THE TECHNICAL POTENTIAL FOR IMPROVEMENT

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Our research activities at the International Institute for Applied Systems Analysis (IIASA) in Austria, focus on long-term environmental, social, economic and technological developments in the world. As you can imagine, energy is a crucial component of that development, and I believe energy efficiency is central to future energy transitions over the next half century. Consequently, I focus mostly on the issues of energy efficiency developments in the world rather than addressing the question of energy efficiency in the United Kingdom. I make inferences to the United Kingdom situation where possible.

Basically, the technical energy efficiency improvement potential in the world is indeed enormous. Over the next half a century it might contribute up to, let us say, 50% of the potential improvement in energy services in the world. However, one cannot look at the technical energy efficiency improvement potential alone, one has to consider the systems context for efficiency improvements. One also has to look at end-use efficiencies, the structural change in energy end use, and the structural change in the energy system itself. Those factors might also be some of the major limiting factors in achieving high efficiency improvement potential. Therefore, one key question is, over which time horizon might we achieve some of those potentials that we know should be out there.

Before directly addressing the question of improvement potential let me set the scene by indicating some of the key energy questions today. When a number of large international energy studies and many national energy studies started about 20 years ago, the key question was whether resource availability would ultimately limit energy use and economic development in the world. This was in the aftermath of the oil shocks and the large price increases, a time when energy was really perceived as a very limited resource.

Today the situation has fundamentally changed. In the meantime, estimates of both energy reserves and resources have increased dramatically. Recently, I estimated with a number of colleagues the energy resource potentials in the world from the literature available on the subject. We came to the conclusion that at the current consumption rate the inferred energy resources might last up to 1000 years. However, even if it is less than 1000 years, say only a few hundred years, the result indicates we have to look for other major bottlenecks in future energy development rather than at the availability of resources.

The environmental compatibility of future energy development might be such a development constraint. In light of the changing debate on energy development, I would say that improvement in energy efficiencies might be one of the key ways to increase energy services without endangering the local and global environment. Consequently, efficiency improvement is now no longer necessary because we believe that we are running out of resources in the more immediate future, but rather because the constraints on energy use might be more stringent than we hitherto believed.

Other contributions here have addressed the question of global carbon dioxide and other greenhouse gas emissions. I would say that limiting these emissions worldwide is one of the pre-conditions for the environmental compatibility of future energy use. Another pre-condition is the reduction of local pollution, acid rain and other regional and local impacts of energy use. I would also like to consider the question of decarbonisation from a slightly different perspective[1]. In addition to the mitigation of global climate change there is another major reason for limiting carbon emissions. Decarbonisation can be considered an alternative efficiency indicator. Therefore, the decarbonisation of energy might be an end in itself in the same way as the efficiency of energy use would be. Before elaborating this concept, the current patterns of carbon emissions and therefore also energy use in the world are summarised.

Chart 1 shows per capita carbon dioxide and methane emissions in different world regions. The vertical scale shows the per capita emissions of carbon dioxide and methane, measured in tonnes of carbon equivalent. For example, in North America the total emissions are in the order of about six tonnes per person per year. The horizontal scale displays the relative population of each region. Multiplying these two scales together gives the area of each quadrant representing total emissions of each world region, and therefore also the relative contribution to the total global carbon emissions of these world regions. The bar code (shading) starts with coal, oil and gas, and ends with all non-energy sources of carbon such as biota emissions and all anthropogenic sources of methane emissions. There are two main features of this global emissions comparison. First, the emissions in industrialised countries range from almost three to six tonnes per capita. North America and Australia are on top of the scale, with about six tonnes per capita. If former Eastern Germany were on this chart, it would also reach roughly six tonnes per capita, but the emissions are now rapidly decreasing with economic reform in that part of Germany. In contrast to that, some of the developing countries like India and China have very large populations but emissions of the order of less than one ton per capita equivalent, both carbon dioxide and methane (energy and non-energy) sources added together. The structure of emissions and consequently also energy use are fundamentally different. Here most of the emissions are due to the commercial uses of coal and much of the emissions are due to the non-energy uses of traditional energy sources, such as fuelwood, that in some cases are not sustainable and therefore result in net emissions of carbon to the atmosphere. In industrialised countries there is a heavy reliance on oil, so that oil is one of the major contributors to total emissions. There are clearly fundamentally different structures of the energy system. The energy systems of the industrialised countries, although they have much higher total emissions, are much more efficient. Structural efficiency changes occur as countries develop from low to high emissions on a per capita basis. Thus, decarbonisation and efficiency improvements offset some of the potential per capita increases and higher levels of energy consumption. This effect did not and does not occur to the same degree in all regions. For example, Western Europe and Japan have roughly the same level of energy services or the same level of economic development as North America and Australia at about half the emissions. We have the same situation in comparing the individual countries. In individual countries,

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[1] The concept of decarbonisation of energy is defined here as reduction of carbon dioxide emissions per unit energy consumed; for example, as a ratio of total energy-related carbon dioxide emissions divided by total primary energy consumption.

regions and economic sectors, economic development is occurring at fundamentally different levels of emissions and therefore also fundamentally different are the levels of energy efficiency.

To illustrate the relationship between decarbonisation, efficiency improvement, economic development and population growth, an identity sometimes referred to in the literature as the Kaya equation is used. It establishes a relationship between population growth, per capita economic activities measured as the gross domestic product (GDP), energy per unit economic activity and carbon dioxide emissions per unit energy on one side of the identity sign, and total carbon emissions on the other[2]. Two of these factors are increasing and two are declining at the global level. The two declining factors are actually the two efficiency indicators - decarbonisation and efficiency improvement. There are several caveats in using such simple and in many ways inadequate indicators for these complex relationships. The identity is used here as a proxy for determining the long-term rates of economic, energy, and emissions growth. The economic growth in the world, measured by GDP, is roughly about 3% per annum today and has been in this range for many decades now, so two of the four factors on the right of the identity are growing jointly at about 3% per annum.

The other two factors are the efficiency indicators. One is how much energy we use per unit of economic activity, often called energy intensity. The other indicator is carbon efficiency or intensity - how much carbon dioxide is emitted per unit energy consumed. These two are decreasing. In the world, energy intensity is decreasing at about 1% per year and carbon intensity is decreasing at about 0.3% per year. If you take these two factors together we have a total decrease of about 1.3% per year, and with the other two we have a joint growth of about 3% per year. Consequently, carbon emissions are increasing very close to 1.7% per year. The important issue is: under what conditions and at what rate can we expect carbon and energy intensities to improve, and whether and to what extent can they offset economic growth in the world in the future, resulting in a relative decrease of carbon dioxide emissions?

Chart 2 shows that carbon intensity of energy is in fact decreasing. The vertical scale shows tonnes of carbon emitted per unit of energy against time on the horizontal scale. The chart measures total energy consumption in the world with a somewhat unconventional unit of energy, the kilowatt year. For those more familiar with other units, that is roughly one tonne of coal equivalent, or about 0.7 tonnes of oil equivalent. Irrespective of the units, you can see that over the last 130 years the carbon efficiency has improved. The amount of carbon emitted per average unit of energy consumed in the world has decreased. One of the major factors for this improvement is the transformation and change of the global energy system. This is not efficiency improvement *per se*, but it is due to structural change.

Chart 3 illustrates the development of the global energy system. In the United Kingdom this process was started earlier than elsewhere. Shown are the relative shares of different energy sources as they contribute to the total primary energy supply in the world. Back in 1860 you

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[2] $CO_2 \equiv (CO_2/E) \times (E/GDP) \times (GDP/P) \times P$, where E represents energy consumption, the gross domestic product (GDP) or value added, and P population. Changes in CO_2 emissions can be described by changes in these four factors.

can see that about 70% of energy came from fuelwood, and much of it was really not used on a sustainable basis. Much of the biomass use unfortunately continues to be unsustainable in many countries so that carbon emissions result. Fuelwood was initially replaced by coal, which did achieve some reductions in carbon intensity because coal emits less carbon than dry fuelwood used on an unsustainable basis. The introduction of oil and later natural gas, both having much lower emissions than coal, have further decreased carbon emissions per unit of energy, or increased the efficiency of carbon use in the world. Most recently, the introduction of nuclear energy and hydropower, both carbon-free energy sources, should also be observed. The primary energy substitution resulted not only in the decarbonisation but also in higher overall efficiencies of the global energy system. Fuelwood was used locally with rather low efficiencies. Typical examples are for cooking and space heating either with open fire or low efficiency stoves and fireplaces. Coal continued to be used for these purposes but usually with higher efficiencies and more sophisticated end-use devices. In addition, coal provided a host of other, new energy services such as steam for locomotion and later also for electricity generation. All of these conversion processes had generally higher efficiencies compared with the average energy conversion efficiencies of the day. Introduction of crude oil, and later also of natural gas, replaced the provision of some of the above energy services by yet more efficient conversion processes, such as the internal combustion engine and gas turbine.

Overall efficiency of the energy system increased because of the new and more efficient energy conversion, transport, distribution and end-use systems and devices, but also the structural change in the energy system that accompanied the substitution of primary energy services is an important integral part of this overall striving toward higher and higher efficiencies. So the question is whether in the future the introduction of new alternative energy sources, such as renewable and nuclear energy, might also lead to further reductions in the carbon and energy intensities of our economies. This possibility is illustrated in Chart 4. We use a simple logistic substitution model to project historical dynamics into the future (Marchetti and Nakićenović, 1979; Nakićenović, 1982). This result should not be interpreted as a forecast but rather as an "as if" type of scenario of possible future developments assuming the following proposition: What will happen in the energy system if the world develops at the same rates of change as it has in the past? The outcome of that exercise is that natural gas would increase its share in the future and that alternative energy sources would expand, such as biomass, other renewable energy sources and nuclear energy. Chart 4 also shows the introduction of a completely new hypothetical, zero-carbon energy source in 2025. It is labeled "solfus" because the new energy option might be solar, fusion or both.

If changes in the energy system in the world continue in this direction, we can expect much lower carbon emissions. This would be consistent with and would continue with the historical development, but would be associated with more complicated transformation of energy and more complicated deliverance of energy services. Therefore, some of the potential energy efficiency improvements might be offset by structural change and need for more elaborate conversion and more sophisticated end-use technologies.

Energy intensity serves as a broad indicator of the average energy efficiency of the whole economy. Chart 5 shows the historical development of energy intensity in a number of countries. On the vertical scale is the amount of energy consumed (in Mega Joules), divided by unit economic activity (measured as GDP) in US$ (constant 1980) in these countries.

Following the curve for the United States, starting from the middle of the last century, you can see that energy intensity improvements on the said curve have been enormous corresponding to an average improvement rate of about 1% per year. There are also periods of retardation. We are probably in such a period today. We have observed actual increases in energy intensity over the past few years. The most extreme cases have been in some of the reforming economies of Eastern Europe and the former Soviet Union, where energy intensity has skyrocketed as the level of economic activity decreased, while energy consumption either stayed level or decreased to a lesser extent.

