principally through the radiation absorption properties of heat retaining gases and particles. These give rise to the greenhouse effect – without them life on earth would not have evolved as we know it (Helm and Schneider, 1989). This explains why the increase in the atmospheric concentrations of greenhouse gases tends to alter the earth's climate. Whilst this fact is indisputed, it is not known to what extent and when climate change might occur, because of the scientific uncertainties of dynamic changes in the earth's energy budget and its geochemical carbon cycle.

6.2.2. Carbon Dioxide Emissions

Berner and Lasage (1989) give the following illustration of the nature of the dilemma and the complexity of the global climatic change *problematique.* Imagine for a moment a doomsday scenario in which all life on the earth is suddenly annihilated. Imagine further that all the carbon in this dead organic matter is burned to form carbon dioxide and that all of it is released to the atmosphere. They estimate that the amount of carbon dioxide this scenario generates is less than we have released by burning fossil fuels during the last two centuries. This illustrates that the biological carbon dioxide cycle is only a small portion of the larger geochemical carbon cycle in which carbon is transferred among the land (sedimentary rocks), oceans and atmosphere. It also illustrates that the cumulative carbon dioxide emissions from fossil fuels are very large compared to the biological carbon releases and fixation rates, and consequently that they could influence future climatic change by altering the flows in the geochemical carbon cycle. Figure 6-3 shows the geochemical carbon cycle indicating the global carbon flows in billion tons per year and most important the carbon reservoirs in billion tons.

The main sources of anthropogenic carbon dioxide emissions are fossil fuel combustion, deforestation and changing land use. The main natural sources are ocean and land releases. Table 6-1 indicates that about 4 percent of the annual carbon dioxide emissions are of anthropogenic origin. However, the emissions from fossil fuel combustion are more than three times higher than those that result from deforestation and land use patterns. The larger part of the fossil carbon dioxide emissions are due to coal burning because it has the highest (specific) carbon content of all fuels. Consequently, coal contributes about 43 percent to total fossil fuel emissions, oil about 40 percent and natural gas about 17 percent. Figure 6-4 shows that the total annual anthropogenic releases of carbon dioxide have been increasing since the 1800s which is in good agreement with the observed concentrations given in Figure 6-1.B. While the deforestation and land use emissions started to decline about a hundred years ago, the



Globaler Kohlenstoffkreislauf. Die Zahlen bezeichnen Kohlenstoffflüsse in Milliarden Tonnen pro Jahr und Kohlenstoffreservoire in Milliarden Tonnen.

Figure 6-3 Geochemical Carbon Cycle (Deutscher Bundestag, 1988).

Table 6-1 Carbon Dioxide Emissions in Million Tons of Carbon per Year.

Natural		Anthropogenic	
Ocean release:	105,000 ± 1,900	Fossil fuel use:	5,400
		Coal	2,300
		Oil	2,200
		Gas	900
Land release:	10,000 - 120,000	Deforestation and land use changes:	1,600 ± 800

Source: Döös (1989), with minor changes. The total fossil carbon dioxide emissions are based on the current primary energy consumption and following emission factors (tons C/Wyr): coal 0.7; oil 0.5; and gas 0.4 (see Ausubel, Grübler and Nakićenović, 1988).

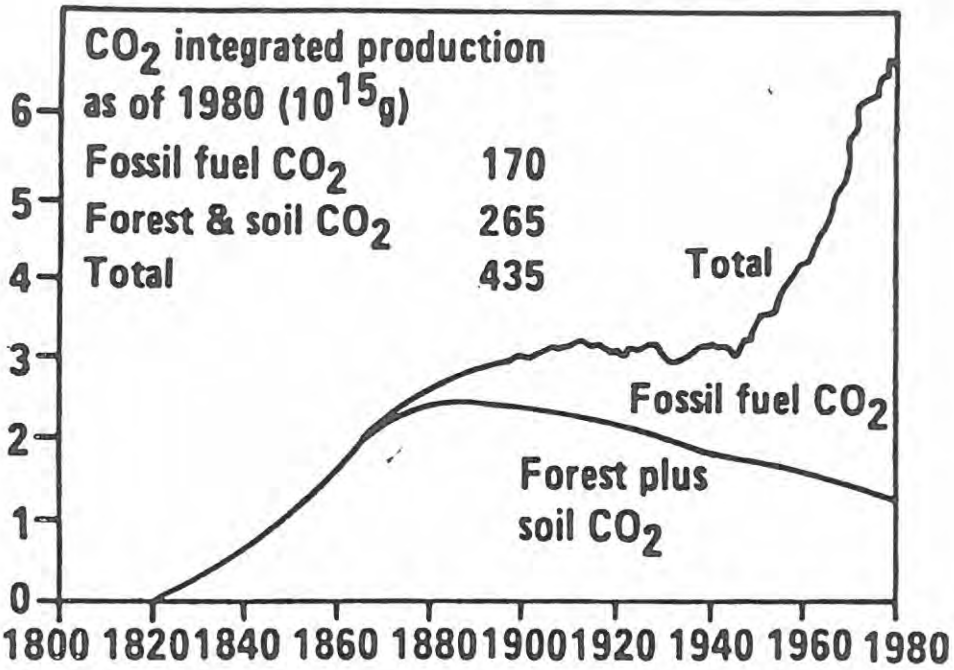


Figure 6-4 Global Carbon Dioxide Emissions in Billion Tons of Carbon (Bolin, Döös, Jäger and Warrick, 1986).

enormous expansion of fossil energy use has led to an exponential increase in energy use related emissions.

The problem is the difference between the dynamics of the geochemical carbon cycle that regulates atmospheric carbon dioxide over geologic time scales, which are measured in millions of years, and the relatively abrupt increase in the atmospheric concentration of carbon dioxide due to anthropogenetic sources such as fossil energy use, deforestation and land use change. Thus, the problem is that man-made releases of carbon dioxide are increasing very rapidly compared to the relative stability of the geochemical cycle over the same time scale of two centuries. There is a great danger that we are "short-circuiting" the carbon cycle (Berner and Lasage, 1989). This has led to great concern that fossil energy consumption could critically influence the climate through the greenhouse effect.

Consumption of different carbon-based energy sources leads to different carbon dioxide emissions. Fuelwood and biomass in general have the highest specific emissions because they have high carbon content per unit of energy (on a dry basis). Coal has basically one carbon atom per one hydrogen, crude oil two hydrogens per carbon and natural gas consists mostly of methane which has the highest ratio of four hydrogens per carbon atom of all hydrocarbon fuels. Consequently, natural gas has the lowest specific carbon dioxide emissions and fuelwood the highest.

Depending on the level of energy consumption and the fuel mix, CO_2 emissions vary widely between countries (Figure 6-5). The three leading CO_2 emitters (USA, USSR and China) together account for roughly half of the total fossil CO_2 emissions worldwide in 1986. Per capita CO_2 emissions (calculated as tons carbon per capita) vary even more. From (Figure 6-5) it can be seen that the US and the GDR have the highest per capita CO_2 emissions, in excess of 5 tons carbon per person and per year. The US and the GDR, thus, have similar per capita climate impacts, however, they are due to entirely different reasons. In the case of the US, high per capita CO_2 emissions are due to very high levels of energy consumption (in particular for private road transport), whereas in the GDR they stem from an entirely different (i.e., lower per capita) energy demand and different supply structure, emphasizing the basic material production sector and the high degree of reliance on low grade fossil fuels (brown coal).

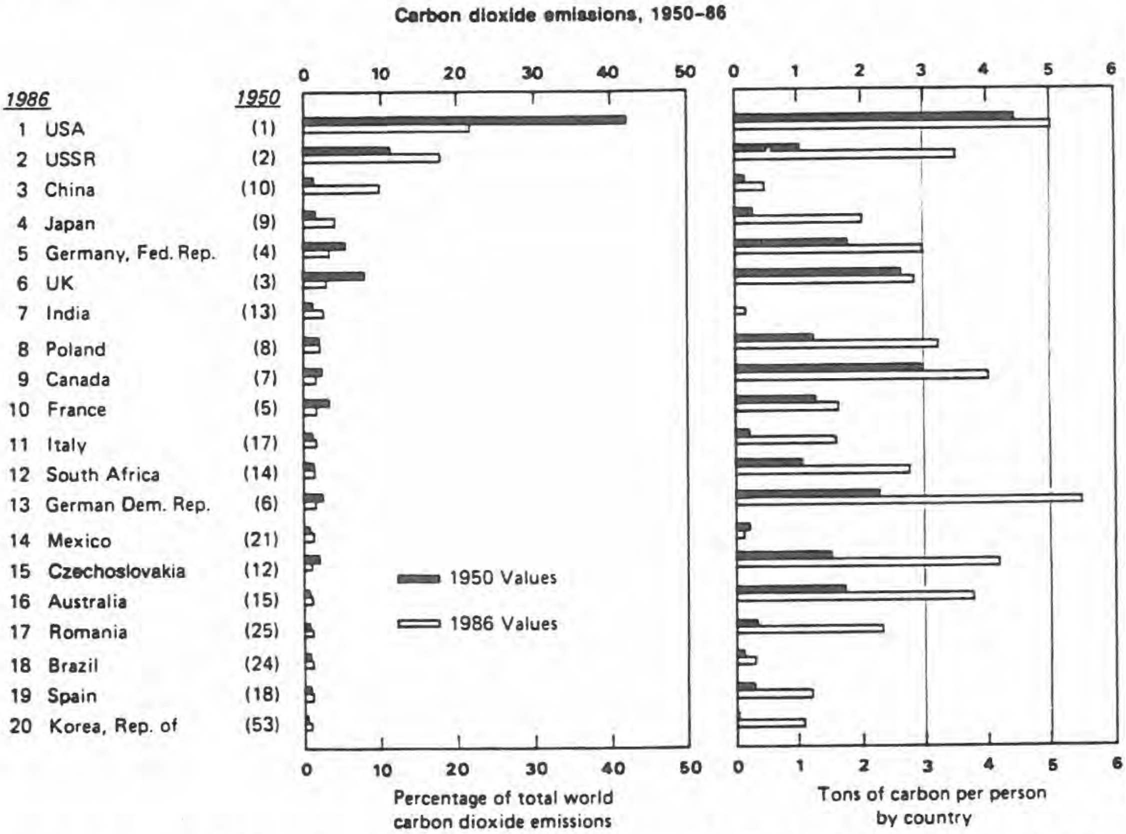


Figure 6-5 Total and Per Capita Carbon Dioxide Emissions, 1950–1986 (Niehaus et al., 1989)

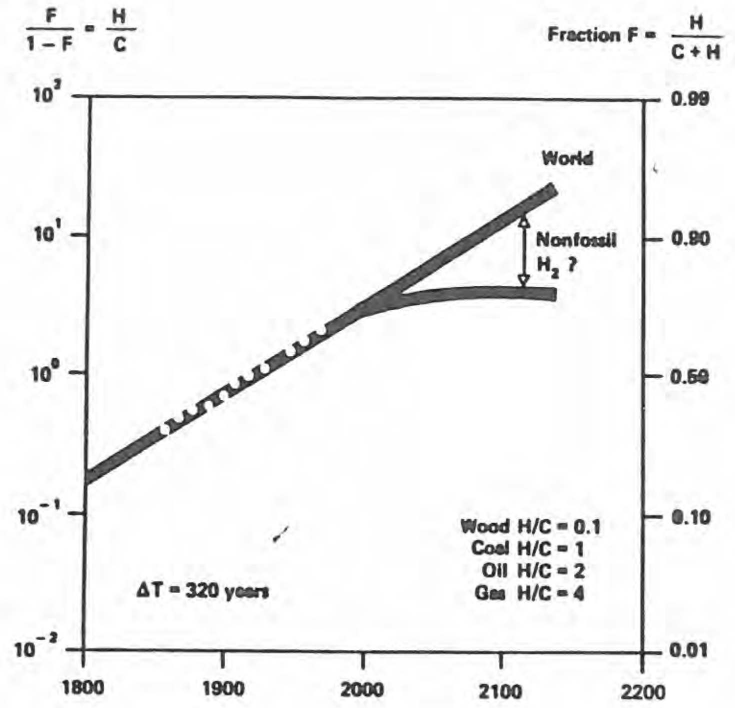


Figure 6-6 Atomic Hydrogen to Carbon Ratio in the Global Energy Consumption (Marchetti, 1982).

The natural question to be asked would be: What is the best we can do with regard to the greenhouse effect if we continue to rely on fossil fuels? A possible solution could be to use natural gas, a resource that appears increasingly more plentiful throughout the world (see Chapter 3). Considering the fact that the relative shares of older fossil fuels with high carbon content are decreasing in the total global energy consumption (see again discussion in Chapter 3), the long-term evolution of the world energy system has been toward an increasing ratio of hydrogen to carbon; and thus, *lower specific* carbon dioxide emissions per unit of primary energy-use. Figure 6-6 shows the evolution of the ratio of hydrogen (H) to carbon (C) in the world fuel mix during the last two centuries and a hypothetical extrapolation into the future. Relative hydrogen to carbon ratios of each fuel are given in the lower right corner of the figure. The number for fuelwood refers to dry wood suitable for energy generation. If the process should continue beyond the present, production of large amounts of hydrogen fuel without fossil energy is required in addition to the expansion of the natural gas share in global energy consumption.

In this spirit, Ausubel, Grübler and Nakićenović (1988) have analyzed the implications on future atmospheric carbon dioxide concentrations of increasing reliance on natural gas to meet global energy demands in the transition to a post-fossil energy system. Two scenarios have been considered, one holding per capita energy consumption at current levels, and the second raising the global average in the year 2100 to the current US level. The first is an "efficiency" scenario that could result from the achievement of all improvements discussed in Chapter 5, and the second ("long wave" scenario) probably represents an upper bound on the conceivable increases in global energy needs.

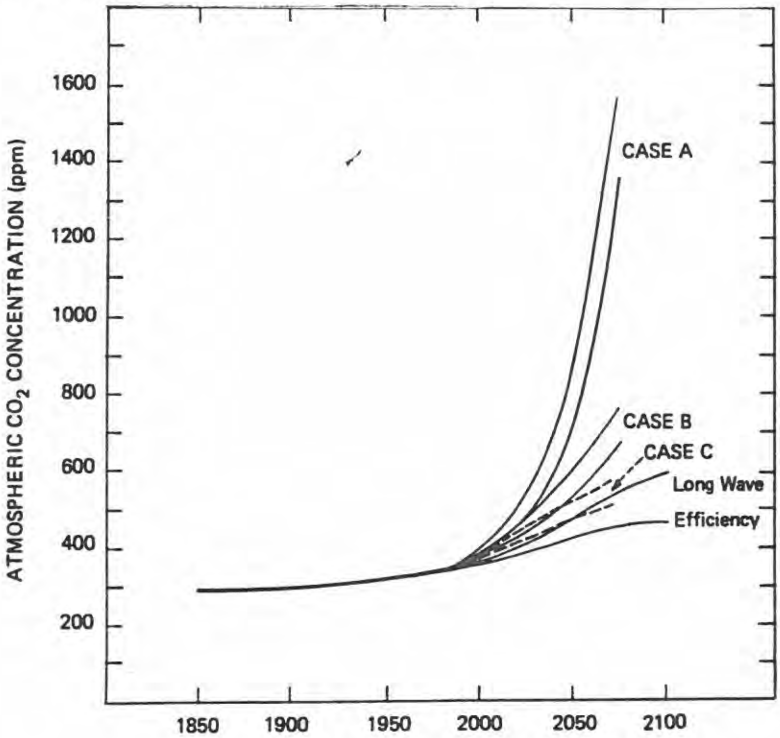


Figure 6-7 Scenarios for Future Atmospheric Carbon Dioxide Concentrations (Ausubel, Grübler and Nakićenović, 1988).

In both of the scenarios natural gas plays a bridge to the future and its share in primary energy will steadily increase until the 2050s when the alternative non-carbon based energy forms are assumed to take-over. Figure 6-7 compares our results with other reference projections of atmospheric carbon dioxide concentrations from energy use. In the efficiency scenario the concentrations peak about 450 ppm, while in the other they near 600 ppm. Both of these projections are substantially lower than the three reference cases prepared for the US Department of Energy (Trabalka, 1985, based on Edmonds et al., 1985). Case A is a high energy demand projection with an energy demand similar to that in the "long wave" scenario, however, it is based on a massive deployment of "dirty fossils", i.e., coal and oil shale, especially for the production of synthetic liquids. Case B is an intermediate scenario, whereas Case C is a low scenario with an energy demand comparable to the "efficiency" scenario. The pair of CO_2 concentrations presented in Figure 6-7 for Cases A, B and C correspond to two scenarios of high and low airborne fractions of CO_2 retained in the atmosphere. These results illustrate that much lower carbon dioxide emissions would be possible in a "methane age", but they also confirm that the issue of global climate warming is likely to be a major planetary concern throughout the twenty-first century. Thus, even the best case of assuming a large expansion of natural gas use, vigorous introduction of non-carbon based energy forms and high energy-efficiency, world energy use is still very likely to lead to at least a 50 percent increase in the atmospheric carbon dioxide concentrations.

These concerns naturally lead to the question whether carbon dioxide abatement measures may become necessary, since apparently both the efficiency and fuel substitution effects are not sufficient to off-set further increases in the atmospheric carbon dioxide concentrations. A number of schemes have been proposed in the literature. An obvious one would be to install carbon dioxide scrubbers on the fossil power plants and other large fuel combustion facilities much in the same way as sulfur dioxide is removed today. However, the costs of such technology are rather high. They are estimated to be about 4 to 5 times higher than those of sulfur dioxide scrubbers, which already represent up to 40 percent of the power plant capital investment and 35 percent of operational costs (Steinberg, Cherg and Horn, 1984; Kram and Okken, 1989; and Balzhiser and Yeager, 1987). Marchetti (1988) proposed another alternative; instead of cleaning after combustion, carbon could be, in principle, eliminated from the fuel prior to combustion. For example, natural gas could be steam-reformed at the well-head into hydrogen and carbon dioxide. Carbon dioxide could be either directly reinjected into gas fields or even better be used for enhanced oil recovery. Hydrogen (or a hydrogen and methane mixture) could then be transported by pipeline to the consumers. A number of other proposals exist that could also help reduce the emissions, but in any case the risk of global warming makes all four strategies timely: namely, efficiency improvements, increase of natural gas use with respect to other fossil fuels, removal of carbon dioxide emissions, and introduction of non-carbon based fuels and other alternative energy sources, such as nuclear or solar generated electricity or hydrogen.

Table 6-2 Characteristics of Greenhouse Gases.

	CO_2	CH_4	N_2O	Ozone	CFC 11	CFC 12
c (ppm)[1]	364	1.65	0.31	0.02	0.0002	0.0003
Δt (yr)[2]	100	10	150	0.1	65	110
Δc (%/yr)	0.4	1.0	0.3	0.5	5	5
DGE (per mole)[3]	1	32	150	2,000	14,000	17,000
ALG ($\Delta t \times$DGE)[4]	1	3.2	22.5	2	9,100	18,700
RGC (%)[5]	50	19	4	8	5	10

Source: Deutscher Bundestag, 1988.

1 All of the concentrations are given as typical average figures. They vary both in time, with altitude and latitude. Ozone concentrations portray very strong variation.

2 Strictly speaking, the residence time of a particular carbon dioxide molecule is about 7 years, but it takes about 100 years before the geochemical carbon cycle removes from the atmosphere released carbon dioxide to one third its original value.

3 DGE: Direct Greenhouse Effect at moment of emittance compared with equal concentration of carbon dioxide ($CO_2 = 1$).

4 ALG: Average Life-Cycle Greenhouse Effect until destruction/absorption, ($CO_2 = 1$)

5 RGC: Estimated Relative Greenhouse Contribution in percent. Shares add to 96 percent because other CFC gases and stratospheric water vapor are not accounted for.

6.2.3. Emissions of Other Greenhouse Gases

Carbon dioxide is not the only greenhouse gas that is associated with anthropogenic activities. Carbon dioxide contributes to an estimated 50 percent of the total greenhouse effect; other important trace gases that also have anthropogenic origins (in addition to natural sources) and contribute to the greenhouse effect are methane, nitrogen oxides, tropospheric ozone and chlorofluorocarbons (CFCs). Table 6-2 shows the concentrations in ppm, the mean residence time in the atmosphere in years, estimated annual concentration increase in percent, their relative greenhouse effect compared to equal concentration of carbon dioxide at the moment of emittance on a per mole basis (DGE), relative greenhouse effect of a molecule over its total atmospheric lifetime (i.e., $\Delta t \times$DGE) compared to CO_2 (ALG), and finally their estimated relative greenhouse contribution (RGC) in percent.

Table 6-2 clearly illustrates that carbon dioxide (CO_2) and methane (CH_4) are the largest contributors to the greenhouse effect with estimated 50 and 19 percent contributions, respectively (Deutscher Bundestag, 1988). Carbon dioxide has a very long residence time of about 100 years in the atmosphere. Strictly speaking, the residence time of a particular carbon dioxide molecule is about 7 years, but it takes about 100 years before the geochemical carbon cycle removes from the atmosphere about a third of the released carbon dioxide. This means that even if all of the emissions were to be abruptly halted it would still take at least 50 years and possibly much longer before the oceans could absorb enough carbon to reduce the concentrations to the preindustrial levels. Methane, on the other hand, has a much shorter residence time in the atmosphere, which means that atmospheric concentrations would respond much faster (in decades instead of centuries) to reductions in the emission rates.

Other greenhouse gases are N_2O (primarily released at coal combustion), ozone and chlorofluorocarbons. The extremely large direct greenhouse effect (radiative absorption capacity) of a molecule of CFC's compared to CO_2 shows the timeliness of international agreements (Montreal Protocol) to curtail production and use and, thus, emissions of CFC's radically.

Table 6-2 does not show carbon monoxide (CO) (main emitter source: automobile exhausts) because it is, strictly speaking, not directly a greenhouse gas itself. Its climatic relevance relates to its role in the complex atmospheric chemistry responsible for the destruction of other greenhouse gases, in particular methane. CO competes for the OH radicals that remove methane in the atmosphere. Increased CO concentration could, thus, lead to prolonged residence times of methane and so contribute indirectly to global warming. The nature and the possible impacts of such a feedback mechanism are, however, very poorly understood, but are unlikely to change the orders of magnitude presented in Table 6-2 significantly.