It is also interesting to note that there are countries like France and Japan that always had greater energy efficiency than most other industrialised countries, but have also managed to improve at the average rate of about 1% per year. The United Kingdom and Germany are somewhere in between.

Then there are some developing countries like India and Pakistan with comparatively high levels of energy intensity. China (CPA) is off the scale and has a high energy intensity if you measure GDP at market exchange rates. The position is very different for China (CPA) if purchasing power parity is used instead of market exchange rates. One of the main challenges when we talk about the potential of future energy improvements is not just to improve energy efficiency in the industrialised countries, where the potentials are large, it is in fact to achieve in the developing parts of the world some of the prevailing energy efficiencies that we see in the industrialised countries. This can be achieved with appropriate policy measures. I think past development and the current phase of development in the world gives us hope that we are heading in the right direction. However, what is occurring right now is not sufficient to achieve the kind of energy use reductions that are necessary.

Another reason for my optimism for future energy and carbon intensities to continue to decline, perhaps even at rates that exceed the historical experience, is that some salient structural features of economic and technological development also suggest higher efficiencies of all human activities. Let us call these structural features "stylized facts" of the development process. These "stylized facts" are images of how the development process might be occurring in the world. For clarity, let me just list four such features in oversimplistic, stereotypical statements which may even be cliches:

> "The poor get richer and the rich slow down". As countries or regions develop their growth rates decline (Rostow, 1980). This is almost a universal phenomenon and is reflected as slow growth of mature economies and rapid expansion of newly industrialised and rapidly developing ones. We consistently observe that the poorer countries do develop while the economic development in the rich countries slows down in time.
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> "Relation exists between population and economic growth." This phenomenon is sometimes also called the population transition. Initially, the population growth rate increases with economic development but eventually it declines leading to stable and aging population in developed economies. It is not clear which way the causality goes, but with the increases in economic development, population growth tends to decline. Slowing population growth might enable economic growth, or economic growth might reduce birth rates.

> Most of the projections for the next century indicate that by the middle of the next century the population may double and we might be living in a world of more than 10 billion people. So this kind of reduction in the rate of population growth is already assumed in these population projections, otherwise we would be living in a world of 20 billion or more people.
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> "Energy intensity declines and energy efficiency increases with economic development." This has been amply illustrated in previous charts that indicate rapid improvement in energy intensities and efficiencies through a number of processes occurring simultaneously including substitution of old by new practices, gradual improvements of individual processes and structural change.
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> "Electrification increases with efficiency improvement." This is a symbolic representation of the need to provide higher quality energy carriers to end use as development progresses. Electricity is one of the highest quality carriers. This tendency leads to more extensive energy conversion and thus offsets some efficiency improvements. But economic development, energy efficiency improves and energy intensity declines. At the same time the structure of the energy system changes to a higher quality of energy services, e.g., exemplified by the increases in the rate of electrification. For example, the share of electricity in final energy delivered to the consumer usually increases and that, of course, leads to some relative decline of overall primary to final energy efficiency because the production of electricity is less efficient than the production of other fuels. Thus, structural change offsets some of the potential efficiency improvements that are achieved in individual technologies.

Chart 6 illustrates this pattern of development, showing the amount of energy per unit of economic activity (measured as GDP) plotted against the level of economic development (measured as GDP per capita). You can see a declining trend for most of the world regions shown in the chart. We have NAM (United States and Canada) with declines since the beginning of the last century with the exception of two loops during the Great Depression and the Second World War. There is CPA region, mainly China, (standing for Centrally Planned economies in Asia) with very high energy intensity, and relatively low levels of official GDP per capita. All other world regions are shown as well as three aggregate regions: developed OECD countries (OECD); reforming countries (REFs); and developing countries (DCs).

Energy efficiency is not the only efficiency that improves with development and I would like to illustrate another important change. Namely, along with the improvements in energy and carbon efficiencies in industrialised countries, the efficiency of human labour and work has also improved. Chart 7 shows that the average working time in many OECD countries decreased from some 3000 hours per year a hundred years ago to as little as some 1500 to 1700 hours per year today. During this two-fold decrease in average working time, the life expectancy increased drastically, leading to more free time and less working time during human life. For example, in the United Kingdom about 30% of life long waking hours are spent at work today compared with almost 70% a century ago. This also means that more time is available for leisure and other nonworking activities leading to new energy demands. Comparison of Chart 5 and 7 indicates that during the last hundred years both working time and energy intensity have been more than halved. Those rates are typical for many different types of efficiency improvements at the aggregate level.

Efficiency improvements of individual processes, technologies and devices are often more rapid. For example, Chart 8 illustrates the average heat rate of coal fired power plants in the world. Originally the efficiency of coal generated by steam engines and electricity generated by steam engines and generators was of the order of about 5%. Today the average efficiency in most of the regions of the world is roughly about 35%. Similar improvement rates of energy efficiency can be observed for many of the technologies ranging from aircraft engines to cooking ranges and stoves. The efficiency of individual energy conversion systems has in many cases changed by a factor of about five over the same period. This corresponds to an efficiency improvement rate of more than 2.5% per year.

At the same time incomes and free time have increased, and therefore the amount of energy services required has increased, offsetting some of the efficiency improvement. For example, industrial production and mobility have increased by very large factors, more than a factor of 1000 during the last century. New energy demands are indeed enormous and are still increasing.

In other words, we have much more time available now for leisure activities and that offsets many of the efficiency improvements. Many of our modern leisure activities are associated with very high energy intensity. So that while incomes are increasing, the free time to consume energy is also increasing, undermining many of the efficiency improvements that we have achieved.

While the improvement potentials have been generally high for most individual technologies, the reason why we are not observing improvement potentials of about 2.5 or 3% per year at the level of the whole economy, is that a part of this individual technological improvement is compensated or offset by the structural changes and demand growth. Consequently, structural changes and substitution of old by new technologies are closely connected with the questions of efficiency improvement potentials.

One of the largest increases for energy services is in mobility. Chart 9 provides an example of mobility growth in France measured in passenger kilometres travelled by average person per day. You can see that originally, when horses were the main way of getting around, mobility was of the order of only 20 metres per person per day. Today it is about 40 kilometres per person per day. The major technological changes were shifts from horses to railways and now to motor vehicles and other passenger transport modes. You can also distinguish the two new emerging technologies for transport, very rapid rail (TGV) and air transport. The reason for showing the evolution of mobility is to indicate that the growth rate of this process is roughly about 4% per year, so that to keep primary energy requirements of transport activities constant, this would mean that mobility growth would have to be offset by a roughly equal, aggregate average efficiency increase at about 4% per year per capita, and that would be very difficult to achieve.

One of the major ways of achieving efficiency improvements, which we have to consider in view of expected growth of energy services, is not the gradual improvement of technologies as demonstrated for electricity generation from coal, but replacement of old by new technologies. Chart 10 shows the replacement of horses and horse carriages, by automobiles as the major form of individual transport in the United Kingdom. The complete replacement process took about three decades. Looking into the future, this means that by the year 2025 at these rates of change, we can indeed experience fundamental changes in our transport system. Another example shown in Chart 10 is the replacement of steam by diesel locomotive engines, also in the United Kingdom. This substitution process was also completed in three decades. An important consequence of this replacement process is that the average efficiency increased enormously throughout the substitution process for total fleets of road vehicles and locomotives since the new technologies were more efficient then the old ones.

A typical figure for gradual efficiency improvements might be about 2 to 3% per year. In contrast let us consider the replacement of horses by cars. The efficiency of a horse, as a transport means in terms of the energy equivalent of the hay it requires, is at most 4% and probably even less. The overall efficiency of the car is about 20 to 25% or about five to six times higher than a horse. This corresponds to an annual efficiency improvement rate of 5.5 to 6% for the whole vehicle fleet over a period of 30 years. Even if it were only a factor of two or three in 30 years, the improvement rate would be about 5 to 6%.

Thus, fundamental improvements in energy efficiency and rapid realisation of efficiency improvements potentials can be achieved by a very swift replacement of old capital vintages by new ones rather than by gradual and incremental improvements in existing technologies. As part of the same process, environmental impacts can also decrease at rapid rates. For example, urban pollution produced by horses, amounts to about 400 grammes of liquid and solid waste (emissions) per kilometre travelled, whereas the automobiles equipped with catalytic converters emit about five grammes of gaseous emissions over the same distance. Thus from the environmental point of view, automobiles represent a big improvement over horses. Nevertheless, these gaseous pollutants can have other environmental and regional air quality impacts once the density of the vehicles increases. High vehicle densities would probably not have been feasible at all with horses. Incidentally, a horse vehicle emits more CO_2 than a car per kilometre, although some of the carbon is recaptured in new horse feed. This comparison of horses and automobiles is summarised in Chart 11.

Basically what we need to do is to assess the efficiencies of all energy chains going from, let us say, primary energy to energy services. In order to reduce complexity, I will illustrate the resulting overall energy efficiency from primary to useful energy forms rather than go all the way to energy services.

In order to assess the energy efficiency improvement potential in the world over the next 30 to 40 years, we need to know first how efficient is the whole energy system today and how large are the technical efficiency improvement potentials, how technologies will be used and to what extent the structure of the energy system might change. We can not just look at the development of a single set of technologies or consumer sectors. Chart 12 captures in a schematic way different stages in energy conversion, transport, distribution and end use encountered in most modern energy systems. Individual technologies form so called energy chains. For example, crude oil is refined into motor and other fuels, motor fuel is used in an automobile to result in motion, or useful energy, which renders the ultimate energy service - distance travelled in getting from A to B.

Charts 13 to 16 illustrate the overall efficiency of the energy system in the world, (industrialised market, plus developing and reforming economies) and Chart 17 shows the global energy improvement potential.

Charts 13 to 16 show that the prevailing efficiencies of energy transformation from primary to useful forms range between 22 and 42%. The global average is about 34% as shown in Chart 13. The highest efficiencies prevail in the conversion of fuels from primary to secondary energy forms. Refinery efficiencies are about 90% and, on average, the conversion (including transport and distribution) of coal and gas also incurs rather low losses with efficiencies ranging from about 60 to almost 90%. The lowest fossil primary energy to final fuel efficiencies can be observed for natural gas in the developing economies (41%) and for natural gas and coal in the reforming economies (56 and 75%, respectively). Lower conversion efficiencies prevail for biomass transformation into final fuels: as low as 20% in the reforming economies. The generation of electricity is just as inefficient in comparison: about 36% in the market economies of the OECD countries, and often lower than 20% in both the reforming and developing economies. The global average is about 31%.

Overall, the primary to final energy conversion processes are quite efficient: the global average is about 74%; it is the highest in the developing economies with about 80% and lowest in economies in transition with 69%. It is perhaps counterintuitive that developing economies should have a *higher* efficiency than the economies in transition, although many individual energy chains such as electricity and natural gas are delivered with much *lower* efficiencies. The reason is that the shares of energy carriers with lower primary to final conversion efficiency at present, electricity and natural gas, are much lower in the developing countries than in the former Soviet Union and Eastern Europe.

In comparison, the final to useful energy conversion efficiency is very low, with 46% at the global level and a range of only 30% in the economies in transition and almost 53% in the market economies. In general, natural gas and electricity have the highest end-use efficiencies compared with the lowest primary to final conversion rates. The lowest end-use efficiencies can be observed for biomass, with 17% at the global level and only 12% in the reforming and developing economies.

The resulting overall primary to useful energy efficiencies are well below 50%. It is 34% at the global level; lowest with 22% in the developing economies and the highest with 42% in the reforming economies. This is indeed a very surprising result. Generally, the energy systems of these economies are rather inefficient, especially when compared with the standards prevailing in the market economies of the OECD. Actually, this is exactly the case. All individual primary to useful energy chains are more efficient in the market than in the reforming economies. In some cases the differences are very large indeed. For example, electricity efficiency, with more than 22% efficiency is double that in reforming economies (11%). The reason for the reverse situation with the overall aggregate efficiency is that the structure of the energy system in the reforming economies *favors* collective consumption and thus also *end-use efficiency*. People travel by public transport modes rather than private cars and they heat their homes using cogenerated heat rather than individual oil burners. Thus, while cars and buses are more fuel efficient in the market economies, travelling by bus in the reforming economies is more efficient than by car in the market economies.

The most important overall result is that energy end use is the least efficient part of all energy systems, and it is in this area that improvements would bring the greatest benefits. It also shows that even the most efficient technologies may not be sufficient to offset the energy-intensive lifestyles prevailing in very affluent market economies. I think this is also very important to keep in mind when we talk about potential efficiency improvement in the future.

So how large is this energy efficiency improvement potential? Chart 17 provides my estimate. The efficiency improvement potential in the world corresponds to at least a doubling of the overall efficiency compared to today. This calculation keeps the structure of the energy system constant, and does not include any of the structural changes discussed earlier. It is obtained simply by replacing every single conversion technology by the best available on the market. Earlier it was stated that the replacement of the vehicle fleets, e.g., the transition from horse to automobile, lasted about 30 years. If you take that as an average duration for the turnover of capital, which is a typical duration, and if nothing else changes, we could expect the efficiency of the energy system to double in about 30 to 40 years. Let us say around the year 2030 or so, the global energy efficiency could in principle double. The ultimate potential is naturally larger.

How large is the theoretical potential? One thing is certain, the theoretical potential is much higher. Briefly, I have tried to calculate what the minimum amount of work required would be to perform a particular energy service or energy task, and compare that to the current energy requirement to provide the same energy service or task.

Chart 18 illustrates the current efficiency in the OECD countries compared to this theoretical limit. Exergy denotes the minimum amount of work required for a particular task as defined by the second law of thermodynamics. The minimum theoretical requirement would be in the order of only a few percent of what we are actually using today. Thus, the theoretical improvement potential is indeed vast. I would say that the efficiency improvement potential is as vast as the energy resources are. The question is not that we are limited by the magnitude of the potential improvement. We are really limited by the time required to implement the potentials. We are limited by the structural and social changes that lead to new energy demands which offset some of the efficiency improvements that are achieved.

I have already mentioned that our societies do not only optimise energy use, they optimise the use of other factor inputs, such as materials, time and capital. Of course, for developing countries and for the poor, capital might indeed be one of the most limiting factors in improving efficiency, but time is important everywhere. I have mentioned that the amount of time available for energy consumption is increasing as working time decreases. Chart 19, based on the United States experience, shows energy efficiency or energy intensity per unit of time per unit of economic activity. It shows the amount of energy in terms of kilogrammes oil equivalent required per hour of time being at home. For example, being at home is relatively energy efficient, one tenth of what would be consumed at work per hour. Services are more energy intensive per unit time, the most energy intensive activity is in fact transport. Thus, mobility increases would indeed lead to a very high increase in the energy demand per unit of time, and the time available for mobility is increasing, as mentioned earlier. Incidentally, Chart 19 also shows the carbon dioxide emissions per unit of time - roughly 1 kilogramme of carbon per day is emitted by an average American.

Chart 20 provides another example of a very large automobile energy efficiency improvements drawn mainly, but not entirely, from the United States experience. The energy efficiency of the United States automobile fleet improved by about 20% during the last 20 years. Similar improvements are mentioned in Al Saje's contribution on the "Performance of Road Vehicles" in Europe here. This is a very impressive improvement, especially considering that it was achieved with the parallel introduction of catalytic converters that in principle require some additional energy. On the other hand, the United States fleet was down-scaled quite a lot in this period, down-sized, so that some of the efficiency improvements have to do with the reduction of the size of the vehicles.

If you look at the carbon emissions *per passenger kilometre* though, you will see that there is no large net improvement and that seems to be a contradiction. How can we have a situation where large efficiency improvement is achieved at a cost of many billion of dollars research and development over a period of 20 years, and at the same time the net carbon emissions associated with automobile use are really not decreasing? In fact, they have even increased a little bit.

Well the reason for that is that empty seats in cars have increased over the same period of time. This is an example where technical measures that lead to very large efficiency improvements are being offset to a considerable extent by relatively simple changes in human behaviour. When we seek to realise the energy efficiency improvement potential over the next 20 to 30 years, I think we also have to keep in mind that some of these problems might recur since they are not new. They have been around for many decades despite the active policies to try to come to grips with them. Half a century ago we had exactly the same problem, as the cartoon shown in Chart 21 demonstrates. Fifty years ago, the United States was gasoline starved because of the war effort, and one of the highest priorities for improving the efficiency of fuel in the transport sector was a recommendation to fill the empty seats. We have the same recommendation today and for the future, namely to improve not only the technical efficiency but also end-use efficiency that is to a large degree a function of our lifestyles and patterns of social behaviour. While it is consoling to know that the technical improvement potential is vast, there is an inherent risk that we do not respond to the need of improving the efficiency of energy end use and that we rely mostly on the promise of technical efficiency improvements.

Chart 1: CO_2 and CH_4 emissions per capita, versus population, for different world regions and by energy source (in tonnes of carbon equivalent per capita). In addition to industrial CO_2, the figure includes CO_2 from deforestation and all anthropogenic CH_4 emissions (1 kg CH_4 = 21 Kg CO_2). Source: Nakićenović *et al.*, 1993.

Chart 2: Global decarbonisation of energy since 1860 measured as the ratio of CO_2 emissions over unit primary energy consumed (in tonnes of carbon per kWyr). Source: Nakićenović *et al., 1993.*

Chart 3: Shares of five major energy sources in the global primary energy consumption (in percent). Source: Nakićenović, 1990.

Chart 4: Substitution of primary energy sources, historical data and future scenario (in percent). Source: Nakićenović, 1990.

Chart 5: Primary energy intensity (including wood and biomass) measured as the ratio of primary energy over unit economic activity (in MJ per constant GDP in 1980 US$ at market exchange rates and purchasing price parity). Source: Grübler, 1991. Source: Nakićenović *et al.*, 1993.

Chart 6: Energy intensity and per capita economic activity for world regions (shown in the legend), energy intensity is measured as the ratio of primary energy over unit economic activity (kgoe per constant GDP in 1980 US$) against per capita economic activity (GDP in 1980 US$ per capita).

Chart 7: Annual working hours in five industrialised countries, expressed in total working hours per year (hours spend on sick leave, strikes and holidays are subtracted from the formal working time). Source: Nakićenović *et al.*, 1989.

Chart 8: Improvements in electric conversion efficiency in the United States, Western Europe, former Soviet Union and Eastern Europe (in percent and Kcal/kWh). Source: Nakićenović *et al.*, 1989.

Chart 9: Growth of mobility in France measured as average distance travelled per capita per day (in passenger-km per capita per day). Source: Grübler, 1990.

Chart 10: Substitution of horse-drawn vehicles by automobiles and steam by diesel and electric locomotives, United Kingdom measured as share in total number of rolling stock (in percent). Source: Grübler *et al.*, 1992.

Chart 11: Emissions and efficiency of horses and automobiles (emissions in grammes per km and effeciency in percent).

Chart 12: Schematic illustration of an energy chain from energy resource extraction to services. Source: Rogner and Britton, 1991.

Chart 13: Final and useful energy efficiencies in the world, conversion efficiencies are shown as percentages of primary energy. Source: Nakićenović *et al.*, 1993.

Chart 14: Final and useful energy efficiencies in developing economies, conversion efficiencies are shown as percentages of primary energy. Source: Nakićenović *et al.*, 1993.

Chart 15: Final and useful energy efficiencies in (industrialised) market economies, conversion efficiencies are shown as percentages of primary energy. Source: Nakićenović *et al.*, 1993.

Chart 16: Final and useful energy efficiencies in reforming economies, conversion efficiencies are shown as percentages of primary energy. Source: Nakićenović *et al.*, 1993.

Chart 17: Final and useful energy efficiencies in the world using best available technologies, conversion efficiencies are shown as percentages of primary energy. Source: Nakićenović *et al.*, 1993.

Chart 18: Final, useful and service exergy efficiencies in the OECD countries, conversion efficiencies are shown as percentages of primary exergy. Source: Nakićenović *et al.*, 1993.

Chart 19: Time and energy consumption of individual activities in the United States, (in hours and kgoe), and energy intensity of time per activity (in kgoe per hour). Source: Grübler, 1991.

Chart 20: Carbon emissions, specific fuel consumption, passenger-km driven and empty seats for passenger cars in the United States (shown as change compared to 1970 average). Source: Grübler, 1993.

Chart 21: World War II poster encouraging car pooling. Source: OTA, 1991.