Next to CO_2, methane is currently estimated to be the second largest contributor to the greenhouse effect. Figure 6-8.A shows the increases in tropospheric methane concentrations in the Northern Hemisphere. The current concentration is estimated at about 1.65 ppm (i.e., over a factor 200 lower than the CO_2 concentration). The first measurements were made in the late 1960s and indicated concentrations of about 1.4 ppm for the Northern Hemisphere and about 1.3 for the Southern. The existence of an upward trend is clearly established. The data shown in Figure 6-8.A are obtained from measurements carried out on aircraft (circles), ships (squares), and at different land based stations during clean air conditions (triangles). The figure also includes data (dots) measured at similar latitudes in air from the Pacific Ocean (see, Bolin, Döös, Jäger and Warrick, 1986). Figure 6-8.B confirms these findings on a much longer time scale. It shows the growth in the atmospheric methane concentrations during the last 3,000 years and illustrates the exponential rise in the concentrations since the beginning of the Industrial Revolution.

However, there is a larger uncertainty about the sources and sinks of methane compared to those of atmospheric carbon dioxide. The sinks of

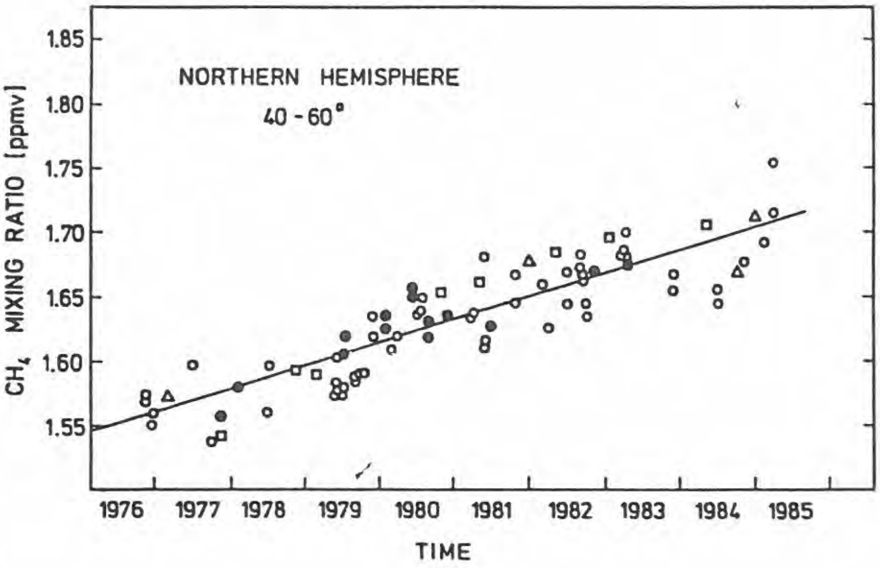


Figure 6-8.A Tropospheric Methane Concentrations, Northern Hemisphere and Pacific Ocean (Bolin, Döös, Jäger and Warrick, 1986).

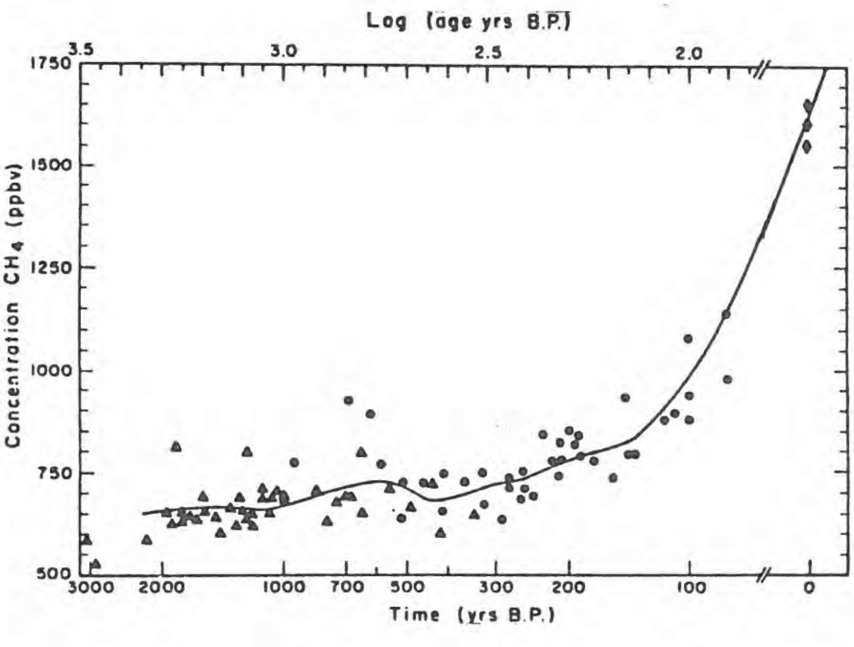


Figure 6-8.B Methane Concentrations from Glacier Ice (Bolin, Döös, Jäger and Warrick, 1986).

atmospheric methane are not well-known; its residence time is relatively short (about 10 years) because it decomposes through chemical reactions with OH radicals. Natural sources of methane include ruminants, termites, oceans, wetlands and tundras; the latter two contributing anywhere between 80 to 180 million tons. The range for estimates of all natural sources of methane is, thus, within a very wide band of 160 to 380 million tons per year.

Table 6-3 Methane Emissions in Million Tons per Year.

Natural		Anthropogenic	
Wetland release:	60–100	Ruminants:	80–100
Termites etc:	5–100	Rice fields:	90–120
Ocean release:	5–15	Biomass burning:	3–120
Wild animals:	2–8	Solid waste:	30–80
Lakes release:	2–6	Methane leaks:	20 ?
Tundra release:	25–80	Coal Mining:	35
		Gas Use:	30–35

Data Sources: Döös (1989), Berger (1988) and Deutscher Bundestag (1988).

Table 6-3 shows that in comparison, the anthropogenic sources might be smaller and are estimated at 130 to more than 300 million tons. The largest single contribution is from rice fields (90 to more than 120 million tons). Additional sources are solid wastes, biomass burning and fossil fuels. All of these figures are very tentative and only give rough estimates. For comparison, current natural gas (methane) consumption comes up to around 1000 million tons annually worldwide. Fossil fuels together contribute in comparison somewhere between 30 and more than 70 million tons per year to total methane emissions. The measurements of the isotopic ratios of atmospheric methane indicate that up to a third may be due to abiogenic sources (Lowe *et al.*, 1988). There are four major classes of potential sources of abiogenic methane concentrations: coal mining and methane leaks from coal beds; oil and natural gas production, gas flaring and venting; leakage during natural gas transport, conversion and end-use; and seepage and leaks of deep gas through the earth's crust. The first three of these sources have definitely contributed toward increased concentrations, though the uncertainty in determining their shares in total annual emissions is large. Even greater uncertainty surrounds the quantities leaked from the earth's crust (see the discussion on fossil energy resources in Chapter 3). Estimates of methane emissions associated with natural gas use range between 30 to more than 35 million tons per year, while the methane emissions from coal beds contribute another 35 million tons annually. With a warming climate methane emissions from permafrost clathrates, possibly the largest form of occurrences of methane in the upper layers of the earth's crust, are possible, but for the time being highly speculative (MacDonald, 1989).

Such methane emissions from permafrost ground could be one of the explaining factors in discrepancies in the isotopic ratios of atmospheric methane records that have puzzled researchers (Wahlen et al., 1989). Other explaining factors relate to the theory of existence of large amounts of abiogenic deep gas (discussed in chapter 3), the seepage of which could also contribute to distort presently estimated atmospheric methane budgets (Gold, 1988b).

Table 6-4 Composite Methane and Carbon Dioxide Greenhouse Effect of Fossil Fuels.

Fuel	CO_2		CH_4			Total	
	tC/Wyr[1]	DGE[2]	kg CH_4/Wyr	DGE[2]	ALG[3]	DGE[2]	ALG[3]
brown coal[4]	0.9	100	0	0	0	100	100
hard coal	0.7	82	6-11	16-30	2-3	98-112	84-85
oil[3]	0.5	71	0	0	0	71	71
gas[4]	0.4	46	14-16	36-42	4	82-88	50

1 Carbon emission factors are from Ausubel, Grübler and Nakićenović (1988).

2 Direct greenhouse effect compared to CO_2 emissions of brown coal (at moment of emittance), calculated as index equal to 100 for brown coal emissions of CO_2.

3 Average life cycle greenhouse effect (i.e., until destruction/absorption of emitted molecules). Index CO_2 emissions of brown coal equals 100.

4 Methane emissions of brown coal are assumed to be negligible.

5 Methane emissions from associated gas production of oil fields are included in gas.

6 Methane emissions from associated gas are included. No data on gas production from oil and gas fields exist on a global basis. Some estimates can be made for 1976 where some 30 percent of natural gas consumed was a byproduct from oil production. In attributing 30 percent of the global methane emissions of oil and gas production and consumption to oil (i.e., some 10 million tons CH_4), resulting methane emissions associated with oil production would be between 2.0-2.3 kg CH_4/Wyr oil. This would add an estimated 5-6 DGE index points to oil and would subtract 11-13 DGE index points from gas (asymmetry is due to the different levels of global oil and gas production in the denominator for a given numerator). The total DGE values for oil and gas with 76-77 and 71-75 index points, respectively, would then become very similar. The index would become 72 and 49 for the total lifetime ALG factor for oil and gas, respectively, under such an accounting assumption.

In order to evaluate the relative contribution to the greenhouse effect of different fossil fuels it is necessary to estimate the composite methane and carbon dioxide greenhouse effect. This is possible because the two gases absorb the infrared radiation over different spectra, so that their total effect is additive. Table 6-4 gives the estimates using the data given by Deutscher Bundestag (1988), and shows that despite the relatively high greenhouse effect of methane compared to carbon dioxide, natural gas is still the most benign fossil energy source, especially when considering the climatic effects over the whole residence time of CO_2 and CH_4 in the atmosphere (ALG index). The relative ranking of different fossil fuels including methane emissions is, thus, from their cumulative climate impact not significantly different from the ranking based on the CO_2 emissions alone.

The CO_2 advantages of inter fuel substitution in direction of natural gas emerging from our above discussion of gas intensive scenarios and from Table 6-4 are, thus, robust even when methane emissions are included in the analysis. For instance, the atmospheric CO_2 concentration of the two gas intensive scenarios presented above (below 450 and 600 ppm by 2100, as shown in Figure 6-7), would increase only by an equivalent of 10 percent, when also methane emissions are included in the calculation (Victor, 1989). If other greenhouse gases (CO and N_2O) are also considered, the relative greenhouse effect advantage of natural gas over other fossil fuels becomes even more eminent. As discussed above, the CO emissions of oil use (competing for OH radicals and lowering, thus, the methane destruction rate in the atmosphere) would increase the greenhouse impact of oil, whereas the emissions of fossil N_2O (mainly from coal combustion) as discussed below, would further deteriorate the relative position of coal with respect to its climate impact.

The most important ones of the greenhouse gases not discussed so far are ozone, nitrous oxide (N_2O) and chlorofluorocarbons.

The major sources of tropospheric nitrous oxide are quite uncertain but they include the use of fertilizers, biomass burning, coal combustion and uses of other fuels, for example in motor vehicles. Table 6-5 gives a summary of major sources of atmospheric N_2O. Since a large share of fossil nitrous oxide emissions is due to coal combustion, this makes the combined greenhouse effect of coal even worse, in addition of the much higher greenhouse effect of coal due to carbon dioxide and methane emissions (see Haw *et al.*, 1987). Figure 6-9 shows the estimated increase of emissions of N_2O during the last hundred years. The upward trend of emissions increased from about 0.1 percent per year at the beginning of the century to about 1.3 percent per year during the last decade, primarily due to increasing emissions from fertilizer applications and combustion of fossil fuels (Bolin, Döös, Jäger and Warrick, 1986). Given the long residence time of more than 150

Table 6-5 Nitrous Oxide (N_2O) Emissions in Million Tons of Nitrogen per Year.

Natural		Anthropogenic	
Soils release:	6.5 ± 3.5	Fossil fuels (mostly coal):	4.0 ± 1.0
Ocean release:	2.0 ± 1.0	Cultivated soils:	1.5 ± 0.5
Lightning:	< 0.1	Fertilizers:	0.8 ± 0.2
		Biomass burning:	0.7 ± 0.2

Source: Döös (1989).

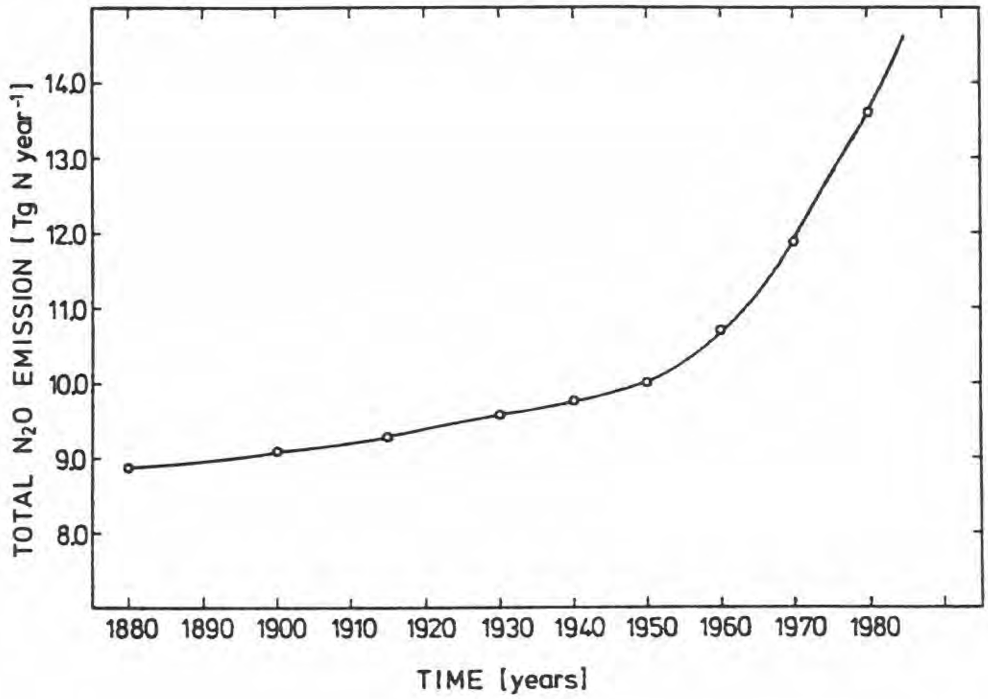


Figure 6-9 Nitrous Oxide, (N_2O) Emissions in Million Tons of Nitrogen (Bolin, Döös, Jäger and Warrick, 1986).

years (see Table 6-2 above), the estimated emissions from Figure 6-9 would imply an annual increase rate of about 0.3 percent which is considerably lower than that of methane. In fact, a secular increase of tropospheric nitrous oxide abundance has been observed in this range. Thus, the nitrous oxide atmospheric concentrations have increased by some 50 percent since the beginning of the Industrial Revolution. The current concentrations are relatively low at approximately 0.31 ppm, but N_2O has a much higher relative greenhouse effect compared with carbon dioxide. Thus, it contributes with about 4 percent toward the overall greenhouse effect. Furthermore, emissions of other nitrogen based effluents, nitrogen oxides (NO_x) and NH_3, are hold responsible for adverse environmental impacts on a regional scale, as discussed in Chapter 6.3 below.

Table 6-6 Anthropogenic Chlorofluorocarbon Emissions in Million Tons per Year and Use in Percent.

	CFC 11	CFC 12
Production (in 10^6Tons/yr)	0.33	0.44
Uses (in %):		
Refrigeration:	8	49
Aerosol propellant:	31	32
Closed cell foams:	36	8
Open cell foams:	19	5
Other:	6	6

Source: Döös (1989).

Chlorofluorocarbons are currently the most important halocarbons present in the atmosphere. They were introduced for the first time in the atmosphere during this century and are entirely of anthropogenic origin. Their presence was detected in the early 1970s which caught considerable attention because they are a possible source for chlorine in the stratosphere and accordingly a possible threat to the ozone layer (Bolin, Döös, Jäger and Warrick, 1986). The depletion of ozone, a greenhouse gas, could have adverse effects for life on earth because of its ability to absorb the ultraviolet radiation of incoming sunlight which causes cancer in humans and other organisms.

The most common chlorofluorocarbons in the atmosphere are CFC 11 ($CFCl_3$) and CFC 12 (CF_2Cl_2), although, both have relatively low concentrations of about 0.2 and 0.3 ppb (parts per billion, see Table 6-2), respectively. As shown in Table 6-6, CFCs are produced for a variety of uses, such as solvents in the manufacture of foams, aerosol spray propellants and refrigeration fluids. Despite the low concentration levels, they are important greenhouse gases because they absorb infrared radiation almost 20 thousand

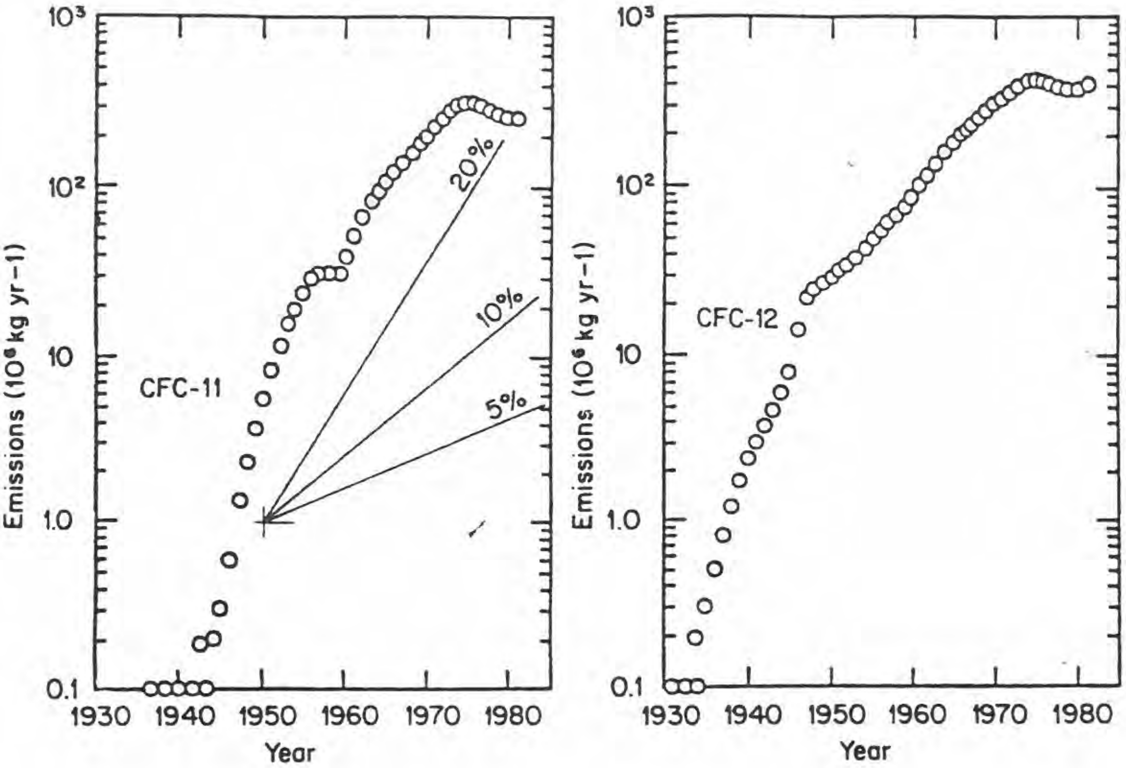


Figure 6-10 Chlorofluorocarbon Emissions in Thousand Tons per Year (Bolin, Döös, Jäger and Warrick, 1986).

times more effectively than carbon dioxide. Together they account for about 15 percent of the overall greenhouse effect. Figure 6-10 shows the increase of the CFC emissions since the 1930s along with three slopes in the left figure denoting annual increases of 5, 10 and 20 percent. A rapid increase, until about 1970, changed into a decline during the latter part of the 1970s, which was caused by restrictions on the use of CFCs introduced by some countries because of their possible threat to the ozone layer. It should be noted, however, that during this period the non-propellant use has continued to increase by about 4 percent per year. Consequently, a marked increase of the total use of CFCs has been reported for the following years. Following the international reduction plans agreed upon CFC's production and consumption (Montreal Protocol) future emission rates will be reduced significantly. In view of the long residence times of CFC's in the atmosphere (see Table 6-2) of 65 to 110 years, several decades are required, however, before a noticeable decrease in the atmospheric concentration of CFC's will set in.

6.2.4. Global Warming

We have shown that a great deal is still unknown about the concentrations of greenhouse gases in the atmosphere and that the uncertainties on their future evolution are very large. What is certain, however, is that the increasing concentrations of these gases will alter the earth's energy balance and could, thus, lead to climatic changes and an increase in average temperature. What is not known is the precise amount of warming and the regional pattern of climatic change that can be expected on the earth from a significant increase in the atmospheric concentrations of greenhouse gases. It is this regional pattern of changes in temperature, precipitation and soil moisture that will determine what impact the greenhouse effect will have on ecosystems, agriculture, water supplies, and our civilization in general (Schneider, 1987). Furthermore, the projections of likely future atmospheric greenhouse gas concentrations are very uncertain, as their generation, circulation, and destruction in the atmosphere are not yet sufficiently understood, and the way man will disturb these natural cycles in the future cannot be predicted very precisely. (Bolle, Seiler and Bolin, 1988; Bolin, Döös, Jäger and Warrick, 1986).

Due to all these numerous uncertainties associated with the natural and anthropogenic sources of atmospheric greenhouse gases, their sinks and, most importantly, the effects of increasing concentrations on the earth's climate, it is not yet possible to prove convincingly that the climate change is only driven by natural causes. Döös argues that any strategy for response to the ongoing change of the global climate, caused by the increasing atmospheric concentrations of radiatively active trace gases associated with human activities, cannot be treated in isolation from other environmental issues; it is closely interrelated to problems of depletion of the stratospheric ozone layer, acidification of soils and lakes, and tropical deforestation (Döös, 1989).

The observed general increase of the mean global surface temperature over the last century provides a strong indication of a "greenhouse signal" (Döös, 1989). It is compatible with model results and corresponds to the analogous increases of most important greenhouse gases – carbon dioxide and methane. Figure 6-11 illustrates the extent of global warming during the last hundred years by showing the variation in time of the global mean annual surface temperature observed from land and marine temperature records (Hansen, 1986).

Results from climatic models suggest that global average surface temperatures will increase by some 2^o to 6^oC during the next century (Schneider, 1989). These results are based on various scenarios projecting the future emissions of greenhouse gases. Figure 6-12 gives the calculated

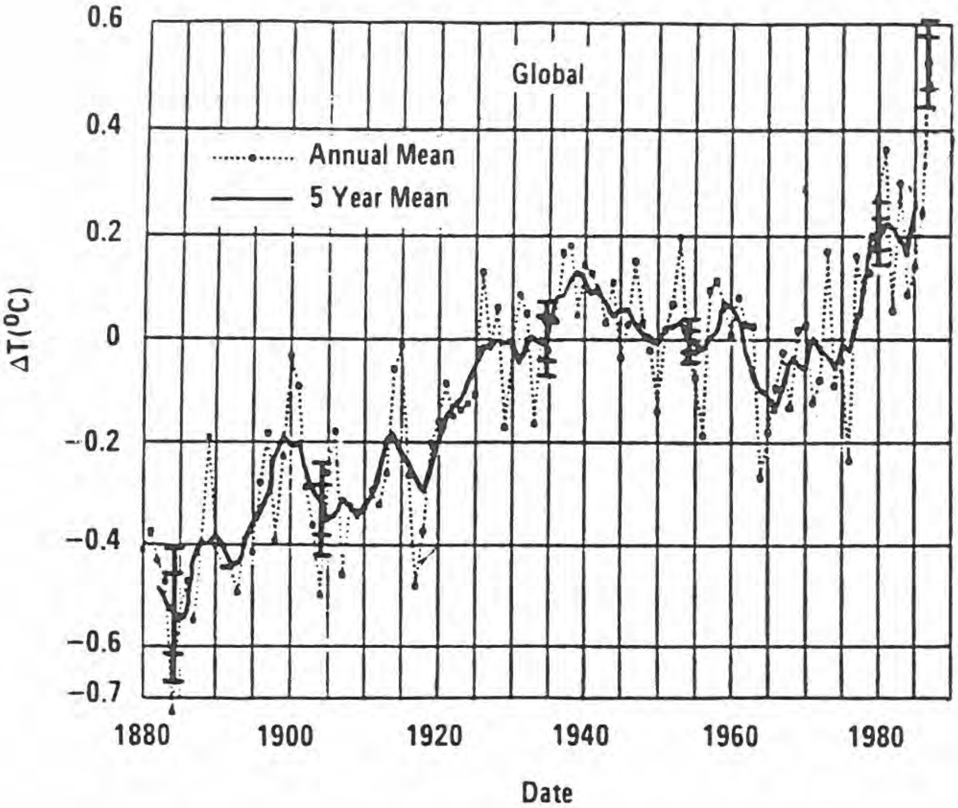


Figure 6-11 Variation of Global Mean Surface Temperature (Hansen, 1986).

values of the increase of the mean annual surface temperature from two hundred years ago up to the middle of the next century (Wigley, 1987). Calculations are based on estimated future greenhouse gas concentration increases. The range between the two projections represents the degree of uncertainty inherent in climate models. Despite the fact that the estimates of present and future effects have significant uncertainties, these results are extremely useful for understanding the scale and extent of human interference with future climatic changes. Most of these results indicate that the doubling of the carbon dioxide concentrations alone, without considering the composite effect of all other greenhouse gases, would increase the average global temperatures somewhere between 1.5 and perhaps up to 5°C. We have seen that even very efficient use of energy in the future could still lead to carbon dioxide increases in this range.

The average temperature change of a few degrees could have catastrophic effects due to very large climatic and other environmental changes. It should be noted that during the geological time, equivalent temperature changes were associated with very large changes in climatic conditions. A few degrees warmer climate led to tropical conditions in high latitudes and a

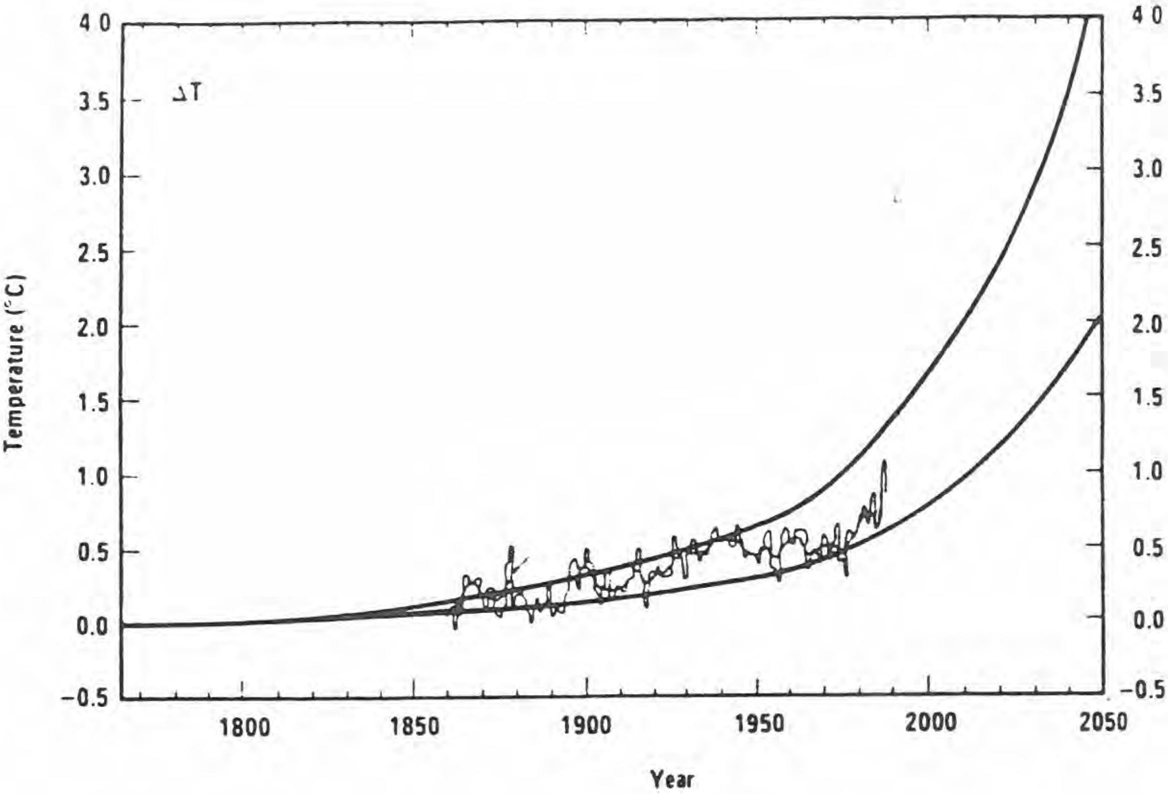


Figure 6-12 Calculated Global Mean Surface Temperature (Wigley, 1987).

few degrees colder climate to conditions that dominated 20 thousand years ago during the last Ice Age.

It is estimated that the global climate warming would lead to a rise in the sea level due to the melting of glaciers and polar caps and also due to the thermal expansion of the upper ocean layers. It is estimated empirically that the average temperature increase in the range of 1.5 to 5.5°C could lead to a eustatic sea level rise of about 25 to 165cm (Bolin, Döös, Jäger and Warrick, 1986). Further impacts of global warming would range from direct effects of rising carbon dioxide concentrations on increasing the plant growth to indirect effects of climatic changes. More important than the average temperature increase is the possibility that the global warming would cause a higher variability of climate. Thus, rather than focus on global averages we need to better understand regional distribution, variability and evolving patterns of climatic and weather change that could result from an altered radiation balance of the planet. However, these questions cannot be conclusively answered with the current climatic models.

Environmental impacts with possible effects at a global scale include, in particular, increases in atmospheric CO_2 emissions and the depletion of tropospheric ozone levels. Whilst, the future emission paths, as well as the size and type of possible impacts on the global environment are highly uncertain, one can, nevertheless, identify particular energy options resulting in lower emission levels. With respect to CO_2 emissions these energy options include a reduction of the overall level of energy consumption due to efficiency improvements and conservation, as well as the gradual shift to low CO_2 emitting fuels, such as natural gas or non-carbon based energy sources, such as nuclear, solar, and other renewables based on a sustainable exploitation.

Altogether there are three possible responses to global warming (Schneider, 1988):

1. The engineering countermeasures to minimize the potential impacts of climate change, such as the building of dams to avoid flooding from sea level rise or deliberately changing the albedo of the atmosphere to reduce the incoming radiation (by spraying reflective particles). Due to the high risks of other environmental consequences and unintentional effects of such measures they do not appear to be very likely in the foreseeable future.
2. Adaptive responses to climatic change might include migration from affected regions to those where more favorable climatic conditions continue to prevail. Other responses might include changing agricultural and other activities to adapt to new climatic conditions. In view of the fact that it takes decades to establish new settlement patterns and to build new infrastructures, it is not likely that such an adaptation process could be initiated before it is definitely known which regions might be affected by climatic change and how. However, by that time it might also be too late to respond by using adaptive strategies.
3. Prevention or postponement of climatic warming by avoiding further increase of anthropogenic sources of greenhouse gases appears to be the most attractive alternative. These measures could include the replacement of CFCs and other ozone reducing substances by other alternatives, improvements in energy efficiency, substantial reductions of coal use by more vigorous introduction of alternative energy sources and natural gas as a bridge to a non-carbon based energy supply and finally carbon dioxide removal.

In IIASA's proposed study on climatic change the following strategies are envisaged for reducing greenhouse gas emissions and thereby delaying climatic change (Döös, 1989):

1. Identification of the numerous available opportunities to reduce the emission of greenhouse gases using existing and new technologies. The different categories of emission reductions will include:
    a. Energy (reduction of CO_2, CH_4, N_2O).
        - Technological measures: improvement of energy efficiency and conservation, expanded use of alternative energy sources, etc.
        - Policy measures: introduction of emission taxes, promotion of nuclear energy production, replacement of coal and oil by natural gas, etc.

    b. Acceleration of the reduction of the use of chlorofluorocarbons (CFCs) initiated by the international agreement on the reduction of gases that deplete the stratospheric ozone layer (the Montreal Protocol 1987).

    c. Reduction of carbon dioxide emissions by reducing and reversing the ongoing rapid rate of deforestation in the tropics.

    d. Reduction of emissions of CH_4 and N_2O through improved agricultural practices.

2. For each one of the identified opportunities the following characteristics need to be evaluated:
    a. Realistic rate of implementation expressed in the reduction of the emission of the greenhouse gas(es).

    b. Financial investments required for the implementation as a function of time.

    c. Resulting rate of reduction of the increased atmospheric concentration of these gases taking into account their residence times in the atmosphere.

    e. Resulting delay of climatic change.

3. Based on this information, evaluated for the individual measures, various optimum combinations of measures can be designed by taking into account a number of "boundary conditions", e.g.,
    a. the effect of overlapping absorption bands of the greenhouse gases, implying a reduction of the efficiency of certain combinations of measures;

    b. the risk for health and safety connected with the implementation of certain measures;

c. certain measures may have undesirable impacts on the environment;

d. the desirability to implement certain measures for reducing greenhouse gas emissions in view of their positive effect on other environmental problems (e.g., acid deposition, tropical deforestation and stratospheric ozone destruction);

e. the feasibility of implementation of measures varies radically from country to country, and on a regional level.

6.3. Regional and Local Impacts

Human activities have not only increased concentration of greenhouse gases in the atmosphere, but have added enormously to the atmospheric burden of many chemical substances and particulate concentrations. The increasing abundance of many of these constituents of the atmosphere can have far-reaching consequences for the environment. In contrast to possible consequences of global warming, the increased abundance of nitrogen and sulfur compounds have a more immediate impact. Evidence of this impact is very clear, for instance, in the case of "acid rain" that results from dry and wet deposition of sulfur and nitrogen based effluents and their transformation products.

According to Mohnen (1988), acid rain is a direct consequence of the atmosphere's self-cleansing nature. The tiny droplets of water that make up clouds continuously capture suspended particles and soluble trace gases. When precipitation coalesces from cloud water, it washes the impurities out of the atmosphere. This is the same mechanism that removes some other trace gases and not only nitrogen and sulfur compounds. However, not all atmospheric trace gases can be removed in that way, sulfur dioxide (SO_2) and oxides of nitrogen (NO_x) emitted into the atmosphere are chemically converted into forms that are readily incorporated into cloud droplets to result in sulfuric and nitric acids. Acid rain can fall hundreds of kilometers from the original pollution source. Thus, acid rain is an international problem extending over the continent, but not over a global scale as is the case with greenhouse gases. Rainwater that contains dilute sulfuric and nitric acids undergoes a number of chemical and physical alterations in the ground. The acid can be retained or buffered in the soil or it can reach streams and lakes affecting their chemistry.

Regional environmental impacts of acid rain were first noticed in the 1960s, although, the local impacts have been known since the beginning of the coal era. Most of the regionally established and suspected impacts concern the biological death of many lakes in Europe and North America, as well as the drastic decline in the vitality of forests, the so-called *Waldsterben*. Acid rain also contributes to contamination of groundwater, degradation of buildings and other structures and most recently contamination of coastal waters (North Sea and North Adriatic).

Regional environmental impacts stem from the emission of sulfur dioxide, nitrogen oxides, VOC's (volatile organic compounds), and ozone which are related to energy use, but also (although to a lesser extent) by ammonia emissions from overfertilization in agriculture and intensive stock farming. Energy related emissions are sulfur dioxide (SO_2, nitrogen oxides (NO_x), carbon monoxide (CO), VOC's and (via transformation) ozone. Sulfur dioxide is emitted in combustion of coal and most oil products with sulfur content (such as fuel oils). Nitrogen oxides are emitted during all combustion processes, such as high-temperature combustion of fossil fuels in power plants, or prime movers, such as automobile engines and gas turbines (jet engines). Carbon monoxide is produced in all combustion processes, be them from stationary or mobile sources. The latter are also the main sources of emissions of VOC's. In this context it has to be noted that, contrary to the ozone depletion at high altitudes (stratosphere) discussed as environmental problem at a global scale, ozone concentrations at the lower levels of the atmosphere, closer to the earth surface have adverse environmental impacts. Therefore, a distinction is made between "good" ozone (i.e., at high altitudes in the stratosphere) and "bad" ozone at altitudes close to the earth surface.

Of the energy related emissions with environmental impacts at the regional level, sulfur dioxide and nitrogen oxides have been studied most, as they are hold principally responsible for the "acid rain" effects on terrestrial and aquatic ecosystems.

Emissions of SO_2 and NO_x have possible environmental impacts at a meso scale, ranging from the country level to the continental scale. With increasing scale, scientific uncertainty about the types, causes and consequences of adverse environmental impacts of emissions becomes larger. On the local scale, the negative effects of high concentrations of SO_2 and NO_x are sufficiently well documented and have resulted in corresponding maximum emission concentration standards in practically all industrialized countries. In contrast, uncertainty still remains with respect to type and scale of impacts of emission depositions resulting from transboundary air pollution. On the one hand, examples of quantitative assessments of transboundary SO_2 emissions and depositions (e.g., EMEP or the IIASA RAINS Model) illustrate that the state-of-the-art of models in this area is already relatively highly developed. On the other hand, regional environmental impact models are still in their early phase of development.

Environmental effects of energy consumption at the local and regional scale stem, thus, primarily from the emission of particulates, sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and VOC's, among others. These emissions are a function of the conversion process deployed (e.g., whether oil is fired in a power plant or used to fuel an internal combustion engine) and are also a function of the quality of the energy carrier (e.g. hydroelectricity and nuclear energy produce no emissions at all, coal combustion results in particulate emissions, while natural gas use does not), the widely different quality grades of energy carriers (e.g. the sulfur content in coal or in oil products), and whether appropriate abatement technologies are used in energy conversion facilities (desulfurization units, catalytic converters, etc.). The environmental control technologies deployed for retention of these emissions can be either implemented at central conversion facilities such as refineries or power plants (electrostatic precipitators for particulate removal, scrubbers and DENOX-units to remove SO_2 and NO_x) or at the final consumers (e.g. catalytic converters in automobiles). As a rule, stringent emission standards and faster implementation of control measures are more likely in large, central conversion units than at the final consumer. Therefore, grid dependent energy carriers such as district heat, natural gas, and electricity are instrumental for reducing ambient concentrations of pollutants in densely populated areas.

6.3.1. Environmental Standards

Emissions of Particulates, SO_2 and NO_x and other substances can have adverse impacts on human health and on the environment ranging from the local (e.g. urban smog) level to impacts at a meso scale (from regional and national to continental scales). Scientific uncertainty about the types and causes of negative environmental impacts of emissions is increasing with spatial scale. At the local scale the negative effects of high concentrations of emissions such as particulates, SO_2, NO_x, etc., are sufficiently well documented and have resulted in corresponding maximum permissible ground level concentration standards in practically all countries. Adverse environmental impacts at a higher spatial scale are also increasingly recognized. International agreements, such as the Geneva Convention on Long-range Transboundary Air Pollution of 1979, call on a significant reduction of emissions such as SO_2, in order to reduce depositions of atmospheric pollutants stemming from transboundary flows of emissions.

Frequently one distinguishes two types of impacts of anthropogenic emissions: *"direct"* local impacts, caused by high ambient concentrations of pollutants at a local or regional scale and *"indirect"* impacts, which result from long-range atmospheric transport of emissions and as a result of complex chemical transformations of pollutants during atmospheric residence times.

As an example of direct impacts, one can mention the adverse effects of high ambient SO_2 concentrations on human health and on vegetation (vegetation damage due to high local SO_2 concentration have been documented already in the 19th century). Finally, increased corrosion rates and damage to historical buildings and landmarks have to be mentioned; in this case sandstone is particularly vulnerable (carbonates transformed through the influence of sulphuric acid to sulphates, which are washed out by rain, leading to "defacing" and ultimate destruction of sandstone sculptures and buildings). In order to minimize these direct adverse effects, different maximum emission concentration values have been introduced in most countries. Table 6-7 gives an overview of maximum permissible ground level concentrations for a number of countries (WEC, 1988).

Table 6-7 Maximum Permissible Sulfur Dioxide Ground Level Concentrations (WEC, 1988).

Pollutant	measured as	FRG, IW1 /209/	Switzerland [4] /214/	Spain[1]	China[3] /215/	USSR	USA
Particulates		150	70	300	500	150	75
Lead in Particulates	(Pb)	2	1	100[2]	-	0.7	-
Cadmium in Particulates	(Cd)	0.04	0.01	-	-	-	-
Chlorine	(Cl)	100	5)	50	-	-	-
Chloral hydrate (HCl)	(Cl)	100	5)	50	-	200	-
Fluor	(F)	-	5)	20	-	-	-
Fluor compounds	(F)	1	5)	10	-	0.5	-
Carbon monoxide	(CO)	10,000	8000	15,000[2]	6000	1000	10,000
Sulphur dioxide	(SO_2)	140	30	400	250	50	80
Nitrogen dioxide	(NO_2)	80	30	200	150	85	100
Benz(a)pyrene	($C_{20}H_{12}$)	-	5)	-	-	0.001	-
Formaldehyde	(HCOH)	-	5)	-	-	12	-
Benzene	(C_6H_6)	-	5)	-	-	800	-
Photochemical Oxidants	(O_3)	-	100[6]	-	-	-	160
Non-CH_4 Hydrocarbons		-	5)	-	-	-	160

Due to the policy decision to allow the construction of high stacks (i.e., reducing ambient concentrations not by reduction of emissions but by their dispersion), direct impacts at the local level have increasingly been replaced by indirect impacts, due to depositions of imported emissions and their transformed products. As a prime example of such indirect impacts, one can mention the effects of "acid deposition" on aquatic and terrestrial ecosystems. Table 6-8 presents an aggregate geographical breakdown of sulfur dioxide, nitrogen oxides and ammonia emissions, the principle effluents causing acid rain in Europe.

The emissions of SO_2 presently amount to some 53 million tons (SO_2) annually and have increased slightly (by 11%) since 1970. Over this time period the regional breakdown of SO_2 emissions has, however, changed drastically. Sulfur emissions of Western Europe have, due to control and abatement measures, decreased by 40 percent (from 20.6 to 12.5×10^6 tons SO_2/year) between 1970 and 1985. As a result Western Europe's share in the total sulfur emissions decreased from 43 percent of the total European sulfur emissions to less than 24 percent. This decrease was, however, more than compensated by increasing sulfur emissions, in particular in Southern Europe, the European USSR, and Eastern Europe with increases of emission levels since 1970, of 73, 61, and 33 percent, respectively.

Table 6-8 Emissions of SO_2, NO_x, and NH_3 Per Broad Geographical Region in Europe, in 1985 (1980 for NO_x), in Million Tons

	SO_2 (as SO_2)	NO_x (as NO_2)	NH_3 (as N)
Western EU	12.5	11.2	2.5
Southern EU	5.1	1.8	0.9
Eastern EU	17.9	4.9	1.5
European USSR	17.5	9.6	2.6
Europe	53.0	27.5	7.5

Source: UN-ECE (1988), EMEP (1988) and IIASA Transboundary Air Pollution Project (1989)

The situation with respect to nitrogen based emissions is to some degree different. NO_x and NH_3 account for nearly equal amounts of nitrogen emissions (if calculated as emitted nitrogen) with 8.4 and 7.5 million tons N, respectively. Contrary to SO_2 emissions, Western Europe is a dominant contributor, accounting for 41 percent of the NO_x emissions and 33 percent of the ammonia emissions, with the other regions accounting each for a smaller quantity than Western Europe. The larger contribution of

Western Europe is explained by the higher automobile ownership and usage levels compared to other regions and that until very recently no NO_x emission reduction measures have been taken at a significant level.

The depositional pattern of emissions is, however, remarkably different from the regional distribution of emissions discussed above. The importance of transboundary air pollution is probably best illustrated with respect to the situation of sulfur emissions and deposition in Europe and North America. According to the source-receptor matrix of sulfur emissions/depositions developed by Eliassen and Saltbones (1983) for the year 1980, one can conclude that out of the total 23.8 million tons sulfur (calculated as tons 5) deposited in Europe (including the European USSR) in 1980, 13.2 million tons (55 percent) originated from countries outside the recipient area. Only 45 percent of the total sulfur depositions resulted from national sulfur emissions. Depending on geographical location and predominant wind direction, the rate of (net) export or import and the relation between sulfur emissions and depositions can differ widely between different countries. Figures 6-13.A and 6-13.B illustrate the spatial sulfur emission and deposition patterns in Europe.

Figures 6-14.A and 6-14.B provide at a higher degree of spatial resolution the deposition pattern of sulfur and nitrogen emissions of Europe. From above figures the high sulfur emissions and depositions of heavily industrialized areas and in particular the coal producing regions become apparent. Highest sulfur emissions and depositions are all located in coal provinces, such as Middle-England, the triangle of Northern Czechoslovakia-Poland - GDR, and the Moscow and Donetsk coal basins in the USSR. Low depositional values, however, do not necessarily imply low environmental impacts. The possible effects are a non-linear function of (cumulative) deposition that depends on various properties like soil buffering capacity, which is particularly low in Scandinavian countries. For Nitrogen deposition patterns the highest depositions are observed in central Europe with deposition values decreasing towards the peripheral areas of Europe.