References:

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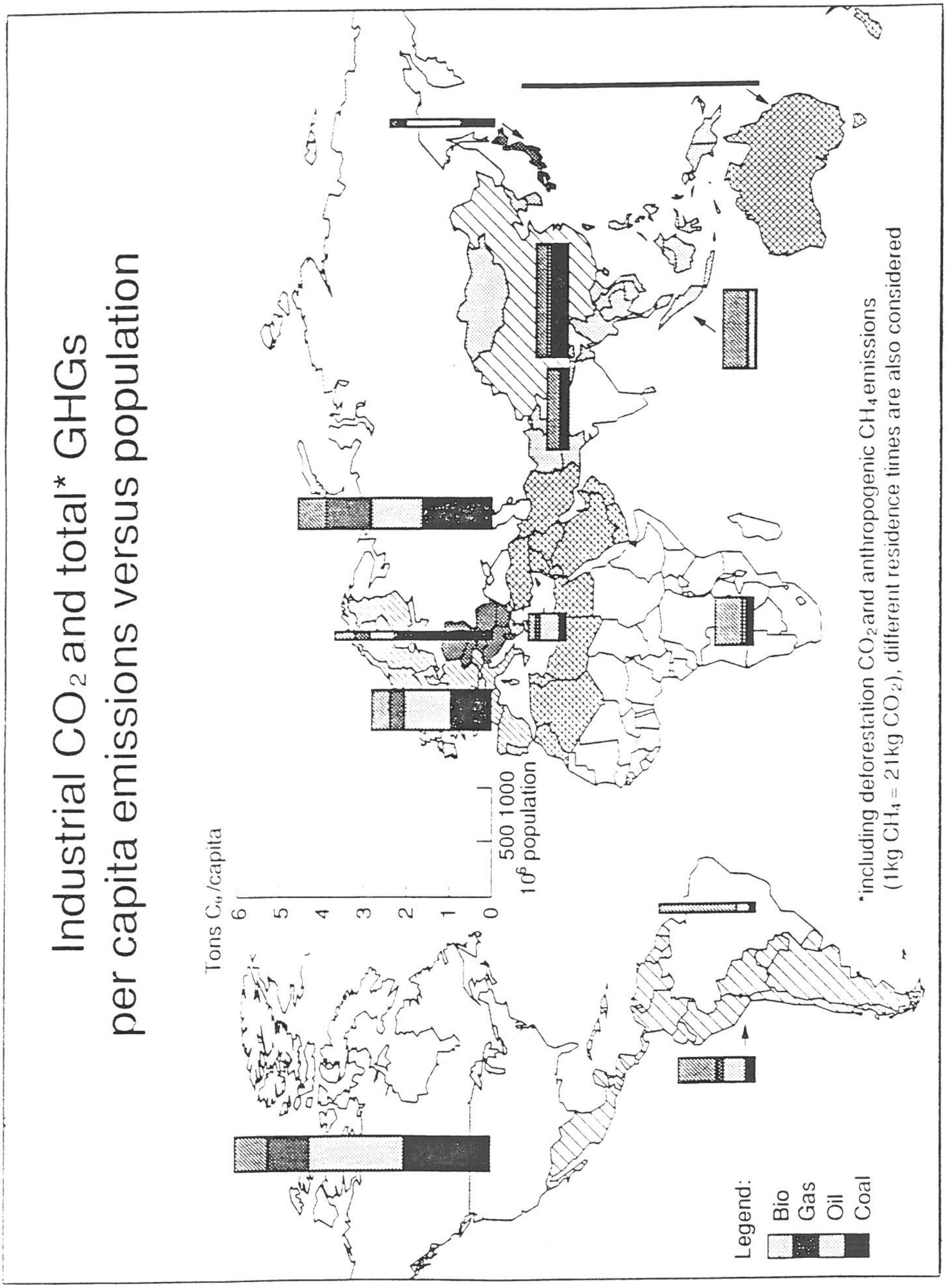
CHART 1



Industrial CO_2 and total* GHGs per capita emissions versus population

*including deforestation CO_2 and anthropogenic CH_4 emissions (1kg CH_4 = 21kg CO_2), different residence times are also considered

CHART 2

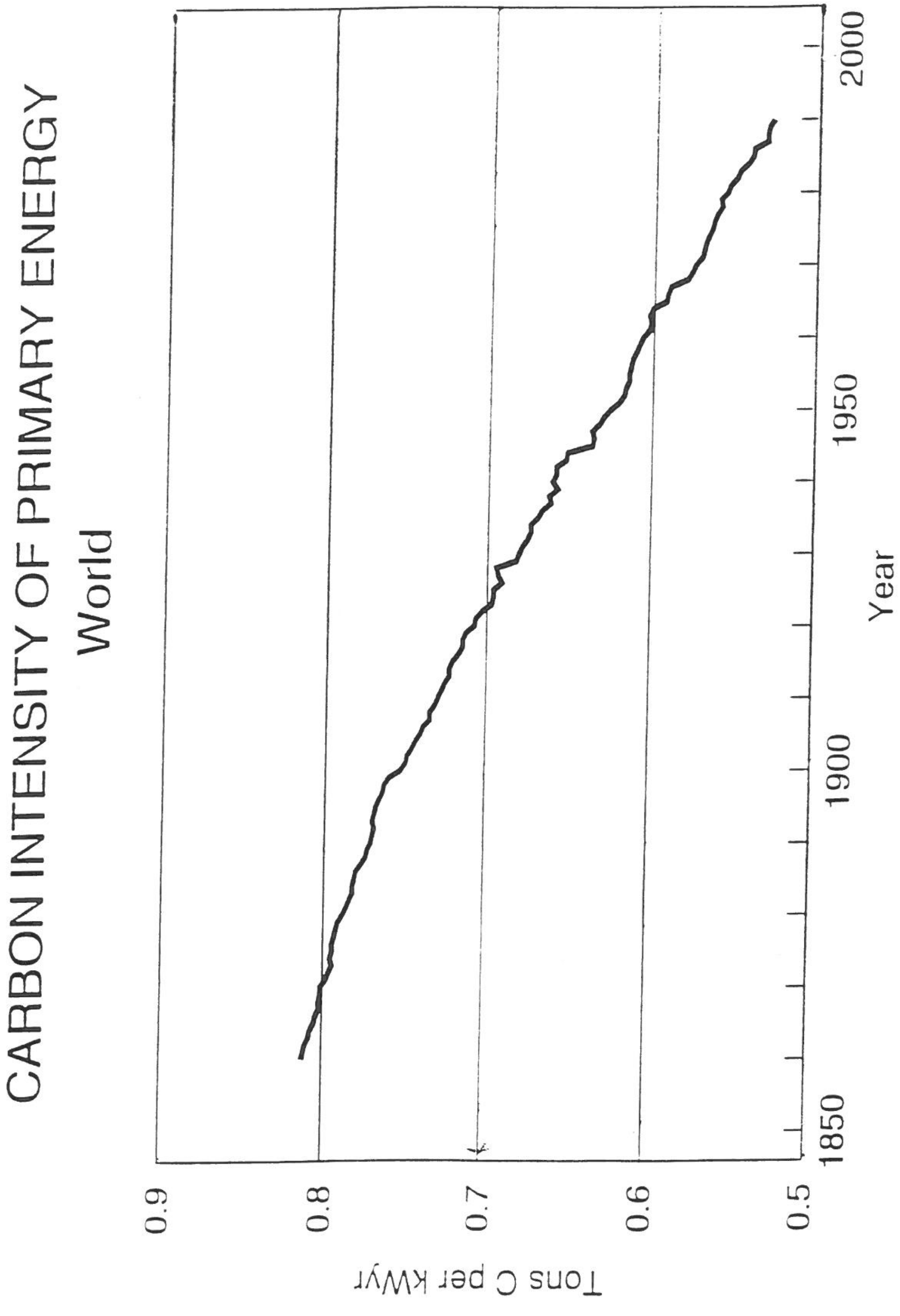

CARBON INTENSITY OF PRIMARY ENERGY
World
Tons C per kWyr
0.9
0.8
0.7
0.6
0.5
1850
1900
1950
2000
Year

CHART 3

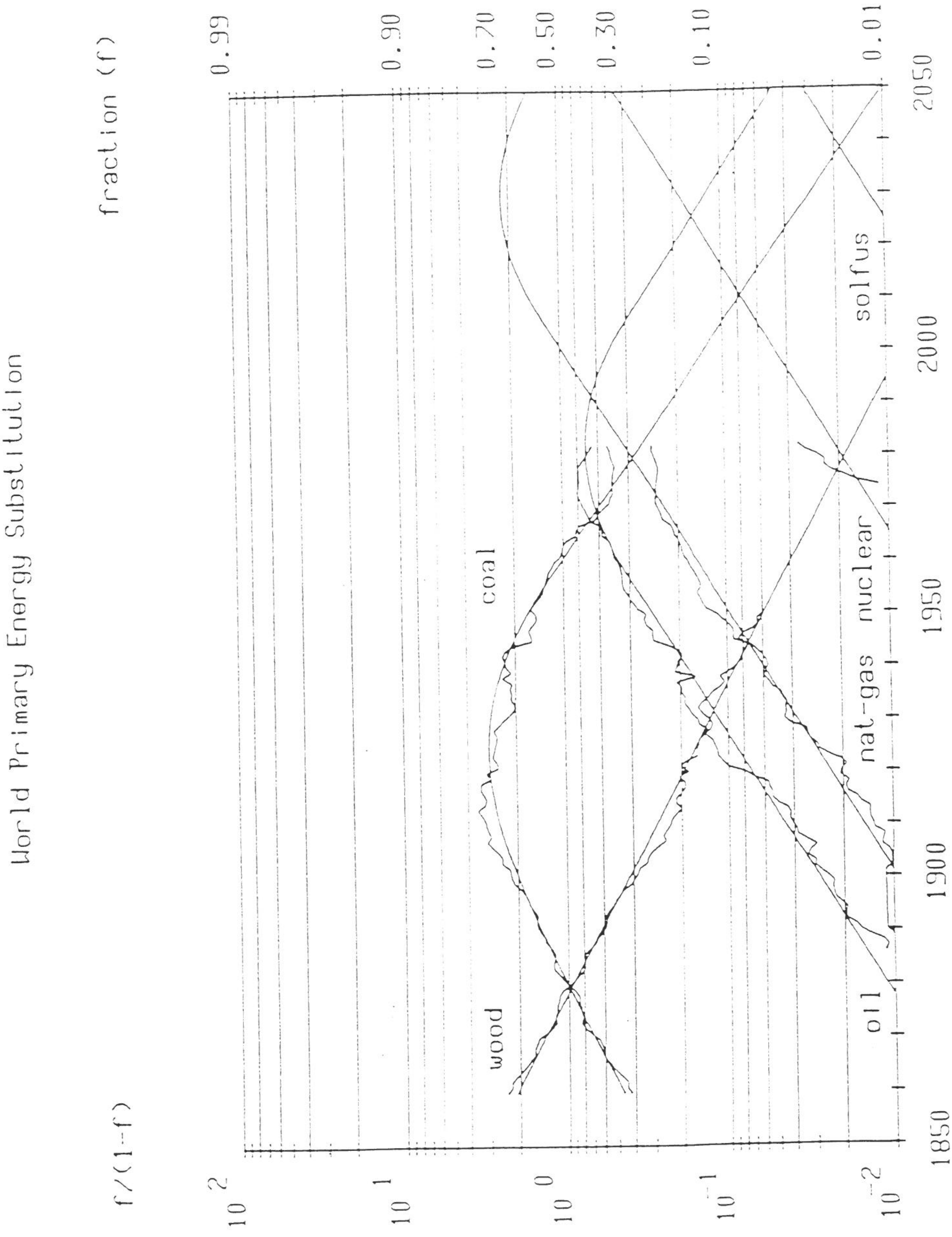

World Primary Energy Substitution
fraction (f)
f/(1-f)
0.99
0.90
0.70
0.50
0.30
0.10
0.01
10^2
10^1
10^0
10^-1
10^-2
1850
1900
1950
2000
2050
wood
coal
oil
nat-gas
nuclear
solfus