The indirect (i.e., not local) effects of acidic deposition resulting from transboundary flows of SO_2 and NO_x emissions and their transformations formed during atmospheric transport, have received increased attention over the last 10 years due to consequences, such as lake acidification in Scandinavia, resulting reduction in fish population (Swedish Ministry of Agriculture, 1982), and the so-called *Waldsterben* (e.g., Last *et al.*, 1984). Local negative environmental effects on soil and water, chemistry and biology do not only result from (dry) deposition of sulfur dioxide and nitrogen oxides, but also from wet deposition of transformed products (via sulphuric and nitric acid, hydrogen (H^-), ammonium (NH_4^-), nitrate (NO_3^-), and

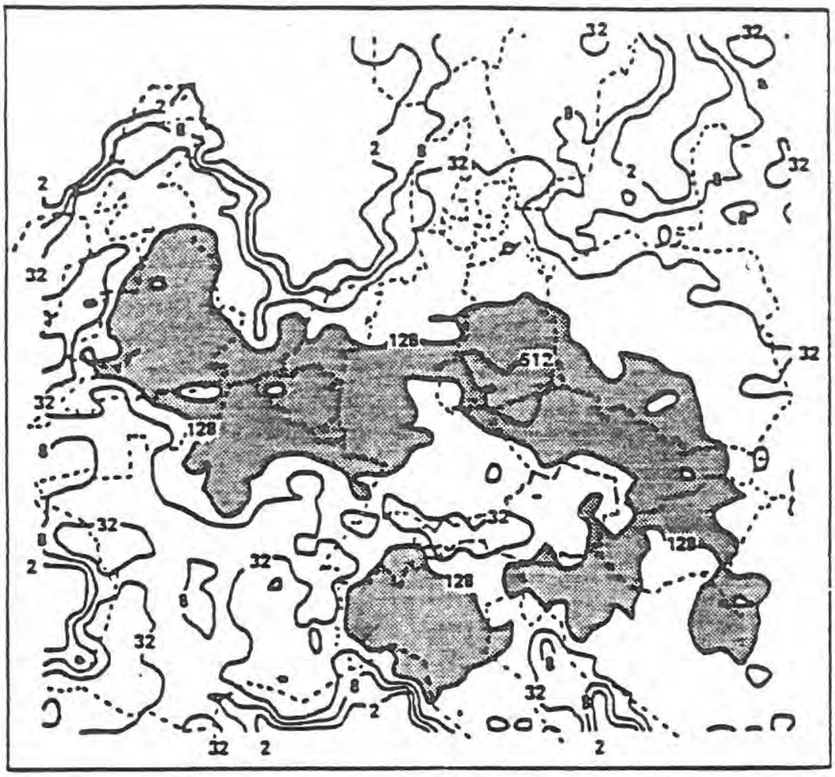


Figure 6-13.A Spatial Sulfur Emission Density in Europe in 1978, in 100 kg SO_2 per km^2 (Deutscher Bundestag, 1983).

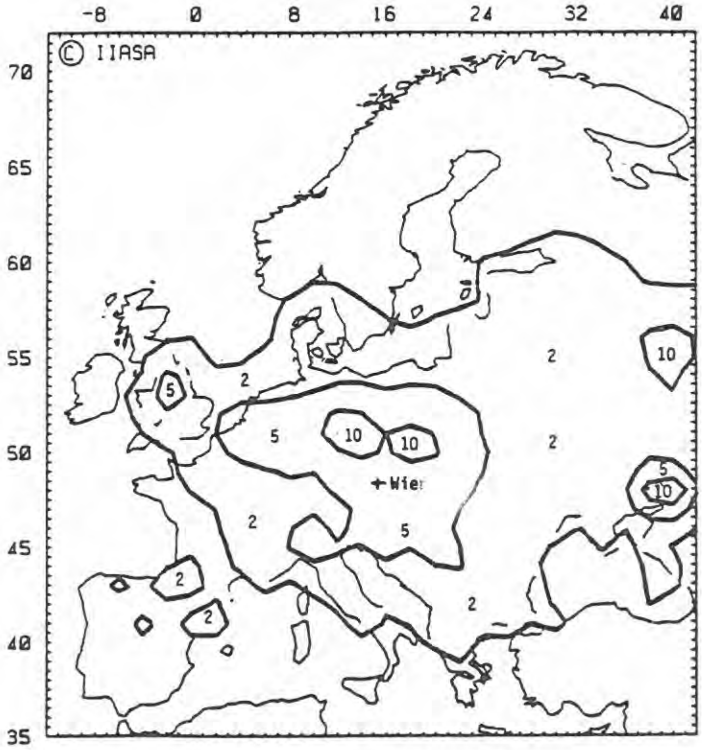


Figure 6-13.B Sulfur Deposition in Europe in 1980, in isolines of grams sulfur per m^2 (IIASA Acid Rain Project, based on UN-ECE/EMEP model).

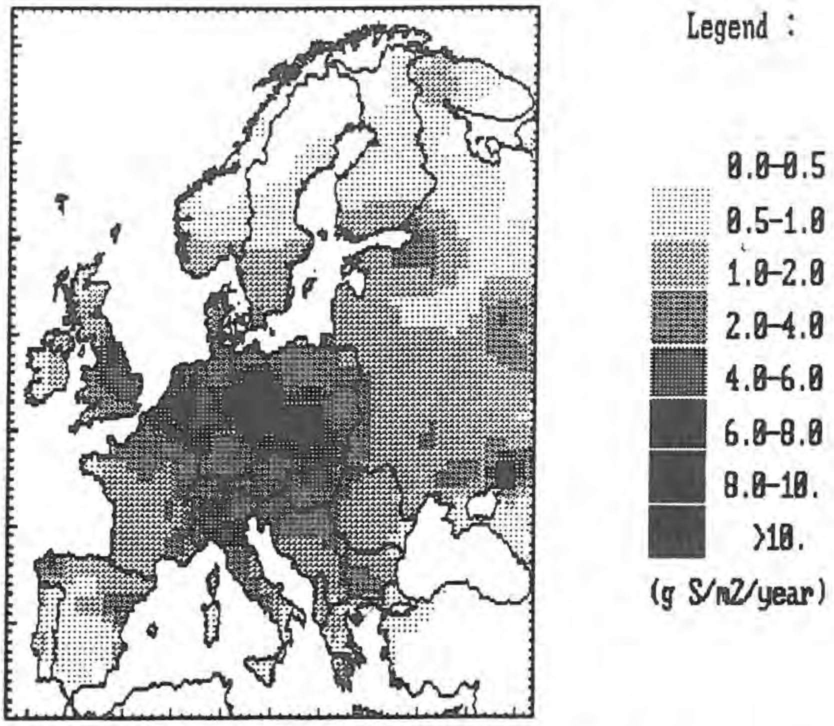


Figure 6-14.A Sulfur Deposition Pattern in Europe in 1980, in grams S/m^2/year (IIASA, Transboundary Air Pollution Project, 1989)

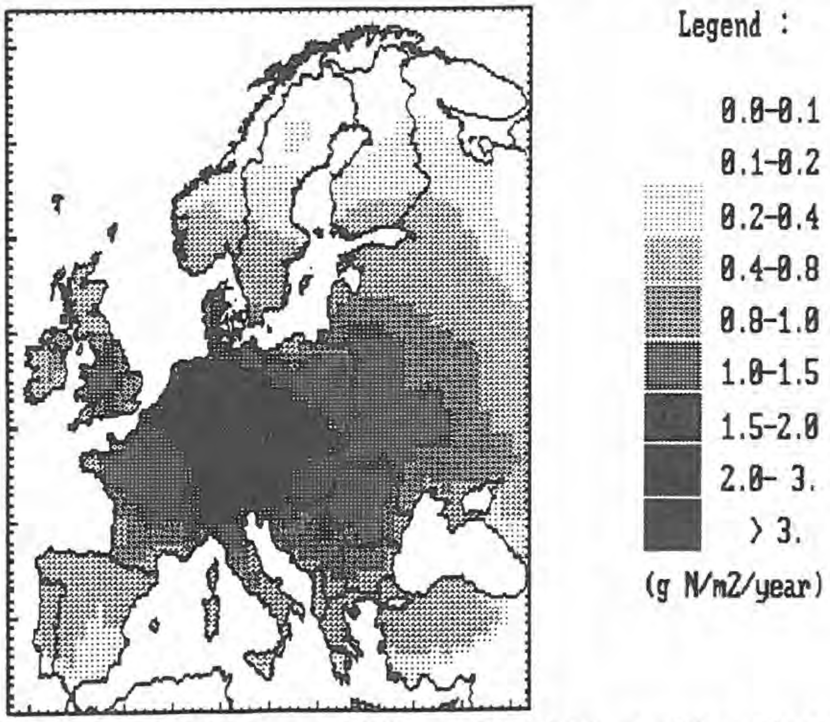


Figure 6-14.B Total Nitrogen (NO_x + NH_3) Deposition Pattern in Europe in 1980, in grams N/m^2/year (IIASA, Transboundary Air Pollution Project, 1989)

sulphate (SO_4^-) ions are formed and deposited with rain, fog, or snow). In addition, secondary pollutants (in particular ozone) generated from nitrogen oxides in presence of hydrocarbons are considered as critical additional factors responsible for adverse effects on vegetation.

Further reductions, particularly of SO_2 and NO_x emissions, beyond currently agreed reduction plans are, thus, necessary. Especially emission reductions in Eastern Europe, are required to improve decisively the environmental situation in Eastern Europe and those regions of Western Europe affected by long-range transport of pollutants. The different degrees to which reduction measures have been implemented already in the past (i.e., exhausting the cheapest reduction potentials), as well as the complex interdependencies resulting from the long-range air circulation, call for a revision of traditional emission reduction policies. Based on the results of IIASA's RAINS (Regional Acidification Information and Simulation Model, Alcamo *et al.*, 1987) model, the environmental and economic benefits of a move away from traditional flat rate reduction, to a system of targeted reduction agreements, have been demonstrated (Shaw, 1989).

Figure 6-15.A illustrates the differences in costs incurred in reducing national SO_2 emission levels on the basis of the FRG and the GDR. It can be shown that, in case of the FRG, reduction of national *deposition* would be cheaper to achieve in investing in reduction of sulfur emissions abroad. Such targeted optimized reduction plans could enhance environmental benefits of a given sum of committed funds for sulfur reduction at least by a factor two at the European level (Shaw, 1989), and possibly by a larger factor in specific areas of Central Europe.

In a prominent IIASA study, Amann (1989) points out, that targeted emission reductions are also a necessary element to maximize environmental benefits and minimize economic costs of nitrogen emission reduction in Europe. The need for considering more complex reduction strategies beyond flat rate reduction policies, is illustrated in Figure 6-15.B showing different national cost curves for NO_x emission reduction in the FRG and the GDR. Thus, in order to reduce national environmental impacts (i.e., depositions) cost effective strategies will have to consider the different reduction cost profiles prevailing in different countries, as well as the long-range transport of pollutants. Such strategies, however, call for a new system of international negotiations and agreements, in addition to those signed thus far.

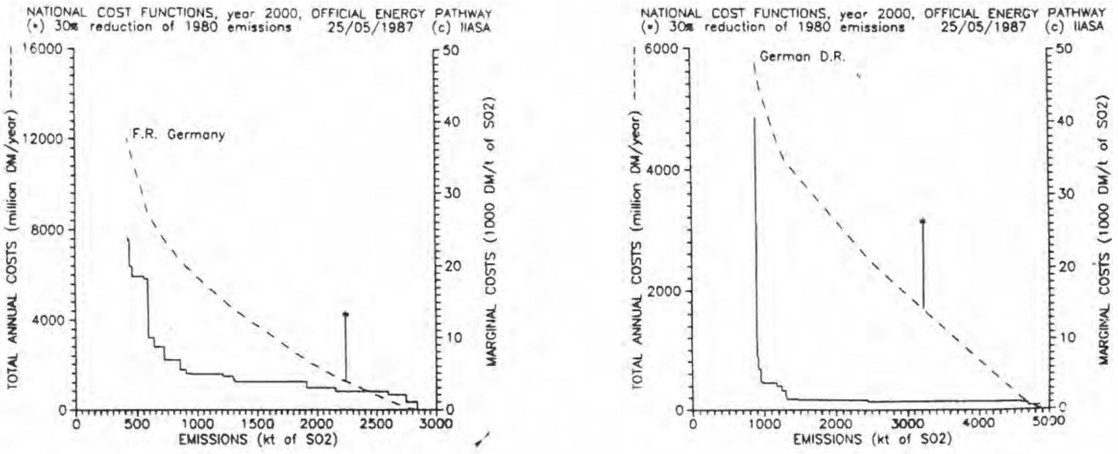


Figure 6-15.A Total and Marginal Sulfur Emission Reduction Cost Profile in the FRG and the GDR (Amann and Kornai, 1987)

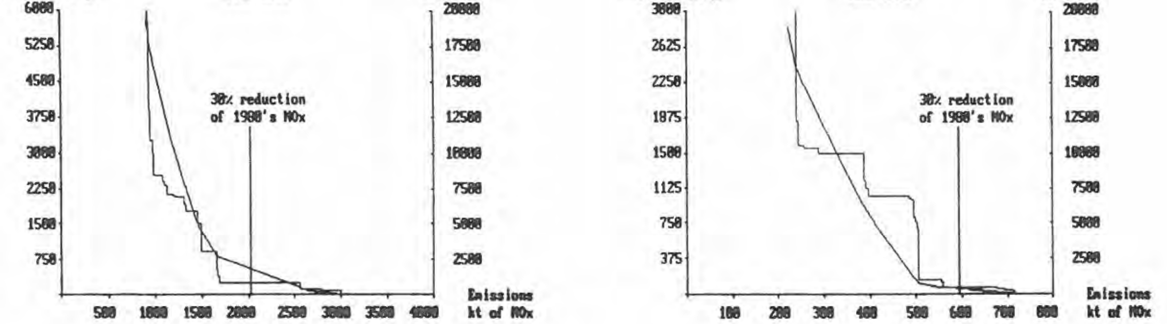
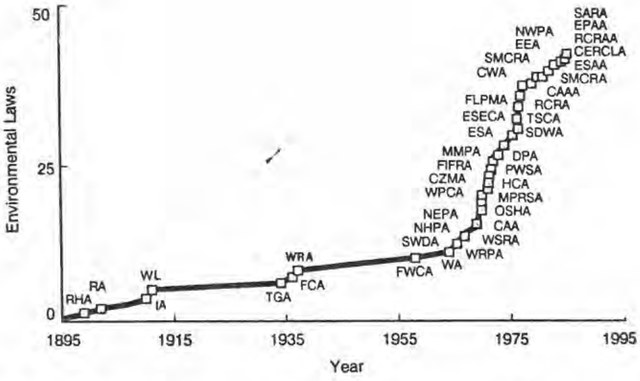


Figure 6-15.B Total and Marginal NO_x Emission Reduction Cost Profile in the FRG and the GDR (Amann, 1989)

6.3.2. Legal Regulation and International Agreements

Increasing awareness of the negative local and regional effects of emissions have led to increasing complexity of environmental legislation at the national level. Efforts to curtail emissions and to reduce transboundary air pollution have resulted in a number of international recommendations and agreements to reduce transboundary air pollution, in particular SO_2 and NO_x emissions. Figure 6-16 illustrates this increasing complexity in the environmental regulatory framework in case of the USA.



1899 - River and Harbors Act (RHA)
1902 - Reclamation Act (RA)
1910 - Insecticide Act (IA)
1911 - Weeks Law (WL)
1934 - Taylor Graring Act (TGA)
1937 - Flood Control Act (FCA)
1937 - Wildlife Restoration Act (WRA)
1958 - Fish and Wildlife Coordination Act (FWCA)
1964 - Wilderness Act (WA)
1965 - Solid Waste Disposal Act (SWDA)
1965 - Water Resources Planning Act (WRPA)
1966 - National Historic Preservation Act (NHPA)
1968 - Wild and Scenic Rivers Act (WSRA)
1969 - National Environmental Policy Act (NEPA)
1970 - Clean Air Act (CAA)
1970 - Occupational Safety and Health Act (OSHA)
1972 - Water Pollution Control Act (WPCA)
1972 - Marine Protection, Research and Sanctuaries Act (MPRSA)
1972 - Coastal Zone Management Act (CZMA)
1972 - Home Control Act (HCA)
1972 - Federal Insecticide, Fungicide and Rodenticide Act (FIFRA)
1972 - Parks and Waterways Safety Act (PWSA)
1972 - Marine Mammal Protection Act (MMPA)
1973 - Endangered Species Act (ESA)
1974 - Deepwater Port Act (DPA)
1974 - Safe Drinking Water Act (SDWA)
1974 - Energy Supply and Environmental Coordination Act (ESECA)
1976 - Toxic Substances Control Act (TSCA)
1976 - Federal Land Policy and Management Act (FLPMA)
1976 - Resource Conservation and Recovery Act (RCRA)
1977 - Clean Air Act Amendments (CAAA)
1977 - Clean Water Act (CWA)
1977 - Surface Mining Control and Reclamation Act (SMCRA)
1977 - Soil and Water Resources Conservation Act (SWRCA)
1978 - Endangered Species Act Amendments (ESAA)
1978 - Environmental Education Act (EEA)
1980 - Comprehensive Environmental Response Compensation and Liability Act (CERCLA)
1982 - Nuclear Waste Policy Act (NWPA)
1984 - Resource Conservation and Recovery Act Amendments (RCRAA)
1984 - Environmental Programs and Assistance Act (EPAA)
1986 - Safe Drinking Water Act Amendments (SDWAA)
1986 - Superfund Amendments and Reorganization Act (SARA)

Figure 6-16 Number of Environmental Laws in the USA Since the Turn of the Century (Lee and Loftness, 1987).

The growing tendency depicted in Figure 6-16 may, of course, only be indicative of the situation in other countries. Nevertheless, it becomes clear that this increasing regulatory complexity is, and will continue to be, a major force shaping the future of the energy system.

The environmental regulatory framework is developing progressively at the international level. The last decade has seen a number of major breakthroughs in international agreements, aimed at the reduction of transboundary pollution. Among these recommendations and agreements are:

- Declaration of the Conference of the United Nations on Human Environment (Stockholm, 1972)
- OECD Council Recommendation on Principles Concerning Transfrontier Pollution (1974)
- Convention on Long-range Transboundary Air Pollution (UN ECE, Geneva, 1979) and the two resulting Protocols to reduce SO_2 and NO_x emissions at the European level (Helsinki Protocol of 1985 and Sofia Protocol of 1988)
- Draft Rules on International Law on Transfrontier Pollution of the International Law Association (1980)
- Montreal Protocol on Substances that Deplete the Ozone Layer, coming into force on January 1, 1989.

In contrast to this increasing complexity of environmental legislation in and between industrialized countries, environmental legislation in developing countries is likely to lag behind that of developed countries, with a potential threat of relocation of high-emission production processes from the industrialized world to developing countries. At the same time higher energy use will adversely influence the delicate environmental balance in these countries. This will increase the need for more stringent control in developing countries and a shift to more environmentally benign technologies, which will certainly only be possible with increased financial assistance and technology transfer from developed countries.

7. IMPLICATIONS FOR THE FUTURE

7.1. General

The world has changed since the first global energy studies of the early 1970s. The myth of resource limits appears not to be valid anymore. After 15 years of international and global energy studies the emphasis has shifted from availability of oil and its price to overall environmental impacts of energy use and human activities in general.

There is really no conclusive way to predict the ultimate impacts of these changes and to assess accurately future energy needs, the structure of economic growth and prevailing efficiencies at which energy and other factor inputs will be used. This is the reason why a scenario approach is often used to derive some aggregate indicators of future energy use and efficiency improvements. Assumptions are made about the likely economic growth, the amount of travel or the thermal integrity of dwellings, availability of resources and so on. Before we summarize findings of this study in the next chapter, we will briefly review the results of other studies that have assessed the future global and international energy needs. Instead of analyzing in great detail the individual assumptions made in these studies, we will view them as a collective wisdom of energy experts on the energy future. Thus, we will analyze them as an aggregate view of the future and look for consensus and variance. This discussion will draw heavily on the results of the seven years experience of the IIASA International Energy Workshop (IEW).

7.2. Global and Regional Energy Scenarios

Most of the scenarios of future global energy needs and possible supply patterns are based on exogenous assumptions. An important underlying determinants of future energy needs is the expected population growth. The future economic outlook represents the second driving variable that determines the energy needs. Thus, it should not be surprising that the conclusions about the future energy consumption and possible ways of supplying this energy vary depending on the assumptions made in a particular study and the methodology used for establishing the relationships among the assumptions. We will compare here the projections of energy prices, economic growth and primary energy consumption.

7.2.1. International Studies

There have been only a few studies of the long-term global energy outlook during the 1970s. The most notable of these were the Workshop on Alternative Energy Strategies (WAES, 1977), the World Energy Conference Reports (WEC 1978, 1983, 1986, and 1989) and the global energy study undertaken at IIASA (Energy in a Finite World, Häfele *et al.*, 1981 and Rogner, 1984). However, the WAES study did not consider the whole world, it focused mostly on the industrialized countries. In contrast, the IIASA and the WEC studies are comprehensive reviews of the whole world situation. All these three studies and their subsequently revised global energy outlook have in common that they were based on elaborative assessment of future energy needs involving large teams of experts. From these three early studies, the IIASA global energy study was perhaps the most elaborate and comprehensive because it both involved the formal modeling of future energy demand and supply and it encompassed the whole world divided into seven regions. Despite the different approaches undertaken in these studies they all have in common the expectation of lower growth in global energy consumption than was experienced in the world during the post-war period. Up to the 1970s the global energy consumption grew at almost 5 percent per year, while the long-term average growth rate was much lower with about 2.5 percent per year. In these three studies and their subsequent derivatives, the future energy consumption was expected to increase over the next decades at between 2 and about 3.5 percent per year. Thus, the growth rates were much lower than those during the pre-1973 period and about the same as the long-term evolution of global energy consumption.

Despite this overall consensus of lower future energy consumption growth, these studies varied widely both with respect to their basic assumptions, the coverage of the world regions and with respect to the methodology used for the assessment of future development. These differences also reflect the large uncertainties, both in any attempts to forecast future developments and in possible future linkages between demographic, economic, social, technological and environmental developments, that will determine the energy use patterns. Usually a range of scenarios is developed in order to reflect these uncertainties. For example, the IIASA study (and most other studies) used two scenarios to describe a range of possible developments rather than to give a single point estimate. During the last ten years the IIASA low scenario turned out to be quite close to the actual development of energy use.