CHART 4

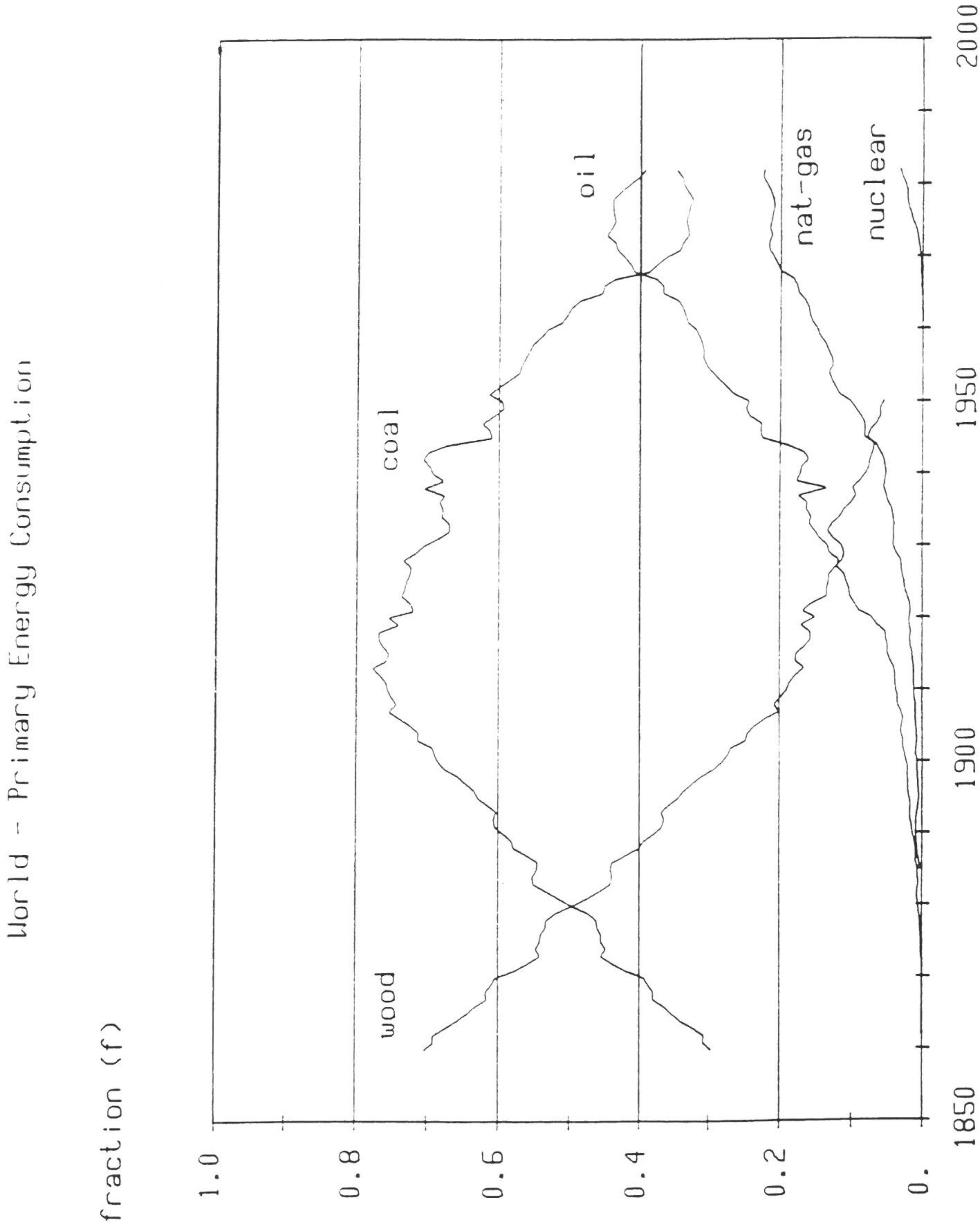

World - Primary Energy Consumption
fraction (f)
1.0
0.8
0.6
0.4
0.2
0.
1850
1900
1950
2000
wood
coal
oil
nat-gas
nuclear