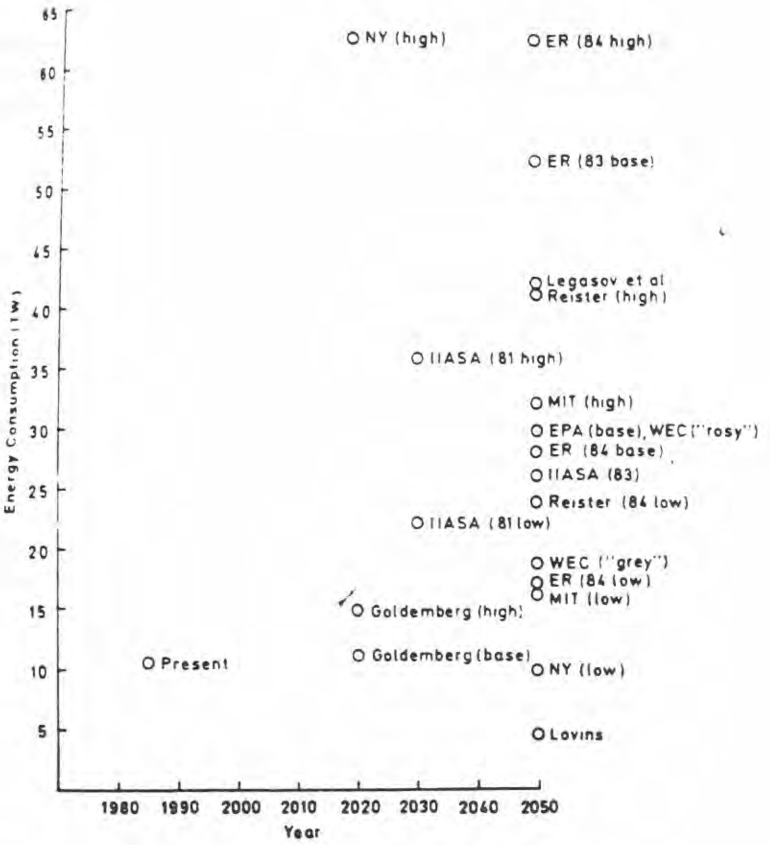


Figure 7-1 Global Primary Energy Projections in TWyr/yr (Bolin, Döös, Jäger and Warrick, 1986).

Figure 7-1 compares the projections of global primary energy consumption for a few global energy studies (Bolin, Döös, Jäger and Warrick, 1986). As observed above, the ranges are quite large and increase with the forecasting time horizon reflecting the increasing uncertainty associated with the distant future.

The scenarios include IIASA high and low scenario (Häfele *et al.*, 1981) and a revised IIASA-83 base case scenario for the year 2050 (Rogner, 1984); the scenarios developed by Edmonds and Reilly, (ER 1983 base case and 1984 low, base and high cases), as well as scenarios elaborated by the US Environmental Protection Agency (EPA base case) and the Massachusetts Institute of Technology (MIT low and high) and by Reister (84 low and high scenario), based on the Edmonds and Reilly model (Edmonds and Reilly, 1983a and 1983b; Seidel and Keyes, 1983, Rosi *et al.* 1983 and 1984; Reister 1984); the World Energy Conference "grey" and "rosy" scenarios (WEC, 1983) and scenarios developed by the Soviet analysts Legasov and Kuzmin (1981). In addition, Figure 7-1 also shows the two scenarios by Nordhaus and Yohe (NY low and high), which have already been discussed in Chapter

6 when we compared scenarios of future CO_2 emission and atmospheric concentrations. Last but not least, Figure 7-1 also shows scenarios of proponents of the socalled "low energy path" (Lovins *et al.*, 1981 and Goldemberg *et al.*, 1987). These scenarios are especially interesting because they illustrate the extreme variance in future energy projections by substantially increasing the domain of projected futures in different scenarios. Thus, to some extent it is more interesting to compare the variation and the extent of consensus in the estimates of future energy projections rather than their specific values.

7.2.2. International Energy Workshop

This approach was undertaken in the International Energy Workshop (IEW) organized by IIASA and Stanford University (Manne and Schrattenholzer, 1988). IEW was initiated in 1981 with the aim to compare the most up-to-date long-term energy projections available throughout the world, and to obtain a better understanding of the reasons for their differences. The IEW activities include an informal network for communication between energy experts throughout the world and an annual conferences where the studies are compared. The communication is facilitated with a standardized poll reporting on the projections of various groups that is up-dated every six months. During the annual conferences the reasons for differences and the consequence of various energy projections are discussed. To ensure comparability, each poll response includes estimates for the statistical base-year of the study and for the three standardized dates in the future: 1990, 2000 and 2010 (Manne and Schrattenholzer, 1988). Each edition of the poll results includes frequency distributions comparing the responses provided for the individual countries, regional groupings and the world.

According to Manne and Schrattenholzer (1988) the majority of the projections encompassed by the poll responses are "surprise-free", although a few of them bear labels such as "restructuring" and "muddling through". In most of these projections, the future primary energy needs depend to a large degree on the assumptions about economic growth (GNP or GDP) and oil prices. Each poll response includes the information on GDP and oil price projections, consumption of commercial primary energy by source and total electricity generation. Oil prices are expressed in terms of 1985 U.S. Dollars per barrel. GNP or GDP growth is measured as an index number (1980=100) in constant purchasing power currency units, primary energy in tons oil equivalent and electricity in TWh (Manne and Schrattenholzer, 1989).

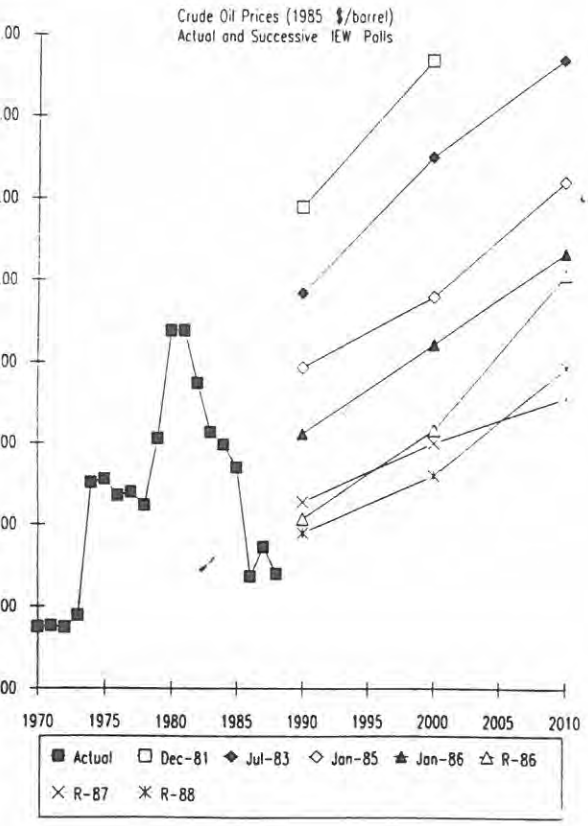


Figure 7-2 Median Crude Oil Prices and Seven IEW Poll Results 1985 $/barrel (Manne and Schrattenholzer, 1989).

7.2.2.1. Oil Price Forecasts

Taken together the various future energy projections implied by the studies give a powerful illustration of how the perceptions of the future are changing. We will first illustrate this in Figure 7-2 with the sequence of future oil price expectations starting with the first projection from 1981 ending with the most recent one from 1988. Each path gives the median oil prices of all responses from a particular poll. There are seven median projections resulting from seven poll responses over the last eight years. In addition, Figure 7-2 gives the actual development of world oil prices since 1970.

According to Figure 7-2, long-term oil price projections have mirrored the secular instability of price levels. In 1981 when the crude prices reached a historical maximum, the median responses also projected the highest absolute increases for the future. Conversely, after the collapse of world oil prices, especially after 1986, the median poll responses reflected this development with the lowest projections and to a lesser degree also with the lowest rate of increase (see 1987 and 1988 poll responses). Despite these differences in future oil price expectations, together their evolution in time portrays a pattern that can be characterized as one of "adaptive expectations" (Manne and Schrattenholzer, 1988). The median response illustrates that the "conventional wisdom" of future oil price developments is extrapolated on the basis of current prices in a given period. It should be noted, however, that these projections are to a degree inter-dependent, many of them are intended to be consistent with as many others as possible.

This should be compared with the actual long-term development of oil prices given in Chapter 4. There we argued that they were remarkably stable over the whole history of oil use of more than one hundred years (with the exception of the three price flares, the most recent of which is also visible in Figure 7-2). Whereas the long-term development showed constant average prices, the poll medians imply an average price increase for the future of about three percent per year (albeit with a declining trend). The projections may eventually converge toward even lower levels. In this context it is an interesting feature of energy projections that the trend is toward lower future oil and consequently also energy prices. However, the extreme projections include more information about the future expectations than the median. The lowest is close to the constant real price and the highest represents a four-fold increase.

7.2.2.2. Economic Growth Forecasts

Another important determinant of energy use in most of the studies is the expected pace of economic growth. In the IEW poll results the GDP or GNP growth is reported as an index (1985=100). The medians indicate a 60 percent increase by 2000 and a factor 2.2 increase up to 2010. This translates into average annual growth rates of of about 3.2 percent (assuming exponential trend). The range of the responses is quite high varying from 150 to 270 in the year 2010 (growth rates from 1.6 to 4 percent per year).

There are also substantial differences in the GNP growth rates between different world regions. Table 7-1 shows that growth rates range between 2.7 and 7.4 percent per year between 1985 and 2010 for the poll median. In Chapter 4 we have shown that 4 percent per year sustained increase is rather high by current standards but represents an average for longer historical periods. In the OECD countries, the GDP increased at 3.7 percent between 1960 and 1986 (a 25 year period), while in Japan the growth rate was 6.6 percent per year during the same period. Over a very long-term from 1800 the GNP increased in the United States at 3.9 percent per year. Thus, most of the projections of future global economic growth are well within historical experience. The most noteworthy exception appears to be for China where economic growth rates projected by the poll medians exceed

Table 7-1 Real GNP Forecasts, Median of IEW Poll Responses, 1985 = 100 (Manne and Schrattenholzer, 1989).

	1985	1990	2000	2010	Growth rate 1985-2010 %/year
USSR & Eastern Europe	100	117	165	226	3.3
China	100	149	315	589	7.4
OECD	100	114	149	195	2.7
OPEC	100	111	164	247	3.7
NODC[1]	100	122	185	264	4.0
World	100	115	162	220	3.2

[1] Non-OPEC developing countries

even the growth rates achieved by Japan over the last 25 percent.

7.2.2.3. Primary Energy Consumption Forecasts

The median response projects the global primary energy consumption at 18 TWyr/yr by the year 2010, which is close for the projections of the IIASA low scenario for the year 2010. This gives an implicit growth rate of 2.3 percent per year, almost identical to the long-term average growth rate since 1860 of about 2.5 percent per year (given in Chapter 3).

Again large differences are projected in the regional growth rates as is illustrated in Table 7-2. They range from an average 1.3 percent per year growth rate in OECD countries to over 4 percent annually in the case of China. However, it is surprising to observe that the range of projected energy consumption levels in 2010 is smaller than that for global economic growth. The projections imply that energy consumption may increase more or less within a narrow range, but that it can be associated with rather high rates of economic growth and also with to rather low ones. This is the link to the foregoing discussion about the efficiency of energy use. Thus, the projections apparently have a large range of assumptions about how efficient the energy consumption will be in the future. While there is smaller disagreement about the amount of energy consumed, there is quite a disparity of how efficiently this energy will be used in the future global economy.

Table 7-2 Primary (Commercial Energy Forecasts, Median of IEW Poll Responses, TWyr/yr (Manne and Schrattenholzer, 1989).

	1985	1990	2000	2010	Growth rate 1985-2010 %/year
USSR & Eastern Europe	2.45	2.75	3.29	4.02	2.0
China	0.74	0.92	1.38	2.02	4.1
OECD	5.28	5.81	6.50	7.28	1.3
OPEC	0.39	0.48	0.67	0.98	3.8
NODC[1]	1.21	1.42	2.12	2.95	3.6
World[1]	10.23	11.65	14.64	17.95	2.3

[1] Non-OPEC developing countries

[2] Regional totals do not add exactly to world totals, as independently estimated by contributors to the IEW Poll.

7.2.2.4. Energy Intensity and Elasticity

Another way of showing these differences is to compare the energy intensity (energy to GDP ratio) of different scenarios. Table 7-3 illustrates the improvement of energy intensity (1985=100) implied by the median IEW poll projections, disaggregated by world regions. By the year 2000 the median intesity is 88 and by 2010 it is 80. This implies average improvement of less than one percent per year up to the end of the century and about one percent per year up to 2010. Particularly noteworthy is the decreasing energy intensity implied by the GNP and primary energy demand forecasts of the IEW for China. It is projected that by 2010, the energy intesity for Chine would be less than half of the 1985. This decrease implies an annual improvement rate of 3 percent per year. This appears to be highly optimistic compared to the projected efficiency improvements in OECD countries of 1.4 percent per year, which is about the same as the observed historical, long-term efficiency improvement rates in the OECD region.

We have shown in Chapter 4, that the historical improvement of energy intensities has been about one percent per year in the US and UK and also in the OECD countries since 1960. Higher declines in energy intesity occurred in the OECD countries since the so-called energy crisis in 1973 of about 2 percent per year. However, it is possible to view this as a kind of catch-up effect since little improvement was achieved during the 1950s and

Table 7-3 Primary Energy – GDP Intensity of Median IEW Poll Responses, index, 1985 = 100.

	1985	1990	2000	2010
USSR & Eastern Europe	100	95.9	81.4	72.6
China	100	83.4	59.2	46.4
OECD	100	96.5	82.6	70.7
OPEC	100	110.9	104.8	101.7
NODC[1]	100	96.2	94.7	92.4
World	100	99.0	88.3	79.8

[1] Non-OPEC developing countries.
Data Source: Tables 7-1 and 7-2.

1960s. It is interesting, that the median poll response for the world total implies basically "business as usual". Zooming in on individual projections this patterns tends to strengthen: there is an impressive consensus with respect to the future energy consumption in the OECD countries, while the projections for developing countries vary considerably. The impression that emerges is that the developed world will be in a position to achieve a high degree of efficiency in energy consumption, while developing countries might even deteriorate as they restructure toward more energy intensive activities.

Given the projections on primary energy demand and GNP growth discussed above, it is possible to calculate the implied energy-GNP elasticity given by the poll medians. At a global level the elasticity is projected to decrease from around 0.7 in the period 1985-2000 to 0.6 for the decade thereafter. In OECD countries the elasticity is projected to decrease from around 0.5 (1985-2000) down to 0.4 for the period 2000-2010. A value of 0.5 means that the output of the economy could increase by a factor of four while primary energy demand would only double. Thus, the projections outline a slow "decoupling" of energy and economic growth. The median response is not much different from the long-term historical values given in Chapter 4 on energy and GNP elasticities in the US during the last two-hundred years. The average elasticity was slightly above 0.6. Thus, the aggregate median result is slightly surprising since it does not indicate a stronger decoupling of energy from economic growth than was achieved in the past. This should however, not mask the fact that the range of implied elasticities is indeed quite large in the poll responses. They are between 0.4 (OECD) and above 1 (OPEC countries). The lowest refers to developed regions and means that there will be a relatively weak linkage between energy demand increases and the rate of economic growth, while the latter refers to developing regions where much larger dependence between energy and economic growth should be expected.

Almost all studies that include the future evolution of electricity generation in their projections project large increases during the next 25 years. By 2010 the electricity generation is expected to increase by a factor of 2.4 which gives an implicit growth rate of about 3.5 percent per year. This is much lower than the historical growth rates (up to 7 percent per year), but compared with the primary energy consumption electricity portrays relative increases over the next two decades. The median poll response gives the primary energy growth rate of about 2.3 percent per year, so that electricity is expected to grow at about 1.3 percent per year faster, gradually increasing its share with respect to other secondary energy forms.

In summary we can conclude, that the aggregate view of global energy futures, as reflected in the median poll responses, does not reflect any more dramatic increases in the overall efficiency of energy use worldwide than the historical averages of the last decades. While the consensus appears quite strong about the expected rates of primary energy growth, the variance in the projected rates of economic growth was greater. This implies that the expectations about the efficiency improvements are rather differentiated; very similar increases in primary energy consumption are expected to be associated with quite different economic development trajectories. Both in the case of longer-term projections of future oil price levels and in the case of energy intensity projections, the large variance in the poll responses reflects higher uncertainties that are inherent in underlying critical aspects of future technological change and social and economic development.

List of Poll Respondents, July 1989 (Manne and Schrattenholzer, 1989)

Organization/project		Last Year Reported	Country/ Region Coverage
ABRTO	J.L. Aburto, Comision Federal de Electricidad, January 1989	2010	Mexico
ADLMN	M. Adelman, MIT Energy Research Laboratory, competition scenario, March 1989	2000	7
AMOCL, AMOCU	Amoco Corporation, lower and upper price cases, May 1989	2010	1-8, Canada, Japan, OECDE, USA, USSR
ASSUH, ASSUL, ASSUM	Academy of Sciences, USSR, high, low and moderate energy price scenarios, April 1986	2010	Japan, OECDE, USA
BHP	Broken Hill Proprietary Petroleum, January 1989	2010	7
BPP	BPP Teknologi, MARKAL model, March 1988	2010	Indonesia
CEE	Centro de Estudios Energeticos, November 1986	2010	Mexico
CEGBL, CEGBU	Central Electricity Generating Board - lower and upper oil price scenarios, October 1988	2000	7
CERG	Cambridge Energy Research Group, November 1987	2010	4,7, DC, OECDE, OECDN, OECDP
CFPL, CFP	CFP Total, MAREN - lower and upper oil price path, February 1988	2000	4, 7, DC, Japan, OECDE, OECDN
CHVRN	Chevron Corporation, World Energy Outlook, October 1987	2000	4
CIESH, CIESL, CIESM	Centre for International Energy Studies, Erasmus University - high, low and mid-point demand growth, December 1988	2010	3-8
CMREE	Centre for Mineral Resources and Energy Economics, November 1988	2010	Poland
CONCL, CONCU	Conoco, lower and upper price cases, November 1988	2000	4,7, DC, Japan, OECDE, USA

CRIE, CRIEP	Central Research Institute, Electric Power Industry, November 1988 and July 1986	2010	8, Japan
DOE	US Department of Energy, December 1987	2010	4-7, USA
DRI	Data Resources Inc., Spring 1986	2010	USA
DRIE	DRI Europe, December 1986	2000	OECDE
ECC	Economic Council of Canada, October 1986	1990	Canada
ECE	Economic Commission for Europe, March 1987	2000	1, OECDN
ECONH, ECONL	ECON, Center for Economic Analysis, Oslo, high and low oil price scenarios, December 1988	2010	4-7, USA
EIAH, EIAL	US Energy Information Administration, high and low price simulations, May 1988	2000	USA
EMVEN	Ministerio de Energia y Minas, Venezuela, August 1986	2010	Venezuela
ENEA	E. D'Angelo, ENEA Energy Analysis Service, March 1989	2000	Italy
ENEL	Ente Nazionale per l'Energia Elettrica, 1988	2000	Italy
EPRIH EPRIL, EPRIM	O. Yu, Planning and Evaluation Staff, Electric Power Research Institute, high, low and middle electricity growth scenarios, July 1988	2010	USA
ESCNC, ESCNG, ESCNN	Energy Study Centre, Netherlands, coal, gas and nuclear scenarios, September 1987	2010	Netherlands
GATLY	D. Gately, New York University, September 1986	2000	7
GDRIE	GDR Institute for Energetics, Leipzig, November 1987	2010	GDR
GOSSR	A.B. [illegible]by and D. Dreyfus, Global Outlook for Service Sector Energy Requirements, November 1988	2010	2-8, Japan, USSR
GRIB, GRIL, GRIU	Gas Research Institute - baseline, lower and upper energy price scenarios, December 1988	2010	USA
HOMSH, HOMSL	W. Hogan and P. Leiby, Harvard Oil Market Simulation, high and low price cases, May 1989	2010	4,7, USA
IAEAH, IAEAL	International Atomic Energy Agency, high and low energy scenarios, 1988		1, Latin America, OECDE, OECDN, OECDP

IEA	International Energy Agency, April 1989	2000	3,4,8, DC
IEAGH, IEAGL	International Energy Agency, "Natural Gas Prospects", high and low oil price scenarios, 1986	2010	OECDE
IEAL, IEAU	International Energy Agency, Secretariat, May 1988	2000	4
IEE	Institute of Energy Economics, Tokyo, December 1988	2010	Japan
IEPE	Institut d'Economie et de Politique de l'Energie, November 1986	1990	1-8
IGIDR	Indira Gandhi Institute of Development Research, December 1987	2000	India
IIASC, IIAST, IIATU	International Institute for Applied Systems Analysis - Gas Study, Conventional Scenario, Technological Development, Technical University of Vienna, April 1987	2010	OECDE, Austria
IIP	IIP, University of Karlsruhe, March 1989	2010	FRG, Portugal, Spain
INET	Institute of Nuclear Energy Technology, Beijing, June 1985	2010	2
INSEE	Institut National Statistique et Etudes Economique, February 1987	2000	France
IPE	IPE Model, N. Choucri, MIT, June 1986	2000	4-7, Japan, USA
KAIST	Korea Advanced Institute of Science and Technology, January 1988	2000	Korea
KFAJ	KFA (Nuclear Research Center) Julich, October 1986	2000	FRG
KORCH	M.B. Korchemkin, Erasmus University and Estonian Academy of Sciences, April 1989	2000	USSR
LBL	Lawrence Berkeley Laboratory, December 1986	2000	Mexico
LIEF	Liston International Energy Forecasts, London, December 1987	2010	4-7
LTM	Long-Term Model, A. Manne and T. Rutherford, Stanford University, April 1987	2010	4-7, USA
MRCTI	C. Marchetti, IIASA, 1986	2010	8

MROTA	Y. Murota, Saitama University, March 1985	2000	Japan
NEA	Nuclear Energy Agency, OECD, May 1989	2000	4
NEAS	National Energy Administration, Sweden, January 1989	2010	Sweden
NEBH, NEBL	National Energy Board, high and low price cases, September 1988	2000	Canada
NPCL, NPCU	National Petroleum Council, lower and upper price trends, October 1986	2000	USA
OIW	Austrian Electric Power Company, June 1988	2000	Austria
PAEC	Pakistan Atomic Energy Commission, Applied Systems Analysis Group, July 1986	2010	Pakistan
PAT	Petroleum Authority of Thailand, November 1987	2000	Thailand
PGE	Pacific Gas and Electric Company, Oil Price Forecast, April 1986	2010	7
PILOT	PILOT Model, Systems Optimization Laboratory, Stanford University, November 1987	2010	USA
PLECB, PLECC, PLECR	PlanEcon, Inc. - base, oil production crisis, and rationalization scenarios, October 1986	2010	1
POLH, POLL	Polish Academy of Sciences, high and low scenarios, December 1986	2010	Poland
RESPS	Respondent S, January 1987	2000	7
ROWSE	J. Rowse, University of Calgary, November 1986	2000	Canada
SNYAK	Yu. Sinyak, IIASA and USSR Academy of Sciences, June 1989	2010	1, USSR
SPC	Energy Research Institute, State Planning Commission, March 1989	2010	2
SPILH, SPILL	M. Waterhouse, Strategic Planning International Ltd., high and low oil price scenarios, February 1989	2000	2-4, 7, 8, ANZ, Japan, LATAM, ME, OECDE, OECDN, USSR
TERI	Tata Energy Research Institute, June 1988	2000	India

ULG	A. Umnov, M. Lenko, A. Golovin, CMEA Study, IIASA, February 1985	2000	1
UTV	F. Wirl, University of Technology, Vienna, November 1986	2000	4-7
WBK	World Bank, November 1988	2000	1-8
YOHEH, YOHEL, YOHEM	G. Yohe, Wesleyan University, high, low and median price scenarios, March 1987	2010	8
ZRUBA	P. Zaruba, University of Economics, Prague, June 1989	2010	Czechoslovakia

8. CONCLUSIONS

8.1. General

8.1.1. Study Approach

The objectives of the study were to analyze changes in the efficiency of energy supply and end use against a broader background of socio-economic change; to investigate possible future developments worldwide including Austria; and to assess the potential impacts of these developments. We have analyzed the dynamic changes of the energy system, increasing energy efficiencies, more effective use of energy, and technological development in general, within the context of economic, social and environmental changes.

The study started with the description of the transformations in the world economy that are related to technological advancement and emergence of new institutions and economic activities. Then, a brief analysis of the historical development of the energy system and use was compared to more recent changes in energy production, trade and consumption in the OECD countries and Austria. Against the background of these longer term developments, we outlined some of the more important transformations of the energy system and efficiency improvements during the last decades. Finally, we analyzed in greater detail the currently prevailing efficiencies of energy transformation and end use in the OECD countries and Austria, concluding that they are not very high in absolute terms and that the improvement potentials are very large indeed, especially in the end use. Thereafter, we described some environmental and global climatic changes that are associated with energy emissions and which are considered to be major driving forces for the future evolution of the energy system. Finally, we discussed and compared projections of future energy requirements and the development of energy efficiency they imply.

8.1.2. Study Characteristics

An important characteristic of the study is that it presents the developments of the last few decades, especially since the so-called energy crisis of the early 1970s, against the background of the longer term evolution of the energy system, going back to the beginning of the Industrial Revolution. Furthermore, this comparative analysis of recent trends and long term evolution of the energy system was presented in the context of overall technological and economic development, and structural transformations, as well as against the background of social and environmental changes.

Thus, it was possible to analyze the more recent efficiency improvements, together with the long term structural changes of the energy system, and from the perspective of truly large efficiency improvements achieved over the last two centuries in industrialized countries. This was used as a yardstick for analyzing current energy efficiencies in the OECD countries and assessing possible improvements for the future. For this assessment we estimated current energy efficiencies both in terms of energy and in terms of exergy (available work) balances. This assessment identified energy end use and provision of energy services as the area with the largest potential for efficiency improvements. In adopting this approach, we were able to document the overall efficiencies of energy and exergy chains, starting with conversion of primary energy to secondary fuels, electricity and final energy forms and to go a step further and evaluate useful energy and exergy delivered to end use. At a larger degree of resolution, we have also attempted to assess efficiencies with which actual energy *services* are provided, starting from the useful energy level, although, in the absence of reliable data, our estimates represent only first order approximations. We have applied this approach to the whole energy system in the OECD countries and Austria, covering all main primary energy inputs and most of the end-use categories. This is a novel approach, to be found in only a few studies of energy efficiency, and represents the first attempt to determine energy and exergy balances for OECD countries and Austria.

The major limitation of the study is the inadequacy of quantitative indicators and data available in statistics, and literature in general, for documenting energy efficiencies, especially in some end-use categories. Due to the data gaps, or simply lack of data, it was often necessary to derive estimates or use approximate values. Much more should be done to improve the quality of available data. From this point of view, our efficiency estimates should be considered as tentative and indicative values, rather than as actual observed data. This does not weaken the conclusions made from this analysis, but rather it is a strong argument for the need to improve the documentation of the energy end uses and prevailing efficiencies of *energy services*.

8.2. International

8.2.1. New Perceptions of the Energy Problem

The perceptions of global energy issues have changed since the early 1970s. Resource limits appear more as a myth than reality. The emphasis has shifted from the long-term availability of oil and its price to the overall impacts of energy use and human activities in general. The energy problem is now often viewed through the prism of environment. Possible climatic changes and impacts on the biosphere appear to be larger concerns than the shortage of cheap and easily accessible fuels in the distant future. While energy prices are likely to remain relatively low compared to the forecasts proposed during the last two decades, it appears that the actual costs of energy will indeed be higher, not because of scarcity but rather because of the increasing direct and indirect costs of environmental protection measures.

Therefore, the improvement of prevailing efficiencies of energy transformation and use is even more important than it was during the days of so-called oil shortage. Efficiencies are now expected to reduce the overall energy supply for a given level of demand and in that way avoid some of the adverse impacts of greater energy consumption. Within the energy system the emphasis is on fuels that are clean in end use. The hope is to either supply "cleaner" energy with environmentally more benign primary energy sources, or to apply some of the advanced technological measures for cleaning fuels from substances that are potentially dangerous if released to the atmosphere, water or land. From this perspective, electricity and hydrogen appear to be ideal energy carriers, and natural gas, solar and nuclear energy the appropriate primary energy sources. Against this background of issues, we have considered how technological progress, structural change and efficient energy use might evolve and help resolve the environmental challenge without reducing economic growth and future development. Technological change and restructuring appear to be important means in resolving the adverse impacts of past technological advances and economic growth.

We have shown that in the past new technologies were applied to solve the eminent problems encountered with traditional systems. Coal resolved the fuelwood crisis and kerosene saved the dwindling population of whales. However, technological solutions can be blocked and not all are successful. Social mediation of the process of change is fundamental. There will be very few solutions to current problems that will not imply some trade-offs within the complex structure of social preferences, but social acceptance is a prerequisite for success. In this light, the efficiency of energy use must also be considered. Overall, improved efficiency of energy use is usually beneficial for society at large and for the individual. Efficiency increase means that energy productivity is improved and more yield can be achieved with constant or less inputs. This generally leads to the reduction of adverse environmental impacts, increases the productivity of other factor inputs, and consequently benefits the whole society. Since these relationships are self evident, it is not surprising that the efficient use of energy and other factor inputs was one of the major improvements achieved since the beginning of the Industrial Revolution. These overall efficiency improvements were achieved all along the various steps of the energy chain: in the conversion of primary to secondary and final energy carriers, from final to useful energy (i.e. in end use devices), and finally from useful energy to delivered energy services.

We have concluded that, as a yardstick number, the heat and work for energy service tasks today are supplied with as little as one tenth of the primary energy requirements needed at the beginning of the century. For instance, the average efficiency of a horse as a prime mover in converting primary energy (feed and hay) to the required services (motive energy) for moving people and goods was less than 4 percent. This is a factor 10 smaller than for current oil based internal combustion engines. Similar efficiency improvements (a factor of seven) since the turn of the century have, for instance, also been achieved in the generation of electricity from fossil fuels. These achievements imply an efficiency improvement rate of 2 to 3 percent per year.

These great improvements in the energy systems have meant that every year a unit of value added in the industrialized economies could be generated with less and less energy. The ratio of energy inputs to value added (measured as Gross Domestic or Gross National Product) is usually referred to as the energy intensity of an economy, and despite many caveats concerning the precision with which GDP or GNP represent the actual economic activities, this measure nevertheless is a useful aggregate indicator for the overall energy efficiency of an economy. The energy intensity (input) per unit of economic activity (value added or GNP) has decreased by more than a factor of five since the early 1800s. Thus, energy intensity declined at a rate of about one percent per year over a period of 200 years. Can this process continue forever? Are we not reaching an asymptotic state where any additional improvements are more and more difficult to achieve? If not, can this historical process be accelerated in view of new and apparently irreversible effects on the global climate and biosphere?

These are some of the questions that we have attempted to address in the study. It is clear that there are no unique answers to these questions, but one of our findings is that some of them might be wrongly posed. We are certainly not reaching any upper limits to possible efficiency improvements, although some of the current systems may be close to reaching their limits. For example, it is impossible to design a steam-cycle thermal-power plant that will reach conversion rates of fossil fuels to electricity in excess of 60 percent. But already today new technological solutions, such as the combined-cycle natural gas plants almost reach these conversion efficiencies. Therefore, efficiency improvements cannot consist of only small steps. Technological evolution is a discontinuous process that results in the replacement of old by new systems that have much higher development potentials. However, power plants, and especially fossil power plants, are only one critical component of the energy system. Our objective was to identify opportunities where substantial efficiency gains are both possible and have not been fully exploited in the past. We have concluded that the apparent largest potential for efficiency gains is in energy *end use*, particularly in the transformation of useful energy to *energy services*.

8.2.2. Energy in the Information Age

Opportunities for efficiency gains arise because of technological change and restructuring that could now become pervasive in most developed countries. The emphasis is changing from economies of scale to economies of scope. Quality is replacing quantity as an indicator of performance. This means that higher value densities are achieved in many industrial and service activities. Information content is increasing while material intensity is declining. In the emerging global economy, time is gaining more significance both in commercial and pleasure activities. Just-in-time production or financial services are some of the promising growth sectors. Historically, the territories of human activities have expanded both in private life and business. Distances traveled have increased drastically and flows of information, people and goods have started to become truly global. Communication technologies have connected the world to the point where almost instantaneous information exchange at unprecedented volumes is possible, while express and courier services make tangible goods travel around the globe in a day.

These are some of the salient developments of today. They will have large impacts on energy end use and on the qualitative and quantitative requirements of the energy system, and consequently also on the efficiency and structure of energy supply. Higher value density could mean that less energy will be embedded in products and services per unit value added, while higher mobility implies more travel and worldwide communication, which will certainly require more energy. Thus, we are on the brink of a paradigm shift from an energy intensive era of bulk materials and high power densities to a time when precision, both in time and scale, will be important for providing goods and services where and when they are needed.

Should this picture of future developments be accurate even to a small degree, then exactly these and similar changes will offer the opportunity of improving the prevalent efficiency of energy provision and use. Better control mechanisms in dwellings, vehicles, machines and appliances will reduce specific energy needs. Decreasing materials intensity and enhanced recycling should also drastically decrease energy requirements. These improvements will, to an extent, be off-set by increasing specific demands for energy services for more pleasure activities, more mobility and widespread use of information technologies for recreation and work. One of the great achievements of the industrial age was the replacement of human physical labor and animate power by machines. It is often claimed that the next phase in human development might be to replace some of the human skills by information age devices and systems, thereby freeing men from manual and routine tasks for more creative activities and leisure.

8.2.3. Energy, Recycling and Materials Flow

Most of today's goods are produced from basic materials and eventually discarded after their useful life is completed. The future holds the promise of closing this loop. Industrial metabolism is one of the concepts used in this context. The flow of goods and materials could, in principle, be contained so that only small additional requirements would be needed as they are transformed from one form to another. This is exactly the same kind of material recycling that has drastically reduced the energy requirements of steel production, especially in some small and mini steel mills. Most of their raw material is scrap steel and iron, so that the large energy requirements for making iron from ore are completely avoided.

With regard to flexible manufacturing systems and new robotic technologies, there is a new potential for disassembly and reassembly with the aim of recovering and recycling valuable waste materials and components. The question here is to more fully explore the economic niche of flexible robotic technologies in the light of changing societal values and new concepts, such as "no-waste" manufacturing and "no-waste" societies. The containment of materials flow and reduction of wastes would both reduce specific energy requirements and environmental impacts.

Apart from the recycling of materials that saves energy used for their production, dissipated heat can be recycled as well and is becoming an important energy efficiency measure in the residential, commercial and industrial sectors. The main technologies for this purpose include cogeneration of electricity and heat, heat recovery from exhaust air by means of heat exchangers, application of heat pumps and their combination with heat recovery from waste water, and the use of waste heat from cooling processes in manufacturing and industry. In a wider sense, the free energy in the environment that is tapped by solar collectors, hydropower plants and other conversion systems could also be viewed as recycled energy.

8.2.4. Prevailing Energy Efficiencies

Many potential improvements could lead to drastic reductions in energy requirements. They include a shift in emphasis from materials to value density and recycling, better real time control of energy services both in commercial and private use, better design of energy end-use devices and machines, and more efficient energy transformation and conversion systems.

We have shown that present energy use is not very efficient compared with the best practices already available. The overall efficiency between primary and useful energy is roughly around 40 percent for the OECD countries. Considering however, that not all of the useful energy is transformed to actual *services* (i.e. passenger travel, warm room, illuminated area, etc.), the overall primary energy to services efficiency is in the neighborhood of about 15 percent. In contrast, the primary to useful *exergy efficiency* is also about 15 percent, whereas the overall exergetic primary to service efficiency is not much higher than 5 percent. Exergy in the present context is defined as the ratio (efficiency) between the theoretical minimum amount of available work required for a given service task, divided by the actual available work consumed by a particular device performing this task. Whereas this concept, based on the laws of thermodynamics can be precisely applied to a particular device such as a heat engine, it is very difficult to give precise, quantitative estimates for the whole energy system. Despite the uncertainty of various efficiency estimates, this result is in a good agreement with a few estimates in the literature for the United States, United Kingdom, Germany and Canada, which are all in the range of between 3 and 5 percent. Due to the fact that the estimates are indeed rather uncertain, we have analyzed the sensitivity of our results by changing some of the more critical assumptions. The important conclusion is that the actual primary to service exergy efficiency of the energy system in the OECD countries is certainly not higher than 10 percent, with a mean value of about 5 percent.

At face value five percent is a very low efficiency. One of the reasons why this appears to be a low figure is that, usually, primary to final energy transformation is quoted as 70 percent for the overall efficiency of the whole energy system. This is, of course, an incorrect partial view, because only a small fraction of final energy ends up as actual energy services. Our estimates for the OECD countries show that energy end use and services have very low efficiencies. Thus, many of the improvements in the transformation efficiencies of gathered primary energy to delivered final energy are diluted by the low end-use efficiencies.

Therefore, improvements of energy end-use and service efficiencies would have much larger impacts on increasing the overall energy efficiency, compared with improvements in transforming primary energy to fuels and electricity. This means that the overall efficiency of the energy system could be greatly enhanced by using more efficient energy end-use devices, new technological means for providing a given service task, improving thermal integrity of buildings and switching to final energy carriers with higher end-use efficiencies such as oil products, natural gas and electricity. Provision of more electricity and natural gas to end use, provided that the appropriate environmental measures are applied at primary to secondary energy conversion facilities, could also lead to the reduction of environmental impacts.

In fact, the assessment of potential improvements was the main reason behind this exercise in estimating the actual efficiency of energy use. It is only in this context that the current overall efficiency of the energy system has any relevance. An efficiency of a few percent or the fact that electricity has the lowest primary to service exergy efficiency of all energy carriers is, by itself, just a fact and it is not immediately obvious whether low efficiency of energy use is anything to worry about. After all, efficiency is just one factor in judging the performance of energy services. Time and quality of provision of services are very important and so are the economic costs and environmental impacts. With increases in mobility, speed and just-in-time provision of energy services this might be sometimes even more important than efficiency measures proper. The higher speed of vehicles has a high energy price and decreases the efficiency per passenger and ton-kilometer. Still, traveling between the US and Europe (within only a few hours) would be impossible at present passenger fluxes (around 25 million North-Atlantic passengers annually) based on pre-war ocean liners, taking several days for the same journey. Higher quality forms of useful energy have to be applied also to provide heat, where and when it is needed. However, the required conversions for their provision usually have again some efficiency penalty.

Thus, the structure of the energy system and the patterns of energy use are the result of complex and intricate trade-offs between efficiency, resource availability, cost of capital, time and environmental impacts. At present, not all social and environmental costs are internalized in the current configuration of the energy system and end use. Efficiency improvements are beneficial precisely in this context. However not all energy forms need to be efficient from an environmental perspective. Renewables are notoriously energy inefficient, but nevertheless usually environmentally benign. This is of course only true for sustainable forms of exploitation of renewables.

8.2.5. Efficiency Improvement Potential

A doubling of overall efficiency should be possible just by replacing all stages of energy conversion and end-use by the best technologies and practices available. This process is capital intensive and represents an investment in the future in the same sense as new capital stock increases the productivity in manufacturing and services. New energy conversion and end-use equipment, vehicles and machines would represent a similar investment in the future by reducing the specific primary energy requirement for a given energy service. We have demonstrated that the largest opportunities are at the interface between energy use and energy services. Compared with the conversion of primary energy to final and useful energy forms, energy services and end-uses offer much larger improvement potentials. However, achievement of this potential presumes a pervasive diffusion and acceptance of more efficient end-use appliances, machines and vehicles. In our opinion, the major *impasse* is to be found in the discrepancy between commercial and private activities - between work and pleasure. Economic (bounded) rationality, no matter how imperfect, leads in time to efficiency improvements, but leisure and private activities are often associated with less concern for efficiency in general and energy use in particular. Therefore, in view of a large efficiency improvement potential, the key question is not whether efficiencies will improve in the future, but rather how fast will they improve, especially when considering prevailing consumer behavior.

In our view, the lower bound on efficiency improvement is given by historical experience. Over a longer time horizon there appear no real upper limits. The efficiency could increase by a much higher factor than during the last two centuries or even faster than during the last two decades.

We have illustrated that for industrialized countries the overall energy intensity of their economies improved at a rate of about one percent annually. To illustrate the impact of this efficiency improvement, let us consider the US experience over the period 1800 to 1985. Per capita GNP (in real terms) increased by a factor of 22 over this time period, from (constant 1958) $ 210 to $ 4588 per capita. Based on the energy intensity prevailing in 1800, per capita energy consumption would have increased by the same factor. In reality, however, per capita energy consumption increased by a factor of 3.6 over this period. This means that only about one third of the increase in energy services was due to increases in energy consumption, but two thirds were obtained by efficiency improvements in providing these services. Thus, during the last two centuries the average energy efficiency has increased at a higher rate than the increase in per capita energy use in the

US.

Primary energy use in the world also increased by a factor of 22 since 1860, the population by a factor of 3.6, per capita energy use by a factor of 6 and energy efficiency by at least a factor 3.5. Thus, per capita energy growth and efficiency improvements were also the more dominant factors globally in determining total energy consumption and not population growth.

During the last two decades, however, per capita energy use in most of the industrialized societies has been stagnant or declining due to rationalization measures, conservation and higher efficiencies of new technologies. As technological, economic and social determinants evolve, the efficiency of energy use is likely to increase even further. For many technologies and applications efficiency improvement rates have been much higher in the past than suggested by our above discussion. For instance, today we need only about 15 percent of the fossil primary energy to produce a kilowatt of electricity in steam-cycle power plants compared to the requirements at the turn of the century. This corresponds to an improvement rate above 2 percent annually. By analogy, it should be possible to increase the energy services per capita in the world by another factor of five or so without increasing the actual primary energy consumption at all. Thus, the unresolved question is how much faster could the efficiency improvement potentials be realized.

8.2.6. Time Scale of Efficiency Improvements

The most important feature of the process of efficiency improvements is that the largest leaps in the improvement of the overall efficiency of the energy system were achieved by the replacement of old by new energy technologies throughout all stages of energy production, conversion, transport, distribution and end use. The dynamic aspect of these processes is important since the diffusion of new systems, along with associated social and institutional changes, was not always smooth and often required a long time. At the level of primary energy the substitution of older by new energy forms lasted up to a hundred years. Even end-use technologies diffuse slowly because they are often tied to the structure of capital stock so that the old systems were replaced only at the rate as older capital vintages became obsolete. In the sectors where the longevity is shorter, such as machines or vehicles, the transition processes are faster, taking in the order of a few decades, and in some exceptional cases even less time. Thus, the diffusion of new systems at the level of infrastructures and pervasive innovations that affect many of the economic sectors and areas of human activities last a long time. At this level the rate of efficiency improvements will be difficult to change even assuming a high degree of social and political consensus.

At the same time, end-use devices such as appliances, vehicles and machines have a much shorter useful life, and their replacement by more efficient technologies could surely be much more vigorous. For example, automobile fleets are replaced within decades by new vehicles. Most household appliances and industrial machines could be exchanged by new more efficient vintages even more quickly. Thus, efficiency improvements could be accelerated through economic, regulatory and legal measures. At this level, the pace of efficiency improvement will be largely a function of the dynamics of the capital vintage structures and regulatory frameworks and economic incentives capable of accelerating the obsolescence of older vintages. Davis (1989) from Shell International Petroleum Company illustrates, as shown in Figure 8-1, the potential reductions in specific energy requirements from primary energy consumption to delivered energy services for OECD countries over the next 20 years. Compared to the average 1986 energy intensities, the Shell studies indicate that average efficiency improvements of 10 to 25 percent are feasible by employing today's best available practices, and an additional potential of the same order of magnitude could be realized over the next 20 years as best-practice technologies evolve.

In order to achieve such improvements, emphasis should be placed whenever possible on the development and market introduction of a new, efficient generation of machines, vehicles, appliances and other end-use devices, rather than on replacement of older vintages before the completion of their useful lifetimes. Early replacement would lead to increased waste and an expenditure of capital and energy frozen in the older vintages.

With respect to the extent of further efficiency gains the future is still open. Whatever potentials will become realized, improvements are inherent elements of the dynamics of change since the onset of the Industrial Revolution and should be seen in relation to the pace of change in other important global variables, as summarized in Tables 8-1 and 8-2 at the end of this report.