CHART 5

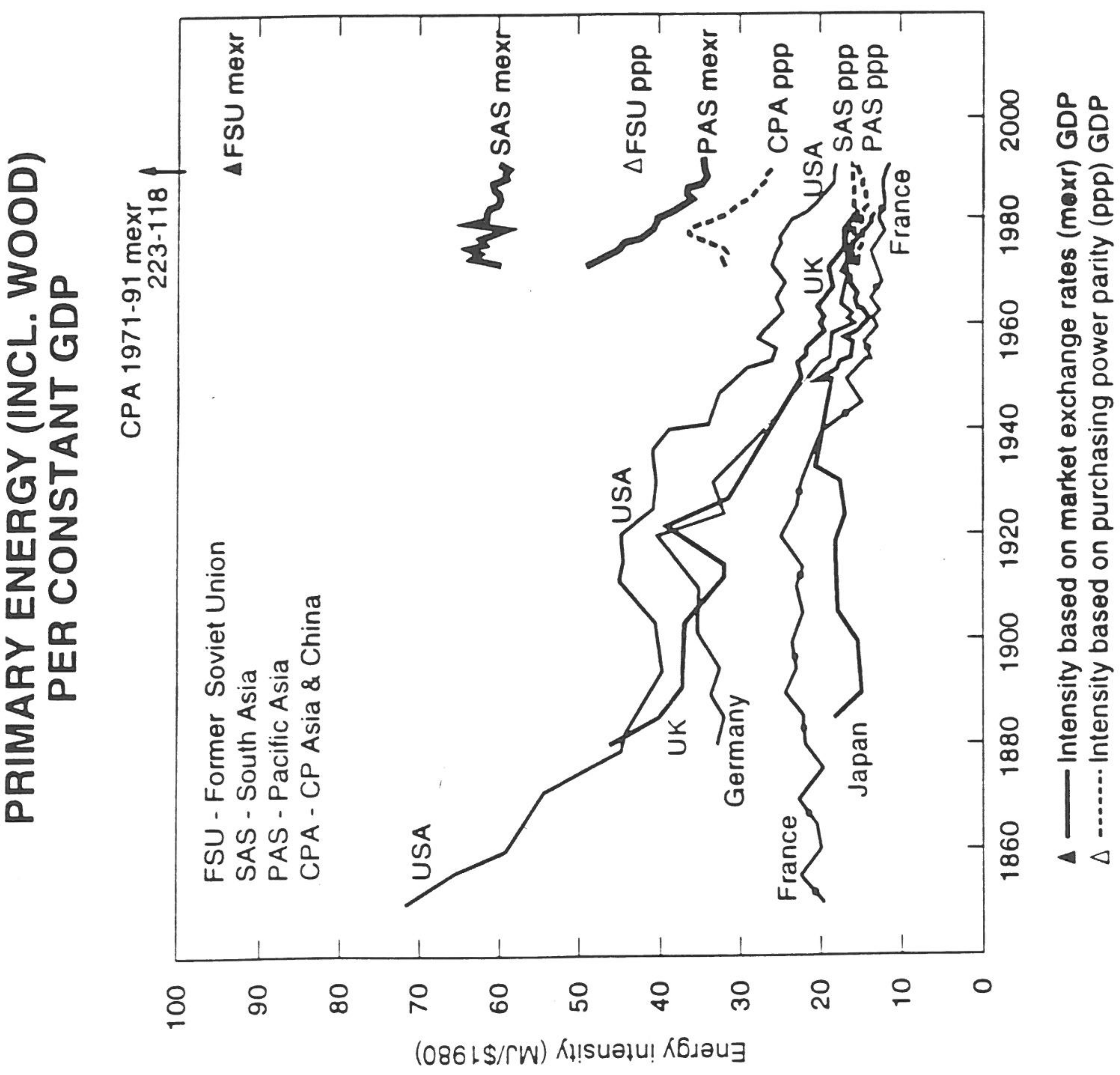

PRIMARY ENERGY (INCL. WOOD) PER CONSTANT GDP

CHART 6

ENERGY INTENSITY RATES

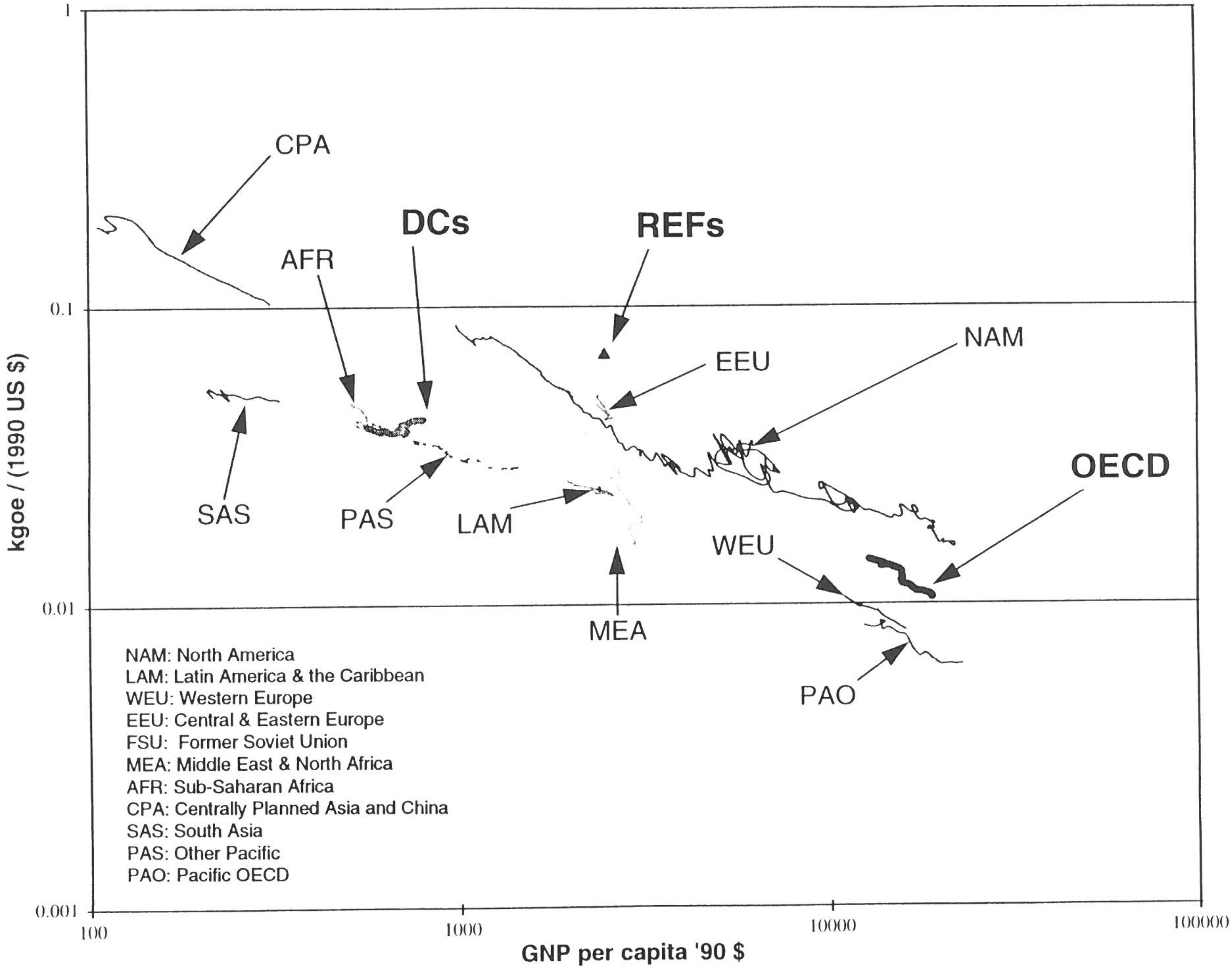


CHART 7

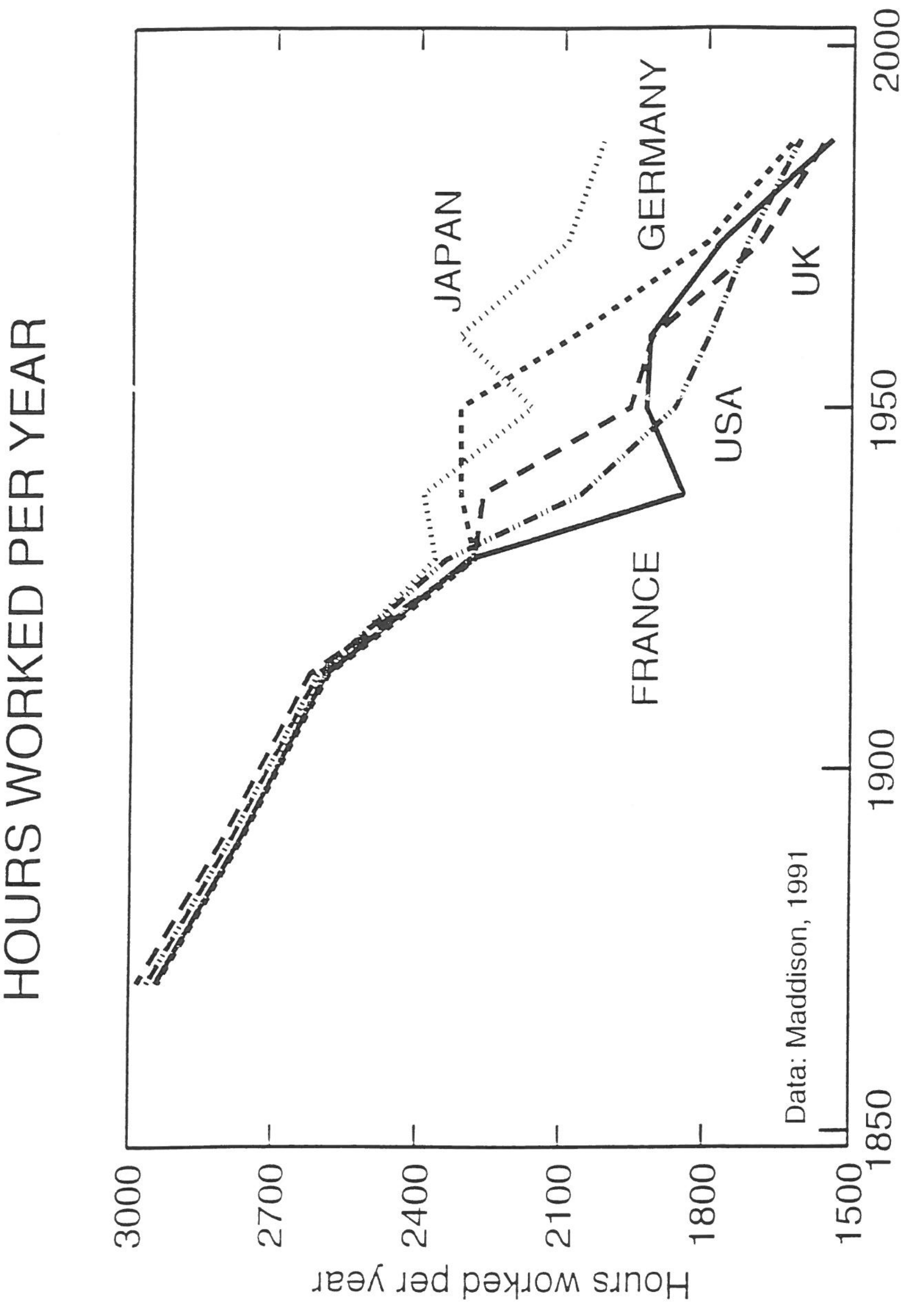
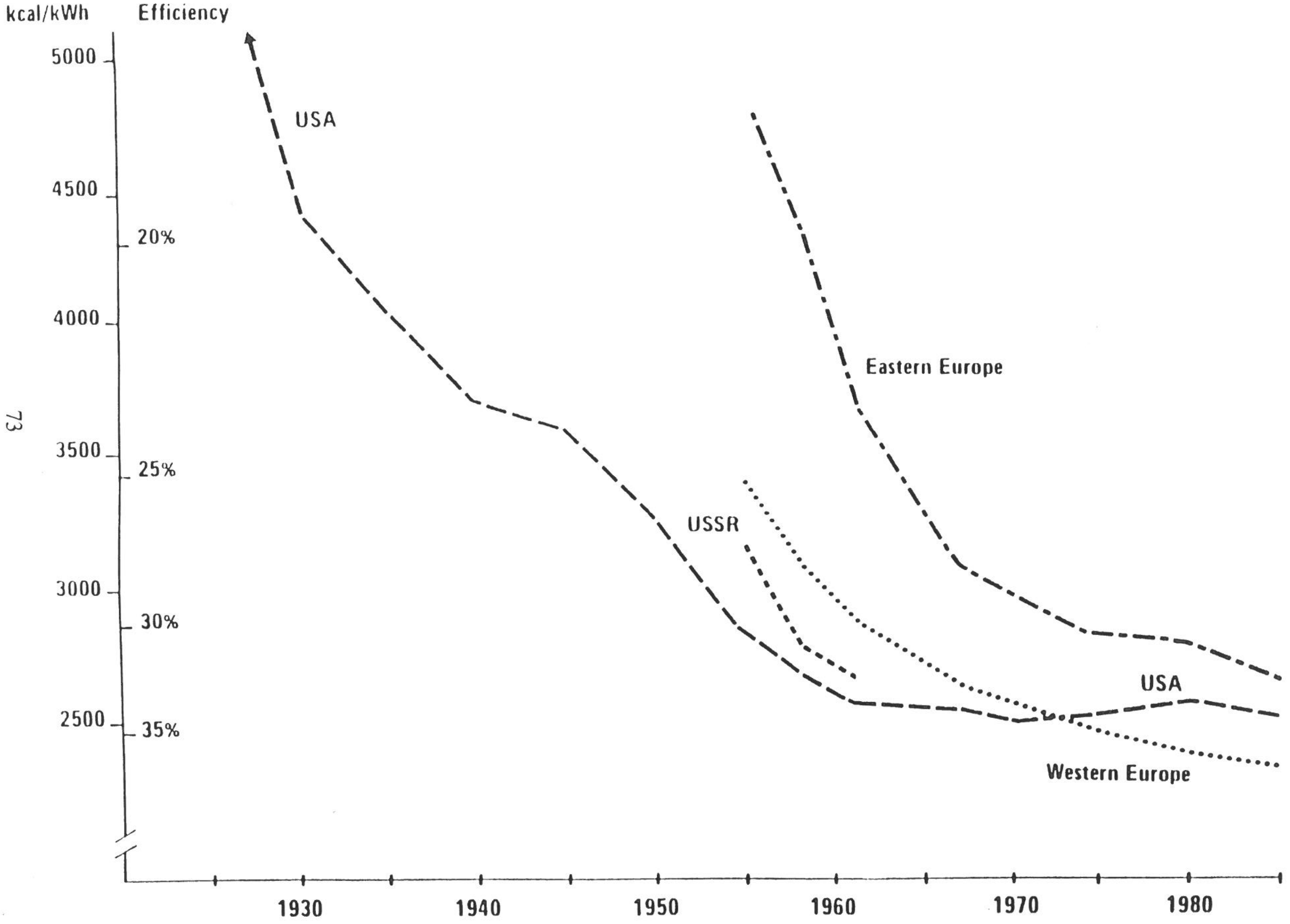

HOURS WORKED PER YEAR
Hours worked per year
3000
2700
2400
2100
1800
1500
1850
1900
1950
2000
JAPAN
GERMANY
FRANCE
USA
UK
Data: Maddison, 1991

CHART 8

AVERAGE HEAT RATE OF COAL-FIRED POWER PLANTS



Data source: ECE

CHART 9

FRANCE: DAILY TRAVEL RANGE
(pass-km per day per capita)

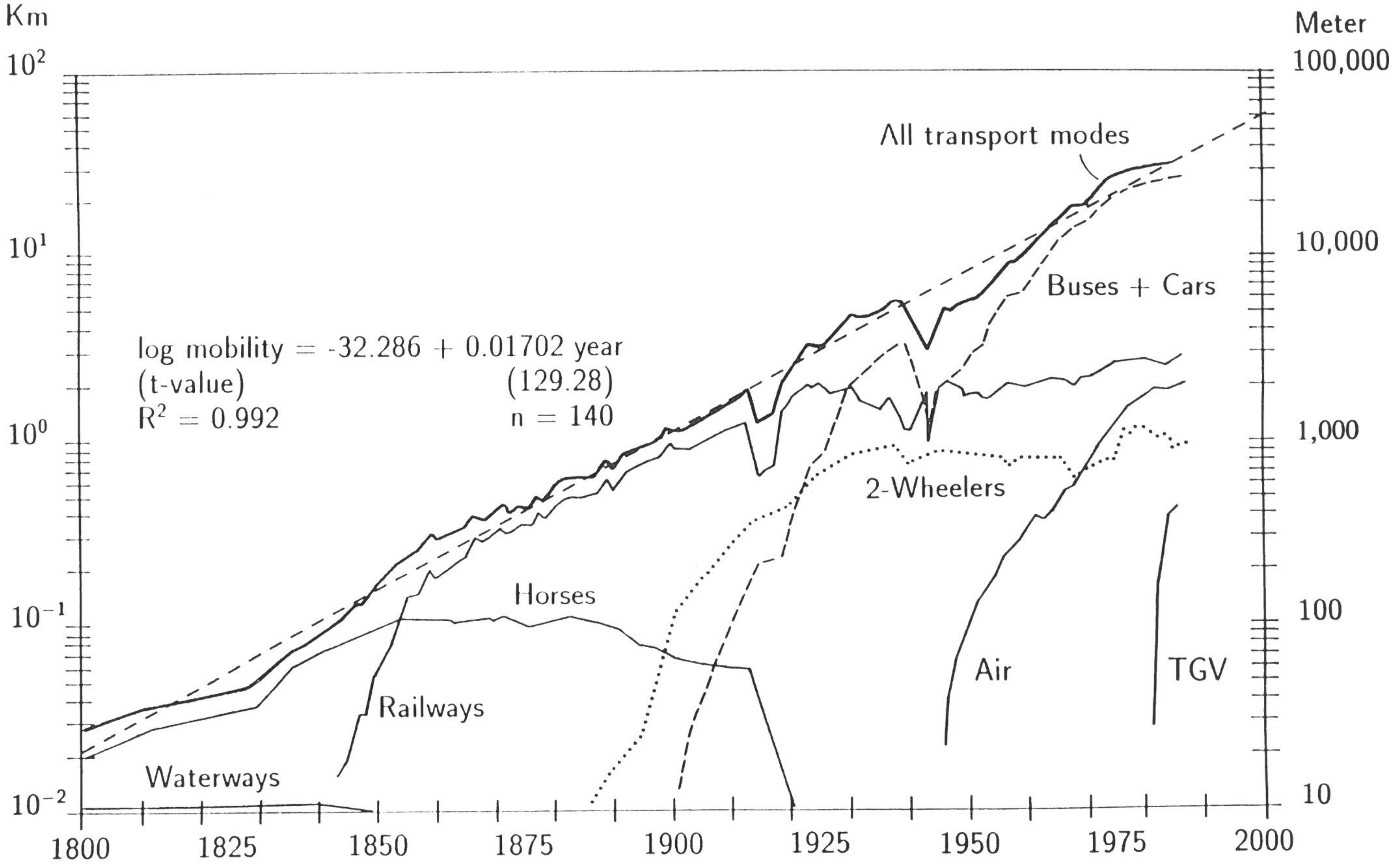
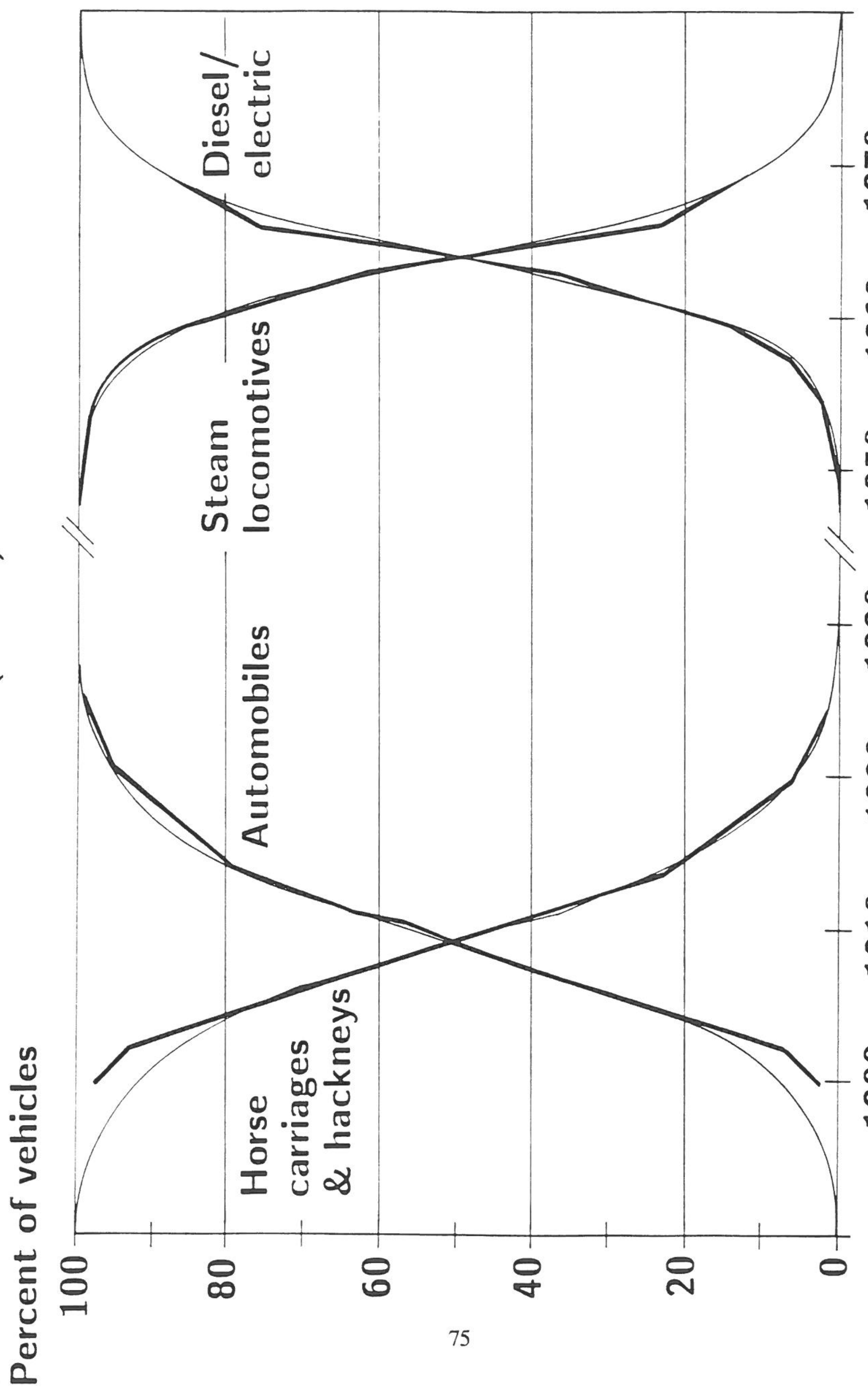


CHART 10



UK: REPLACEMENT OF VEHICLE FLEETS (shares)

CHART 11

Vehicular Pollution and Efficiency

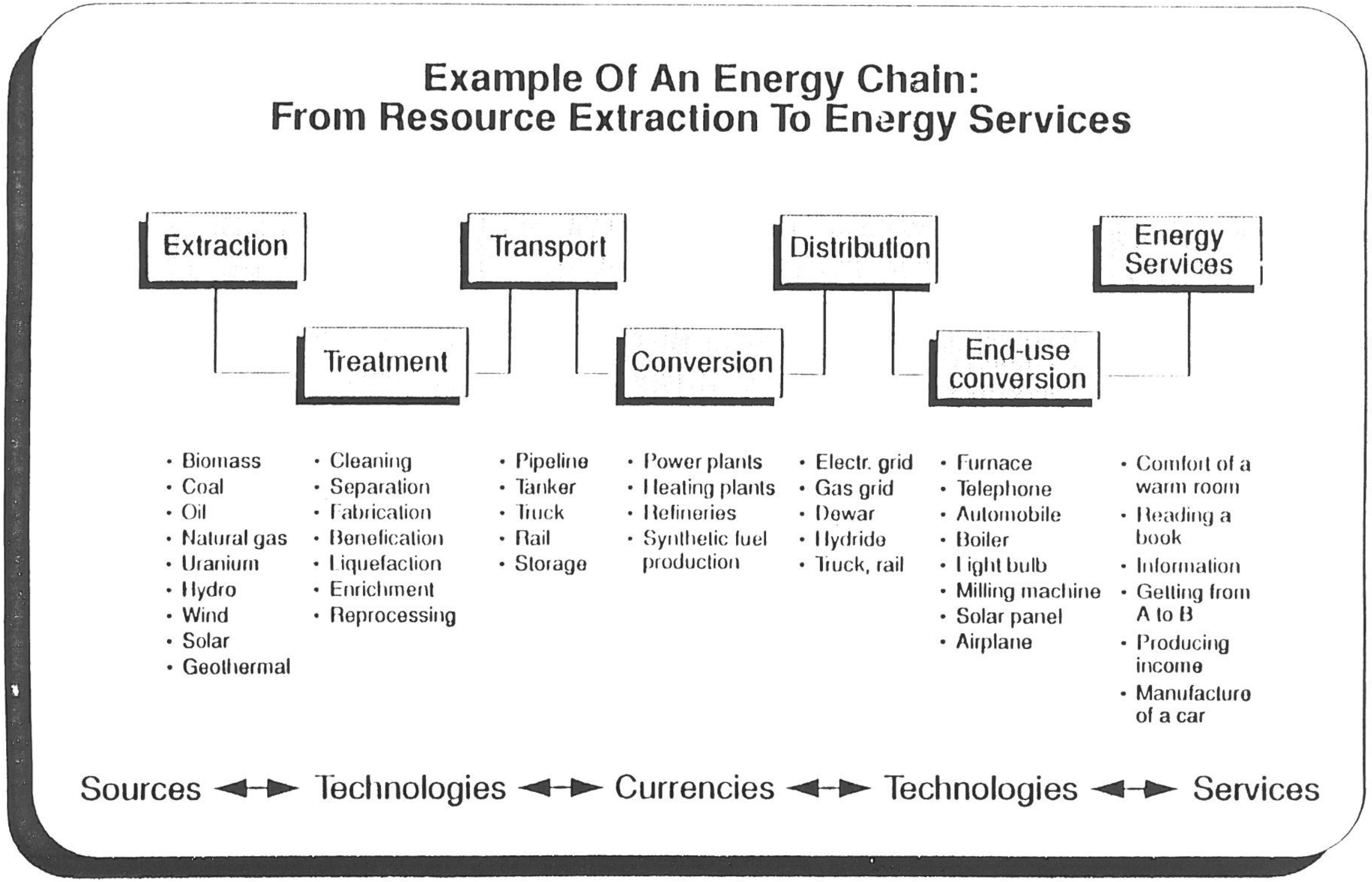
Means of Transport	Pollutant (form)	Emissions (grams/km)	Efficiency (percent)
Horses[a]			
	Carbon, content	170	4
	Waste, solid	400	
	Waste, liquid	200	
Automobiles[b]			
	Carbon dioxide	90	20
	Carbon monoxide	20-4.4	
	Hydrocarbons	2-0.2	
	Nitrous oxides	2-0.2	

---

[a] Calculation of emissions based on average production of 16 kg/day of solid waste and 7.5 kg/day of liquid waste and a range of 40 km/day. Assuming a work animal availability of 2,800 hours/year, load factor of 0.7 and average 3/4 HP output, it generates 1,600 PS-hours/year or about 0.12 kWyr with a total feed requirement of about 3 kWyr (15 kg/animal per day with average energy content of 4 kcal/gram of feed). In terms of carbon dioxide emissions, 3 kWyr of feed correspond to about 2.5 tons of carbon.

[b] Leaded gasoline and 1983 U.S. passenger vehicle standards compared to actual California standard (unleaded gasoline with catalytic converter over 50,000 miles). Engine efficiency assuming compression ratio of 9. Overall vehicle efficiency is much lower. Carbon dioxide emissions based on 121/100 km fuel consumption and annual mileage of 14,600 km correspond to 1.1 tons of carbon.