Efficiency improvements will not, however, be able to offset all of the increases in energy demand. In the industrialized countries the dependence on electricity and grid oriented fuels is increasing, a trend that has direct effects on energy consumption patterns. This is illustrated by the growing importance of electricity, natural gas and motor fuels in the development process of industrialized societies. The demand for these final energy carriers with high quality form is likely to increase in some sectors despite large efficiency improvements. While the energy intensity of industrial activities decreased dramatically in the past, the energy intensity of households and services has increased during the last two decades. The current trends toward higher mobility and more leisure time are likely to lead to new

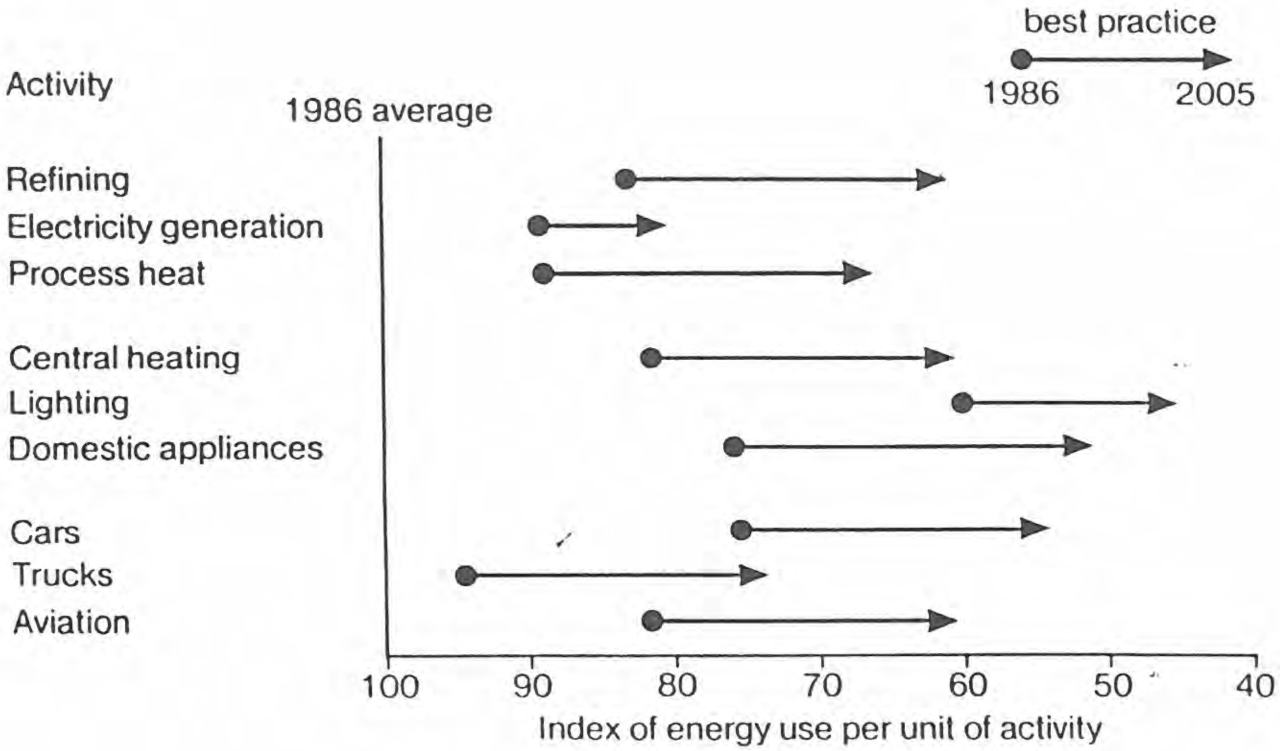


Figure 8-1 Potential Energy Efficiency Improvements in OECD Countries (Davis, 1989).

energy demands for pleasure, while the relative energy demand for industrial activities is likely to continue to decline.

8.2.7. Technological Change, Efficiencies and Environment

We have already mentioned that the adverse environmental impacts of energy consumption are likely to be one of the major driving forces for more vigorous future efficiency improvements in comparison with the prevailing rates of improvement in the past. Environmental impacts have always been important in changing the structure of energy consumption. For example, one of the great successes of the introduction of motor vehicles and replacement of draft animals in road transport was the removal of the environmental pollution associated with horse manure in urban streets. At that time the replacement of horses by a fleet of about 30 million motor vehicles worldwide did not pose any substantial environmental problems, but today this situation is different with almost 400 million motor vehicles in the world.

This also illustrates the non-linear response involved in the social and environmental impacts of technological change. After a certain threshold value is reached, the disbenefits and adverse impacts become very pronounced and start to out-weigh initial advantages and benefits. Today, adverse environmental effects are associated with the use of almost all energy forms and conversion systems. While some environmental problems have short range effects in both time and space (e.g. waste heat release), other potential effects are global in nature and may not be felt for decades (e.g., increase in atmospheric carbon dioxide concentration and ozone depletion). Such unexpected effects of the increasing scale and intensity of human impacts on climatic change and environment provide the need to improve energy efficiencies beyond those dictated by economic rationale even when the externalities are accounted for. The risks of irreversible changes, especially those concerning global climatic change, could cause the creation of appropriate international frameworks to accelerate the pace of technological change and efficiency improvements in order to reduce the anticipated adverse impacts. Often it was the further advancement of technologies and institutional frameworks for social mediation of technological change that offered new opportunities to reduce environmental problems and eventually improve environmental quality; in some sense both the resources and the environment are a function of our social institutions and technology. For this very reason, the acceleration of energy efficiency improvements would be desirable.

8.2.8. Overall Conclusions

In conclusion, we should add that most of the arguments presented for the possible timing and extent of future energy efficiency improvements were based on assuming incremental and cumulative changes and advances in energy supply and consumption. We have mentioned that a number of transformations in the economic structure will, on balance, tend to decrease the energy intensity of many industrial and commercial activities, but perhaps not most of the individual pleasure and leisure uses of energy. With increases in wealth and mobility, the latter developments could lead to increases in energy demand.

On an overall basis, we estimate the lower bound of long-term energy intensity decreases at a rate of one to two percent per year. Such efficiency improvement rates are well within the historical experiences of industrialized countries since the onset of the Industrial Revolution, and especially during the last 20 years. For developing countries, similar efficiency improvements are possible, especially when considering the vast efficiency potentials of a transition away from traditional energy carriers and end-use technologies (e.g. fuelwood for cooking or charcoal for steel manufacture). Such developments are, however, not technology but capital constrained in these countries, so that desirable efficiency improvements in developing countries are likely to materialize at a significant scale only with appropriate technological and financial assistance from developed countries. Such developments would be beneficial globally: lessening the environmental burden, opening development possibilities for the poor, and alleviating the extent and costs for technological and social-behavioral adjustments to global environmental challenges for the rich.

An important deficiency of such arguments on future efficiency improvements is, however, that we cannot assess the impacts of possible new technologies and activities that could emerge during the coming decades. Some of them (such as hypersonic air transport) would result in additional energy demand, whereas others could have a profound influence and may lead to revolutionary and even epochal consequences on further improvements of energy efficiency, and even on economic and social development in general. Should profound basic discoveries, such as the high-temperature superconductivity, abound in the future, they will certainly lead to further efficiency improvements beyond historical average rates, once they are commercialized and start replacing older systems. However, that will take several decades. Thus, over the next 20 years the effects of incremental and cumulative changes will prevail, leading to certain but less dramatic efficiency improvements.

Table 8-1 Orders of Magnitude: Population, GNP and Energy Growth.

	Historical rate of change, %/yr		Hypothetical in 2010 index 1990=100 based on	
	long-term (50-200 yrs)	short-term (since 1970)	long-term rate	short-term rate
Population, World	≈ 1.0	2.0	122	149
Population, US	≈ 2.0	≈ 1.0	149	122
GNP, World	2.8	2.9	174	177
GNP, US	3.8	2.8	211	174
Energy, World	2.5	2.3	164	158
Energy, US	2.8	0.9	174	120
Per capita GNP, World	≈ 1.7	≈ 1.0	140	122
Per capita GNP, US	1.9	1.7	146	140
Per capita Energy, World	1.4	0.3	132	106
Per capita Energy, US	0.7	–0.2	115	96

Table 8-2 Dynamics of Change: Energy Efficiency and Intensity Improvement.

	Historical rate of change, %/yr		Hypothetical in 2010 index 1990=100 based on	
	long-term (50-200 yrs)	short-term (since 1970)	long-term rate	short-term rate
E/GNP, World	≈ −0.1	−1.0	98	82
E/GNP, US	≈ −1.0	−2.0	82	67
E/Industry, OECD		−3.0		54
E/Industry, Japan		−4.0		44
Aircraft fuel/t-km	−1.0	−4.0	82	44
Cars l/km, US	−0.9	−2.0	83	67
Cars l/km, Europe		−1.0		82
Household E/capita, US	0.5	−0.7	110	87
Household E/capita, EU	2.7	1.1	170	124
Household E/capita, J	5.5	2.6	292	167
Refrigerators		−3.5		49
Air condition		−2.0		67
Process heat		−1.5		74
Electricity generation	−2.8	0	57	100

9. REFERENCES

ABB (Asea Brown Boveri) (1989), Kombi-Heizkraftwerk PEGUS E 12 MK 225 MW, Typ HKA-13E-1, ABB, Baden, Switzerland.

AIP (1975), *Efficient Use of Energy*, American Institute of Physics, AIP Conference Proceedings No. 25, AIP, New York.

Ahern, J.E. (1980), *The Exergy Method of Energy Systems Analysis,* John Wiley & Sons, New York.

Alcamo, J., Amann, M., Hettelinch, J.P., Holmberg, M., Hordijk, L., Kämäri, J., Kauppi, L., Kauppi, P., Kornai, G. and Mäkelä, A. (1987), Acidification in Europe: a Simulation Model for Evaluating Control Strategies, *Ambio* Vol. 16 No.5:232-245.

Amann, M. (1989), Potential and Costs for Control of NO_x Emissions in Europe, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Amann, M. and Kornai G. (1987), Cost Functions for Controlling SO_2 Emissions in Europe, WP-87-065, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Ausubel, J.H., Grübler, A. and Nakićenović, N. (1988), Carbon Dioxide Emissions in a Methane Economy, *Climatic Change* 12(1988):245-263.

Ausubel, J.H. (1989), Regularities in Technological Development: An Environmental View, in: J.H. Ausubel and H.E. Sladovich (Eds), *Technology and Environment,* National Academy Press, Washington D.C.

Ausubel, J.H. and Grübler, A. (1989), Working Time, Long-term Trends and the Rise of the Service Economy, International Institute for Applied Systems Analysis, Laxenburg, Austria (forthcoming).

Ayres, R.U. (1988), Energy Inefficiency in the US Economy: A New Case for Conservation. Carnegie Mellon University, Pittsburgh.

Ayres, R.U. (1989), Technology Forecast for CIM, *Manufacturing Review* Vol. 2, No.1 (March 1989):43-52.

Bacastow, R. and Keeling, C.D. (1981), Atmospheric Carbon Dioxide Concentration and the Observed Airborne Fraction, in: B. Bolin (Ed), *Carbon Cycle Modelling,* SCOPE 16, Wiley, Chichester.

Baehr, H.D. (1979), Die Exergie der Brennstoffe, *Brennst.-Wärme-Kraft* 31(1979):292-297.

Balzhiser, R.E. and Yeager, K.E. (1987), Coal Fired Power Plants for the

Future, *Scientific American*, September (1987):92-99.

Bairoch, P. (1983), Energy and Industrial Revolution: New Approaches, *Revue de l'Energie* 356(8/9,1983):399-408.

Berger, A. (1988), Milankovitch Theory and Climate, *Rev. Geophys.* Vol. 26, No.4(1988):624-657.

Berner, R.A. and Lasage, A.C. (1989), Modeling the Geochemical Carbon Cycle, *Scientific American*, March (1989):54-61.

Bolin, B. (1979), Global Ecology and Man, Proceedings of the World Climate Conference, February 1979.

Bolin, B., Döös, B.R., Jäger, J. and Warrick, R.A. (Eds) (1986), *The Greenhouse Effect, Climatic Change, and Ecosystems*, SCOPE 29, Wiley, Chichester.

Bolle, H-J., Seiler, W. and Bolin, B. (1988), Other Greenhouse Gases and Aerosols, in: Bolin, B., Döös, B. R., Jäger, J. and Warrick, R. A. (Eds) (1986), *The Greenhouse Effect, Climatic Change, and Ecosystems*, SCOPE 29, Wiley, Chichester.

Brimblecombe, P. (1987), *The Big Smoke - A History of Air Pollution in London since Medieval Times.* Methuen, London & New York.

BP (British Petroleum) (1982), *BP: Statistical Review of World Energy*, British Petroleum Company, London.

BP (British Petroleum) (1988), *BP: Statistical Review of World Energy*, British Petroleum Company, London.

Brooks, H. (1988), The Typology of Surprises in Technology, Institutions and Development, in: J. Clark and T. Munn (Eds.), *Sustainable Development of the Biosphere*, International Institute for Applied Systems Analysis, Laxenburg, Austria.

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) (1989), *Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen.* BGA, Hannover.

Cipolla, C. (1976), *Before the Industrial Revolution, European Society and Economy 1000-1750,* Methuen, London.

Davis, G.R. (1989), Responding to the Challenge of Global Warming: the Role of Energy Efficient Technologies, in: *Energy Technologies for Reducing Greenhouse Gas Emissions* Vol. 1, pp. 71-85, OECD, Paris.

Deutscher Bundestag (1983), *Waldschäden und Luftverunreinigungen, Sondergutachten März 1983 des Rates von Sachverständigen für Umweltfragen,* Drucksache 10/113, Deutscher Bundestag, Bonn.

Deutscher Bundestag (1988), *Schutz der Erdatmosphäre: eine internationale Herausforderung*, zur Sache 5/88, Deutscher Bundestag, Bonn.

Döös, B.R. (1989), IIASA Climatic Change Study, International Institute for Applyed Systems Analysis, Laxenburg, Austria.

Dosi, G. (1983), Technological Paradigms and Technological Trajectories, the Determinants and Directions of Technical Change and the Transformation of the Economy, in: C. Freeman (Ed), *Long Waves in the World Economy*. Butterworths, London.

Dosi, G., Freeman, G., Nelson, R., Silverberg, G. and Soete, L. (1988), *Technical Change and Economic Theory*, Pinter Publishers Ltd, London.

Dreyfus, D. A. (1987), Alternative Views of the Methane Age, in: T.H. Lee *et al.*, (Eds), *The Methane Age*, Kluwer Academic Publishers, Dordrecht and IIASA, Laxenburg, Austria.

Dreyfus D.A. and Ashby A.B. (1989), *Global Natural Gas Resources,* Gas Research Institute, Washington, D.C.

Eden R., Posner M., Bending R., Crouch E. and Stanislaw J. (1981), *Energy Economics*, Cambridge University Press.

Edmonds, J. and Reilly, J. (1983a), A Long-term Global Energy-Economic Model of Carbon Dioxide Release from Fossil Fuel Use, *Energy Econ.* 5(2):74-88.

Edmonds, J. and Reilly, J. (1984b), Global Energy and CO_2 to the Year 2050, *Energy Journal* 4(3):21-47.

Edmonds, J., Reilly, J., Gardener, R.H. and Brenkert, A., (1985), *Uncertainty in Future Global Energy Use and Fossil Fuel* CO_2 *Emissions 1975 to 2075,* Institute for Energy Analysis, Oak Ridge.

Eliassen, A. and Saltbones, J. (1983), Modelling of Long-range Transport of Sulfur Over Europe: A Two Year Model Run and Some Model Experiments, *Atmospheric Environment* Vol.17, No.8(1983):1457-1473.

EMEP (1988), Estimates of Airborne Transboundary Transport of Sulfur and Nitrogen in Europe, EMEP/MSC-W Report 1/88, Norwegian Meteorological Institute, Oslo.

Euromonitor (1978), *European Marketing Data and Statistics 1977/78*, Euromonitor, London.

Euromonitor (1988), *European Marketing Data and Statistics 1987/88*, Euromonitor, London.

Eurostat (1988), *Useful Energy Balance Sheets 1985,* EUROSTAT, Luxembourg.

Fettweis, G.B. (1976), *Weltkohlenvorräte, eine vergleichende Analyse ihrer Erfassung und Bewertung,* Glückauf, Essen.

Fisher, J.C. (1974), *Energy Crises in Perspective*, Wiley-Interscience, New York.

Flora, P., Kraus, F. and Pfennig, W. (1987), *State, Economy, and Society in Western Europe 1815-1975,* Volume 2, Campus Verlag, Frankfurt.

Fortune (1974), March 1974, quoted in: McCarl *et al.,* (1980).

Fredriksson, R. (1983), *Energy Technol.* Vol. 1, No. 7 (1983).

Freeman, C. and Perez, C. (1988), Structural Crises of Adjustment, Business Cycles and Investment Behaviour, in: G. Dosi *et al.* (Eds.), *Technical Change and Economic Theory.* Pinter Publishers, London and New York.

Freeman, C. and Soete, L. (1987), *Technical Change and Full Employment,* Basil Blackwell, Oxford.

Gold, T. (1979), Terrestrial Sources of Carbon and Earthquake Outgassing, *J. Petrol. Geol.* 1(3):3-19.

Gold, T., (1985), The Origin of Natural Gas and Petroleum and the Prognosis for Future Supplies, *Annual Review of Energy*, Vol. 10(1983):53-77.

Gold, T. (1988a), Origin of Petroleum: Two Opposing Theories and a Test in Sweden, in: T.H. Lee *et al.,* (Eds), *The Methane Age*, Kluwer Academic Publishers, Dordrecht and IIASA, Laxenburg, Austria.

Gold, T. (1988b), Ancient Carbon Sources of Atmospheric Methane. *Nature* Vol. 335 (29th September 1988):404.

Goldemberg, J., Johansson, T.B., Reddy, A.K.N. and Williams, R.H. (1987), *Energy for a Sustainable World*, World Resources Institute, Washington D.C.

Gray, P.E. (1989), The Paradox of Technological Development, in: J.H. Ausubel and H.E. Sladovich (Eds), *Technology and Environment,* National Academy Press, Washington D.C.

Grübler, A. (1987), Technology Diffusion in a Long Wave Context: the Case of the Steel and Coal Industries. CRPEE, Montpellier, France and International Institute for Applied Systems Analysis, Laxenburg, Austria.

Grübler, A. (1989), *The Rise and Fall of Infrastructures, Dynamics of*

Evolution and Technological Change in Transport. Physica Verlag, Heidelberg (forthcoming).

Grübler, A. and Nakićenović, N. (1987), The Dynamic Evolution of Methane Technologies, WP-87-02, International Institute for Applied System Analysis, Laxenburg, Austria.

Grübler, A. and Nakićenović, N. (1988), Diffusion in the US and the USSR, Working Paper, International Institute for Applied Systems Analysis, Laxenburg, Austria (forthcoming).

Grübler, A. and Nowotny, H. (1989), Towards the 5th Kondratiev Upswing, Elements of an Emerging Growth Phase and Possible Development Trajectories, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Häfele, W. (Program Leader), *et al.* (1981), *Energy in a Finite World*, Ballinger, Cambridge, Mass.

Hansen, J. and Lebedeff, S. (1986), *Geophys. Res. Lett.* 15, 323 (1988).

Hawking, S. (1988), *A Brief History of Time,* Bantam Books, New York.

Helm, J.L. and Schneider, S. (1989), What to Do About CO_2, Draft, National Academy of Engineering, Washington, D.C.

Herman, R., Ardekani, S.A. and Ausubel, J.H. (1989), Dematerialization, in: J.H. Ausubel and H.E. Sladovich (Eds), *Technology and Environment*, National Academy Press, Washington D.C.

Humphrey, W. and Stanislaw, J. (1979), Economic Growth and Energy Consumptionin the U. K. 1700-1975, *Energy Policy*, March 1979.

Iansiti, E. and Niehaus, R. (1989), Impact of Energy Production on Atmospheric Concentration of Greenhouse Gases, *IAEA Bulletin* 2/1989:12-20.

IATA (International Air Transport Association) (1987), *World Air Transport Statistics,* IATA, Cointrin-Geneva.

IEA (International Energy Agency) (1987), *Energy Conservation in IEA Countries*, OECD, Paris.

IEA (International Energy Agency) (1988), Energy Balance of OECD Countries 1985/86, OECD, Paris.

IIASA Acid Rain Project (1987), Acidification in Europe, *Ambio* Vol 16, No. 5 (1987):232-245.

IIASA Transboundary Air Pollution Project (1989), Estimated Effects on Deposition in Europe of Presently Committed SO_x and NO_x Emission

Reductions, International Institute for Applied Systems Analysis, Laxenburg, Austria, (10 July 1989).

ILO (International Labour Office) (1988), *Year Book of Labour Statistics,* 48th Issue, ILO, Geneva.

Jahoda, M., Lazarsfeld, P.F. and Zeisel, H. (1933), *Die Arbeitslosen von Marienthal,* Hirzel, Leipzig.

Kram, T. and Okken, P.A. (1989), Two Low CO_2 Energy Scenarios for the Netherlands, in: *Energy Technologies for Reducing Emissions of Greenhouse Gases* Vol.2, pp. 465-486, OECD, Paris.

Krause, F. (1981), The Industrial Economy, an Energy Barrel without a Bottom, paper presented at the *Second International Conference on Soft Energy Paths,* Rome (1981).

Kuuskraa, V.A. and Meyers R.F., (1983), Review of World Resources of Unconventional Gas, in: M. Grenon and C. Delahaye (Eds), *Conventional and Unconventional World Natural Gas Resources,* Proceedings of the Fifth IIASA Conference on Energy Resources, CP-83-S4, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Landau, R., (1988), US Economic Growth, *Scientific American,* June (1988):26-34.

Laxton, P. (1976), The Geodetic and Topographical Evolution of English County Maps 1740-1840, *Cartographic Journal,* June 1976.

Last, F.T., Fowler, D. and Freer-Smith, P.H. (1987), Die Postulate von Koch und die Luftverschmutzung, *Forstw. Cbl.* 103(1984):28-48, Paul Parey Verlag, Hamburg, Berlin.

Lee, T.H. and Loftness, R.L., (1987), Managing Electrotechnology Innovation in the USA, WP-87-54, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Lee, T.H., Linden, H.R., Dreyfus, D.A. and Vasko T. (Eds) (1988), *The Methane Age,* Kluwer Academic Publishers, Dordrecht and IIASA, Laxenburg, Austria.

Lee, T.H. (1988), Combined Cycle Systems: Technology and Implications, in: T.H. Lee *et al.,* (Eds), *The Methane Age,* Kluwer Academic Publishers, Dordrecht and IIASA, Laxenburg, Austria.

Legasov, V.A. and Kuzmin, I.I. (1981), The Problem of Energy Production, *Prioroda* 2(1981):8-23.

Linden, H.R. (1987), World Oil: An Essay of its Spectacular 120 Years Rise, Recent Fall and Uncertain Future, *Energy System and Policy,* Vol 11, No.4 (1987):251-266.

Linden, H.R. (1988), Electrification of Energy Supply - An Essay on its History, Economic Impact and Likely Future, *Energy Sources,* Vol 10, No. 2 (1988):127-149.

Lovins, A.B., Krause, F. and Bach, W. (1981), *Least Cost Energy: Solving the CO_2 Problem,* Brick House Press, Andover, MA.

Lowe, D.C., Brenninkmeijer, C.A.M., Manning, M.R., Sparks, R. and Wallace, G. (1988), Radiocarbon Determination of Atmospheric Methane at Baring Head, New Zealand, *Nature,* 332(1988):522-525.

Manne, A.S. and Schrattenholzer, L. (1988), The International Energy Workshop - A Progress Report, *OPEC Review,* Spring (1988):35-48.

Manne, A.S. and Schrattenholzer, L. (1989), International Energy Workshop, International Institute for Applied System Analysis, Laxenburg, Austria.

Marchetti, C. (1982), When Will Hydrogen Come? WP-82-123, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Marchetti, C. (1988), How to Solve the CO_2 Problem Without Tears, *Int. J. Hydrogen Energy,* Vol. 14, No. 8(1989):493-506.

Marchetti, C. (1989), International Institute for Applied Systems Analysis, Laxenburg, Austria, personal communication.

McCarl, H.N. and Preda, G. (1980), Comparative Analysis of Potential Energy Conservation in Various Industrial Processes in Romania and in United States, in: Proceedings 11th World Energy Conference, Munich, Vol. 1B:218-134, WEC, London.

MacDonald, G.J. (1989), The Near and Far Term Technologies, Uses, and Future of Natural Gas, in: *Energy Technologies for Reducing Emissions of Greenhouse Gases,* Vol. 1, pp. 509-535. OECD, Paris

El Mahgary, Y. *et al.* (1986), Energy in the Transition from Rural Subsistence, *Third World Quaterly* Vol. 8, No.3 (1986):1097-1099.

Masters, C.D. *et al.* (1987), *World Resources of Crude Oil, Natural Gas, Natural Bitumen and Shale Oil,* in: Proceedings Twelfth World Petroleum Congress, Houston.

Martin, J.M., (1988), L'intensité énergétique de l'activité économique dans les pays industrialisés: les évolutions de très longue période livrent-elles des enseignements utiles? *Economies et Sociétés,* 4 (1988): 9-27.

Mitchell, B.R. (1980), *European Historical Statistics 1750-1975,* MacMillan Press, London.

Mitchell, B.R. (1982), *International Historical Statistics: Africa and Asia,* Macmillan Press, London.

Mohnen, V.A. (1988), The Challenge of Acid Rain, *Scientific American,* August (1988):14-22.

Muroyama, J.H. and Stever, H.G. (Eds), *Globalization of Technology,* National Academy Press, Washington D.C.

Nakićenović, N. (1984), *Growth to Limits, Long Waves and the Dynamics of Technology,* International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakićenović, N. (1986), Patterns of Change - Technological Substitution and Long Waves in the United States, WP-86-13, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakićenović, N. (1988), Dynamics of Change and Long Waves, WP-88-74, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakićenović, N. (1989), Expanding Territories: Transport Systems Past and Future, in: D.F. Batten and R. Thord (Eds), *Transportation for the Future,* Springer Verlag, Berlin.

Nef, J. (1932), *The Rise of the British Coal Industry,* Frank Gass and Co Ltd, London,

Neftel, A., Moor, E., Oeschger, H. and Stauffer, B. (1985), Evidence from Polar Ice Cores for the Increase in Atmospheric CO_2 in the Past Two Centuries, *Nature,* 315(1985):45-47.

New York Times, 22 March 1986.

Nowotny, H. (1988), Long-term and Short-term Strategies for Science and Technology Policies in Developing Countries, paper prepared for the meeting of the International Council for Science Policy Studies, Paris, March 24-25, 1988. Draft, University of Vienna.

Nordhaus, W.D. and Yohe, G. (1983), Future Carbon Dioxide Emissions From Fossil Fuels, in: *Changing Climate: Report of the Carbon Dioxide Assessment Committee,* National Research Council, National Academy Press, Washington D.C.

OECD, (1988), *Uranium: Resources, Production and Demand,* OECD, Paris and IAEA, Vienna.

OECD (1989), Energy Prices and Taxes, Fourth Quarter 1988, International Energy Agency, OECD, Paris.

OPEC (1986), Petroleum Product Prices and Their Components in Selected

Countries - 1984, OPEC, Vienna.

Olivier, D. and Miall, H. (1983), *Energy Efficient Futures: Opening the Solar Option,* Earth Resources Research Limited, London.

Pry, R.H. (1988), The Changing Nature of Industrial Management, International Institute for Applied Systems Analysis, Austria.

Putnam, P.C. (1953), *Energy in the Future,* D. Van Nostrand Co., New York.

Reister, D.B. (1984), An Assessment of the Contribution of Gas to the Global Emissions of Carbon Dioxide, Final Report GRI-84/003, Gas Research Institute, Chicago.

Reynold, R. and Pierson, A. (1942), Fuel Wood Used in the United States 1630-1930, Circular N. 641, USDA Forest Service, Washington D.C.

Reynolds, T. (1984), Medieval Roots of the Industrial Revolution, *Scientific American,* July (1984):108-116.

Robinson, J. (1987), Insurmountable Opportunities? Canada's Energy Efficiency Resources, *The International Journal of Energy,* Vol 12, No.5(1987):403-417.

Rogner, H.H. (1984), The IIASA '83 Scenario of Energy Development, in: *Risks and Benefits of Energy Systems,* IAEA, Vienna.

Rogner, H.H. (1988), Technology and the Prospects for Natural Gas, *Energy Policy,* Vol. 16, No. 1(1988):9-26.

Rosenfeld, A.H. and Hafemeister, D. (1988), Energy-efficient Buildings, *Scientific American,* April (1988):56-63.

Rose, D.J., Miller, M.M. and Agnew, C. (1983), Global Energy Futures and CO_2 Induced Climate Change, MITEL 83-015, MIT Energy Laboratory, Cambridge, MA.

Rossi, C. (1984), Energy Aspects of Road Transportation, Future Development in Technology: the Year 2000, The Open University, London.

Schipper, L. (1976), Raising the Productivity of Energy Utilization, *Annual Review of Energy,* Vol 1 (1976):455-517.

Schneider, S. H. (1987), Climate Modeling, *Scientific American,* May (1987):72-81.

Schneider, S. H. (1989), The Greenhouse Effect: Science and Policy, *Science,* Vol. 243, February (1989):771-781.

Schumpeter, J.A. (1935) The Analysis of Economic Change. *Review of Economic Statistics,* 17(1935):2-10.

Schumpeter, J.A. (1939) *Business Cycles, A Theoretical, Historical and Statistical Analysis of the Capitalist Process*, Volume I and II, McGraw-Hill, New York.

Scientific American 1934, October 1934, Reprinted in: 50 and 100 Years Ago, *Scientific American*, October (1984):12.

Schurr, S. and Netschert, B. (1960), *Energy in the American Economy 1850-1975, An Economic Study of its History and Prospects,* John Hopkins Press, Baltimore.

Seidel, S. and Keyes, D. (1983), *Can We Delay a Greenhouse Warming?* EPA, Washington D.C.

Shaw, R., (1989), Working Together to Reduce Acid Rain, *Options*, March (1989):9–11, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Sorenson, B. (1982), An American Energy Future, *The International Journal of Energy*, Vol 7, No. 9(1982):783.

Steinberg, M. and Horn, F.L. (1982), Control of Carbon-Dioxide Emissions From a Power Plant and Use in Enhanced Oil Recovery, *Fuel,* Vol. 61, No.5 (1982):415-422.

Summers, C. M. (1971), The Conversion of Energy, in: *Energy and Power*, Scientific American Book, W.H. Freeman, San Francisco.

Swedish Ministry of Agriculture (1982), *Acidification Today and Tomorrow: A Swedish Study Prepared for the 1982 Stockholm Conference on the Acidification of the Environment,* Ministry of Agriculture, Stockholm.

Tchijov, I. (1989), FMS World Data Bank, WP-89-33, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Tchobanoglons, G., Theisen, G.H., and Eliassen, R.E. (1977), *Solid Wastes – Engineering Principles and Management Issues,* McGraw–Hill, New York.

Trabalka, J.R. (Ed) (1985), *Atmospheric Carbon Dioxide and the Global Carbon Cycle,* ER-0239, Department of Energy, Washinton D.C.

UBA (Umweltbundesamt Berlin) 1989, *Papier – Kunststoff – Verpackungen – Eine Mengen- und Schadstoffbetrachtung,* Berichte 1/89, Erich Schmidt Verlag, Berlin.

UN-ECE (1988), *Annual Review of Strategies and Policies for Air Pollution Abatement,* Report EB.AIR/R.32, United Nations Economic Commission for Europe, Geneva.

US Department of Commerce (1970), *Historical Statistics of the Unites*

States, Colonial Times to 1970, Part 1 and 2, Bureau of the Census, Washington D.C.

US Department of Commerce (1988), *Statistical Abstract of the United States*, Bureau of the Census, Washington D.C.

Verkehr in Zahlen (1985), Der Bundesminister für Verkehr (Ed), Bonn.

Victor, D.G. (1989), Greenhouse Gas Emissions from High Demand, Natural Gas-intensive Energy Scenarios, Working Paper, International Institute for Applied Systems Analysis, Laxenburg, Austria (forthcoming).

WAES (1977), *Energy: Global Prospects 1985-2000,* final report of the Workshop on Alternative Energy Strategies, MacGraw-Hill, New York.

Wahlen, M., *et al.* (1989), Carbon–14 in Methane Soucres and in Atmospheric Methane: The Contribution from Fossil Carbon, *Science* Vol. 245(21 July 1989):286–290.

Weinberg, A.M. (1977), On Time and the Energy Wars, *Nature* Vol. 269(20th October):638.

Weinberg, A.M. (1978), Reflections on Energy Wars, *American Scientist* 66(2)Mar/Apr.:153–158.

WEC (World Energy Conference) (1978), *Survey of Energy Resources,* WEC, London.

WEC (World Energy Conference) (1983), *Survey of Energy Resources,* WEC, London.

WEC (World Energy Conference) (1986), *Survey of Energy Resources,* WEC, London.

WEC (World Energy Conference) (1988), *Environmental Effects Arising from Electricity Supply and Utilization and the Resulting Costs to the Utility,* WEC, London.

WEC (World Energy Conference) (1989), *Survey of Energy Resources,* WEC, London.

White, L. (1972), The Expansion of Technology 500-1500, *The Fontana Economic History of Europa*, Vol. 1, Fontana, London.

Wilson, C.L. (1980), *Coal: Bridge to the Future,* Wocol (World Coal Study) Vol. 1, Ballinger, Cambridge, MA.

Wigley, T.M.L. (1985), Historical Climate Impact Assessment, in: R.W. Kates, J.H. Ausubel and M. Berberian (Eds), *Climate Impact Assessment: Studies of the Interaction of Climate and Society,* SCOPE 27, Wiley & Sons, New York.

Wigley, T.M.L. (1987), The Impact of Climate on Resource Use and Availability, in: D.J. McLaren B.J. Skinner (Eds), *Resources and World Development: Energy and Minerals, Water and Land,* Wiley, Chichester.

Williams, R.H., Dutt, G.S. and Geller, H.S. (1983), Future Energy Savings in U.S. Housing, *Annual Review of Energy.*

Williams, R.H. (1987), Exploring the Global Potential for More Efficient Use of Energy, in: *Resources and World Development,* Mc Loren and Skinner, New York.

Williams, R.H., Larson, E.D. and Ross, M.H. (1987), Materials Affluence, and Industrial Energy Use, *Annual Review of Energy,* Vol. 12(1987):99-144.

Zahavi, Y. (1979), The "UMOT" Project, Report DOT-RSPA-DPB-20-79-3, preparerd for US Department of Transportation and Ministry of Transport, FRG, NTIS, Springfield, Virginia.

APPENDIX

Energy Conversion Factors and List of Abbreviations and Acronyms

CONVERSION FACTORS

The following gives the *definitions of units* of measure used throughout this book as numerical multiples of coherent Standard International (SI) units. The exact definition is indicated by ✓; other numbers are approximate to the number of digits shown.

1 acre = 4,046.8564224 m^2 ✓
1 bar = 100,000 N/m^2 ✓
1 barrel (petroleum, 42 gallons) = 0.1589873 m^3
1 Btu (British thermal unit) = 1,055 J
1 calorie (thermochemical) = 4.184 J ✓
1 electron volt = 1.60210×10^{-19} J
1 erg = 10^{-7} J ✓
1 foot = 0.3048 m ✓
1 gallon (UK, liquid) = 4.546087×10^{-3} m^3
1 gallon (U.S., liquid) = $3.785411784 \times 10^{-3}$ m^3 ✓
1 hectare = 10,000 m^2 ✓
1 horsepower (metric) = 736 W ✓
1 inch = 0.0254 m ✓
1 kilopond = 9.80665 N ✓
1 langley = 41,840 J/m^2 ✓
1 pound force = 4.4482216152605 N ✓
1 pound mass = 0.45359237 kg ✓
1 mile (U.S. statute) = 1,609.344 m ✓
1 millibar = 100 N/m^2 ✓
1 nautical mile = 1,852 m ✓
1 ton (long) = 1,016.0469088 kg ✓
1 ton (metric) = 1,000 kg ✓
1 ton (short, 2,000 pounds) = 907.18474 kg ✓
1 Wyr = $31,536 \times 10^3$ J ✓
1 yard = 0.9144 m ✓

USEFUL APPROXIMATIONS

1 million barrel of oil per day (1 mbd) ≅ 71 GW
1 million barrel of oil per day ≅ 50 million tons of oil per year
1 Btu ≅ 1 kJ
1 TWyr ≅ 30 Quad
1 TWyr ≅ 10^9 tce

Conversion Table for Common Energy Units

	J	Btu	Quad	kcal	mtce	10^6mtce	boe	10^6boe
1 J =	1	947.9×10^{-6}	947.9×10^{-21}	239×10^{-6}	34.14×10^{-12}	34.14×10^{-18}	163.4×10^{-12}	163.4×10^{-18}
1 Btu =	1055	1	1×10^{-15}	0.2522	36.02×10^{-9}	36.02×10^{-15}	172.4×10^{-9}	172.4×10^{-15}
1 QUAD =	1055×10^{15}	1×10^{15}	1	252×10^{12}	36.02×10^{6}	36.02	172.4×10^{6}	172.4
1 kcal =	4184	3.966	3966×10^{-18}	1	142.9×10^{-9}	142.9×10^{-15}	683.8×10^{-9}	683.8×10^{-15}
1 mtce =	29.29×10^{9}	27.76×10^{6}	27.76×10^{-9}	7×10^{6}	1	1×10^{-6}	4.786	4.786×10^{-6}
10^6mtce =	29.29×10^{15}	27.76×10^{12}	27.76×10^{-3}	7×10^{12}	1×10^{6}	1	4.786×10^{6}	4.786
1 boe =	6119×10^{6}	5.8×10^{6}	5.8×10^{-9}	1462×10^{3}	0.2089	208.9×10^{-9}	1	1×10^{-6}
10^6boe =	6119×10^{12}	5.8×10^{12}	5.8×10^{-3}	1462×10^{9}	208.9×10^{3}	0.2089	1×10^{6}	1
1 mtoe =	44.76×10^{9}	42.43×10^{6}	42.43×10^{-9}	10.7×10^{6}	1.528	1528×10^{-9}	7.315	7315×10^{-9}
10^6mtoe =	44.76×10^{15}	42.43×10^{12}	42.43×10^{-3}	10.7×10^{12}	1528×10^{3}	1.528	7315×10^{3}	7.315
1 m^3 gas =	37.26×10^{6}	35.31×10^{3}	35.31×10^{-12}	8905	1272×10^{-6}	1272×10^{-12}	6089×10^{-6}	6089×10^{-12}
1 ft^3 gas =	1055×10^{3}	1000	1×10^{-12}	252.2	36×10^{-6}	36×10^{-12}	172.4×10^{-6}	172.4×10^{-12}
1 kWyr =	31.54×10^{9}	29.89×10^{6}	29.89×10^{-9}	7537×10^{3}	1.076	1076×10^{-9}	5.154	5154×10^{-9}
1 GWyr =	31.54×10^{15}	29.89×10^{12}	29.89×10^{-3}	7537×10^{9}	1076×10^{3}	1.076	5154×10^{3}	5.154
1 TWyr =	31.54×10^{18}	29.89×10^{15}	29.89	7537×10^{12}	1076×10^{6}	1076	5154×10^{6}	5154

	mtoe	10^6mtoe	m^3 gas	ft^3 gas	kWyr	GWyr	TWyr
1 J =	22.34×10^{-12}	22.34×10^{-18}	26.84×10^{-9}	948×10^{-9}	31.71×10^{-12}	31.71×10^{-18}	31.71×10^{-21}
1 Btu =	23.57×10^{-9}	23.57×10^{-15}	28.32×10^{-6}	0.001	33.45×10^{-9}	33.45×10^{-15}	33.45×10^{-18}
1 QUAD =	23.57×10^{6}	23.57	28.32×10^{9}	1×10^{12}	33.45×10^{6}	33.45	33.45×10^{-3}
1 kcal =	93.47×10^{-9}	93.47×10^{-15}	112.3×10^{-6}	3966×19^{-6}	132.7×10^{-9}	132.7×19^{-15}	132.7×10^{-18}
1 mtce =	0.6543	654.3×10^{-9}	786.1	27.76×10^{3}	0.9287	928.7×10^{-9}	928.7×10^{-12}
10^6mtce =	654.3×10^{3}	0.6543	786.1×10^{6}	27.76×10^{9}	928.7×10^{3}	0.9287	928.7×10^{-6}
1 boe =	0.1367	136.7×10^{-9}	164.2	5800	0.194	194×10^{-9}	194×10^{-12}
10^6boe =	136.7×10^{3}	0.1367	164.2×10^{6}	5.8×10^{9}	194×10^{3}	0.194	194×10^{-6}
1 mtoe =	1	1×10^{-6}	1201	42.43×10^{3}	1.419	1419×10^{-9}	1419×10^{-12}
10^6mtoe =	1×10^{6}	1	1201×10^{6}	42.43×10^{9}	1419×10^{3}	1.419	1419×10^{-6}
1 m^3 gas =	832.3×10^{-6}	832.3×10^{-12}	1	35.31	1181×10^{-6}	$1181\ 10^{-12}$	1181×10^{-15}
1 ft^3 gas =	23.57×10^{-6}	23.57×10^{-12}	28.32×10^{-3}	1	33.45×10^{-6}	33.45×10^{-12}	33.45×10^{-15}
1 kWyr =	0.7045	704.5×10^{-9}	846.4	29.89×10^{3}	1	1×10^{-6}	1×10^{-9}
1 GWyr =	704.5×10^{3}	0.7045	846.4×10^{6}	29.89×10^{9}	1×10^{6}	1	1×10^{-3}
1 TWyr =	704.5×10^{6}	704.5	846.4×10^{9}	29.89×10^{12}	1×10^{9}	1000	1

Factor	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12*}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*1 TW (terawatt) = 10^{12} W.

Abbreviations and Acronyms

AIP	American Institute of Physics
API	American Petroleum Institute scale for specific gravity of liquids
atm	Unit of air pressure at mean sea level
bbl	Barrel (159 liters)
boe	Barrel oil equivalent (6.119 10^9 Joule)
BGA	Bundesanstalt für Geowissenschaften und Rohstoffe, FRG
BP	British Petroleum Company Ltd.
Btu	British thermal unit (1054.5 Joule)
CFC'c	Chlorofluorocarbons
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CPE's	Centrally planned economies
ECE	U.N. Economic Commission for Europe
EJ	Exajoule (10^{18} Joule)
EMEP	European Monitoring and Evaluation Program
EPA	Environmental Protection Agency, US
FAO	U.N. Food and Agriculture Organization
FBC	Fluidized bed combustion
FBR	Fast Breeder Reactor
GDP	Gross Domestic Product
GNP	Gross National Product
GW	Gigawatt (10^9 Watt)
GW(e)	Gigawatt electric
GW(th)	Gigawatt thermal
GWhr	Gigawatt hour (3.6 10^{12} Joule)
GWyr	Gigawatt-year per year (31.54 10^{15} Joule)
HHV	Higher heating value
HTGR	High Temperature Gas-cooled Reactor
ICSU	International Council of Scientific Unions
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IEW	International Energy Workshop
IIASA	International Institute for Applied Systems Analysis
J	Joule
K	Kelvin (degrees)
kcal	kilocalorie (4184 Joule)
kW	Kilowatt
kW(e)	Kilowatt electric
kW(th)	Kilowatt thermal
kWh	Kilowatthour (3.6 10^6 Joule)
kWyr	Kilowatt-year per year (31.54 10^9 Joule)

LDC's	Less Developed Countries
LHV	Lower heating value
LNG	Liquified natural gas
LWR	Light Water Reactor
MAB	Man and the Biosphere Program
mbd	Million barrels per day
mbdoe	Million barrels per day oil equivalent
mpg	Miles per gallon (1.609 km per 3.785 liter gasoline)
MW	Megawatt (10^6 Watt)
MW(e)	Megawatt electric
MW(th)	Megawatt thermal
MWh	Megawatt hour (3.6 10^9 Joule)
MWyr	Megawatt year per year (31.54 10^{12} Joule)
NAE	National Academy of Engineering, US
NAS	National Academy of Sciences, US
NASA	National Aeronautics and Space Administration, US
N_2O	Nitrous Oxide
NO_x	Nitrogen Oxides
NSF	National Science Foundation, US
OAPEC	Organization of Arab Petroleum Exporting Countries
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of Petroleum Exporting Countries
OTEC	Ocean Thermal Electric Conversion
PJ	Petajoule (10^{15} Joule)
ppm	Parts per million (per 10^6)
ppb	Parts per billion (per 10^9)
SCOPE	Scientific Committee on Ocean and Polar Exploration
SO_2	Sulfur Dioxide
STEC	Solar Thermal Electric Conversion
tC/yr	Tons carbon per year
tce	Ton coal equivalent (29.29 10^9 Joule)
toe	Ton oil equivalent (44.76 10^9 Joule)
TW	Terawatt (10^{12} Watt)
TW(e)	Terawatt electric
TW(th)	Terawatt thermal
TWh	Terawatt hour (3.6 10^{15} Joule)
TWyr	Terwatt year per year (31.54 10^{18} Joule)
UBA	Umweltbundesamt, FRG
UNCTAD	U.N. Council on Trade and Development
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
VOC's	Volatile Organic Compounds
WAES	Workshop on Alternative Energy Strategies
WEC	World Energy Conference
W/m^2	Watt per square meter