CHART 12



Example Of An Energy Chain: From Resource Extraction To Energy Services

Extraction	Treatment	Transport	Conversion	Distribution	End-use conversion	Energy Services
• Biomass • Coal • Oil • Natural gas • Uranium • Hydro • Wind • Solar • Geothermal	• Cleaning • Separation • Fabrication • Benefication • Liquefaction • Enrichment • Reprocessing	• Pipeline • Tanker • Truck • Rail • Storage	• Power plants • Heating plants • Refineries • Synthetic fuel production	• Electr. grid • Gas grid • Dewar • Hydride • Truck, rail	• Furnace • Telephone • Automobile • Boiler • Light bulb • Milling machine • Solar panel • Airplane	• Comfort of a warm room • Reading a book • Information • Getting from A to B • Producing income • Manufacture of a car

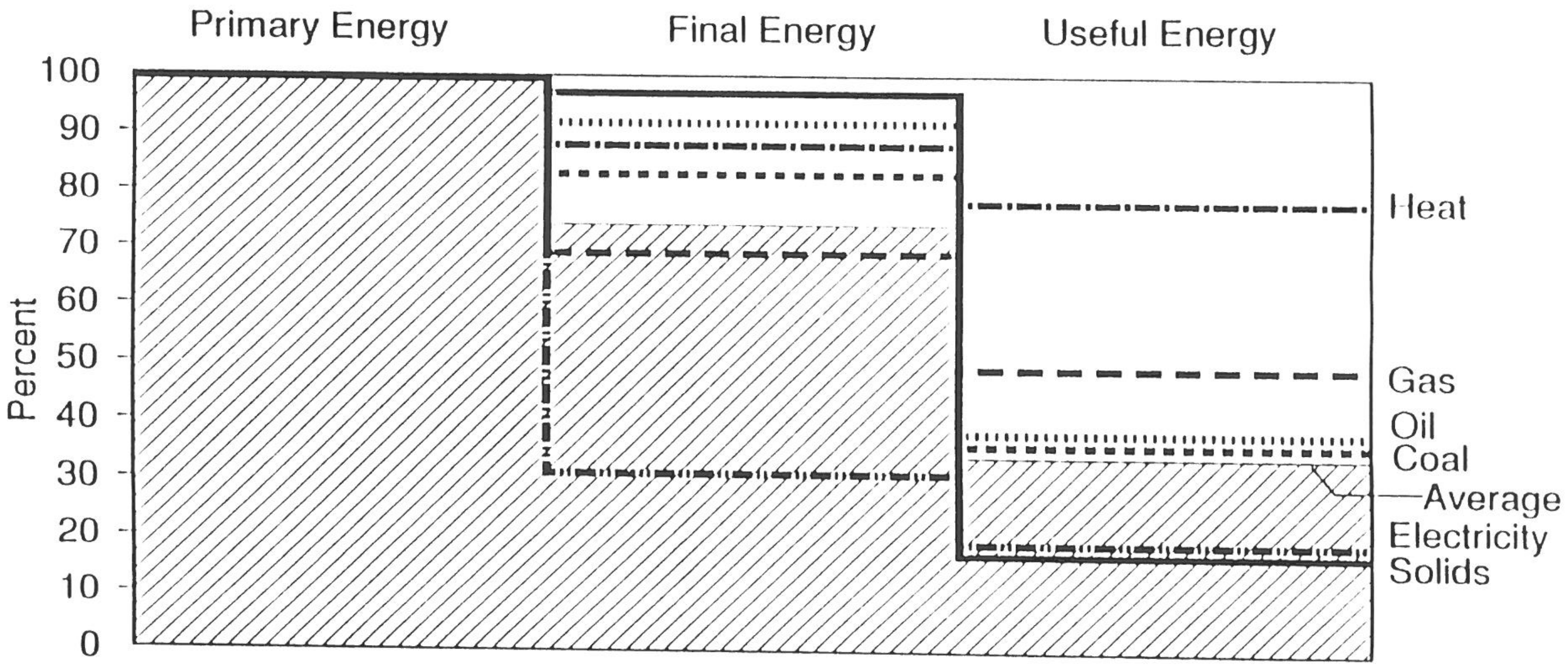
Sources ◄─► Technologies ◄─► Currencies ◄─► Technologies ◄─► Services

CHART 13

ENERGY EFFICIENCY IN PERCENT OF PRIMARY ENERGY*

World

(average for end of 1980's)

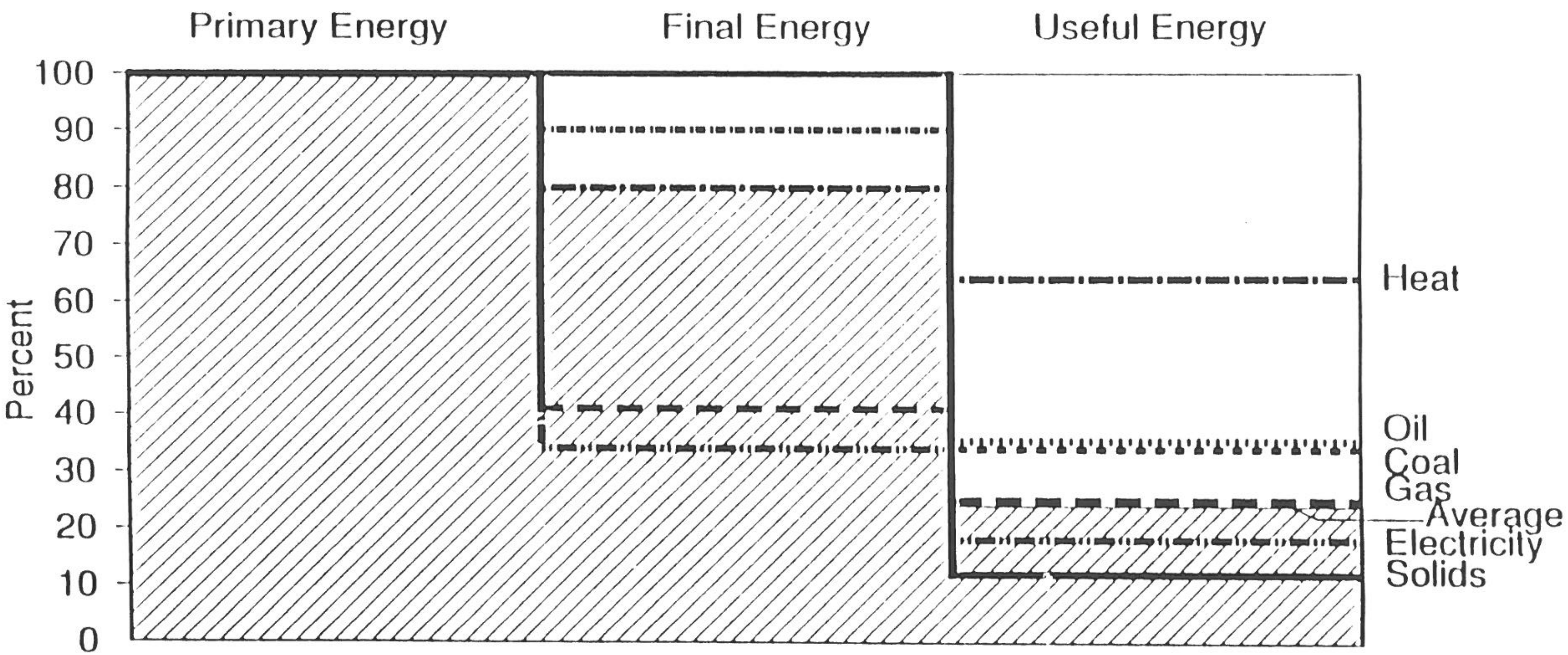


* Vector specific efficiencies exclude cogeneration; average includes district heat and cogeneration

CHART 14

ENERGY EFFICIENCY IN PERCENT OF PRIMARY ENERGY*

Developing Economies

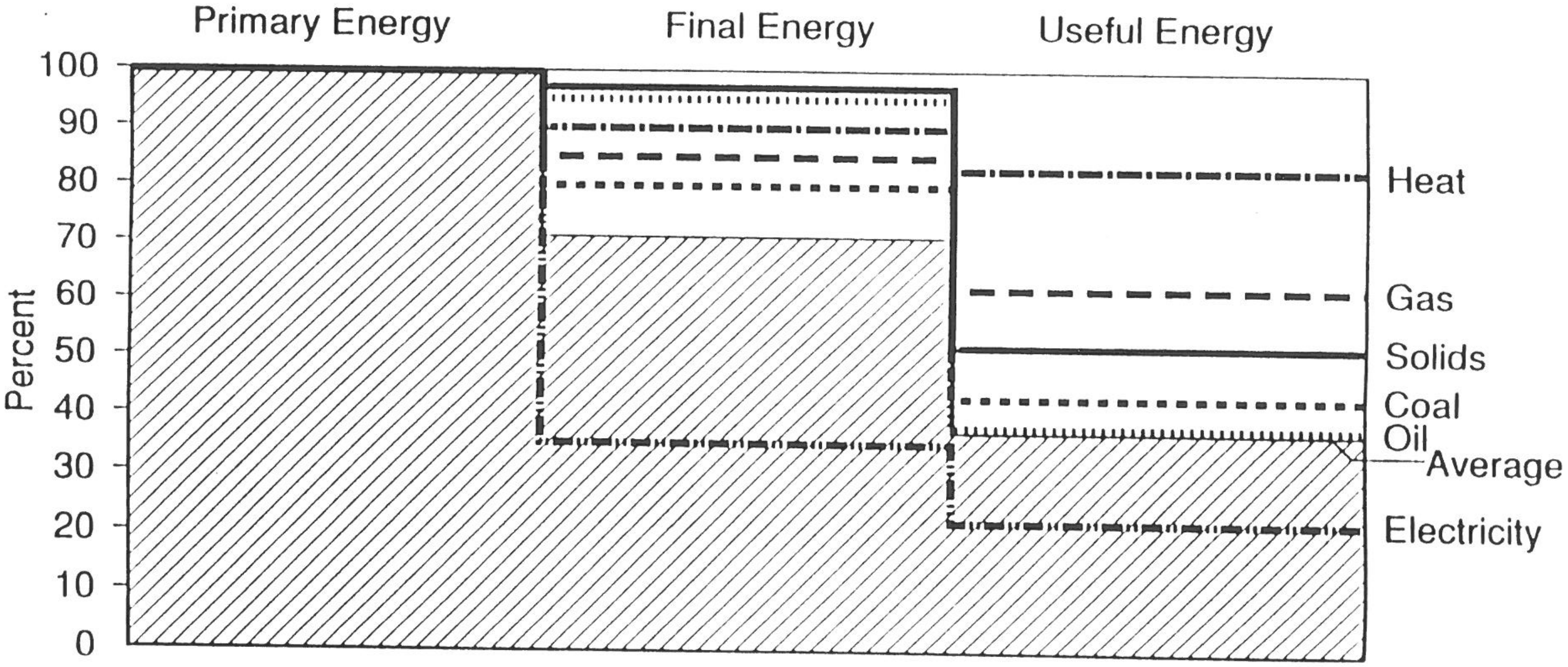


* Vector specific efficiencies exclude cogeneration; average includes district heat and cogeneration

CHART 15

ENERGY EFFICIENCY IN PERCENT OF PRIMARY ENERGY*

Market Economies

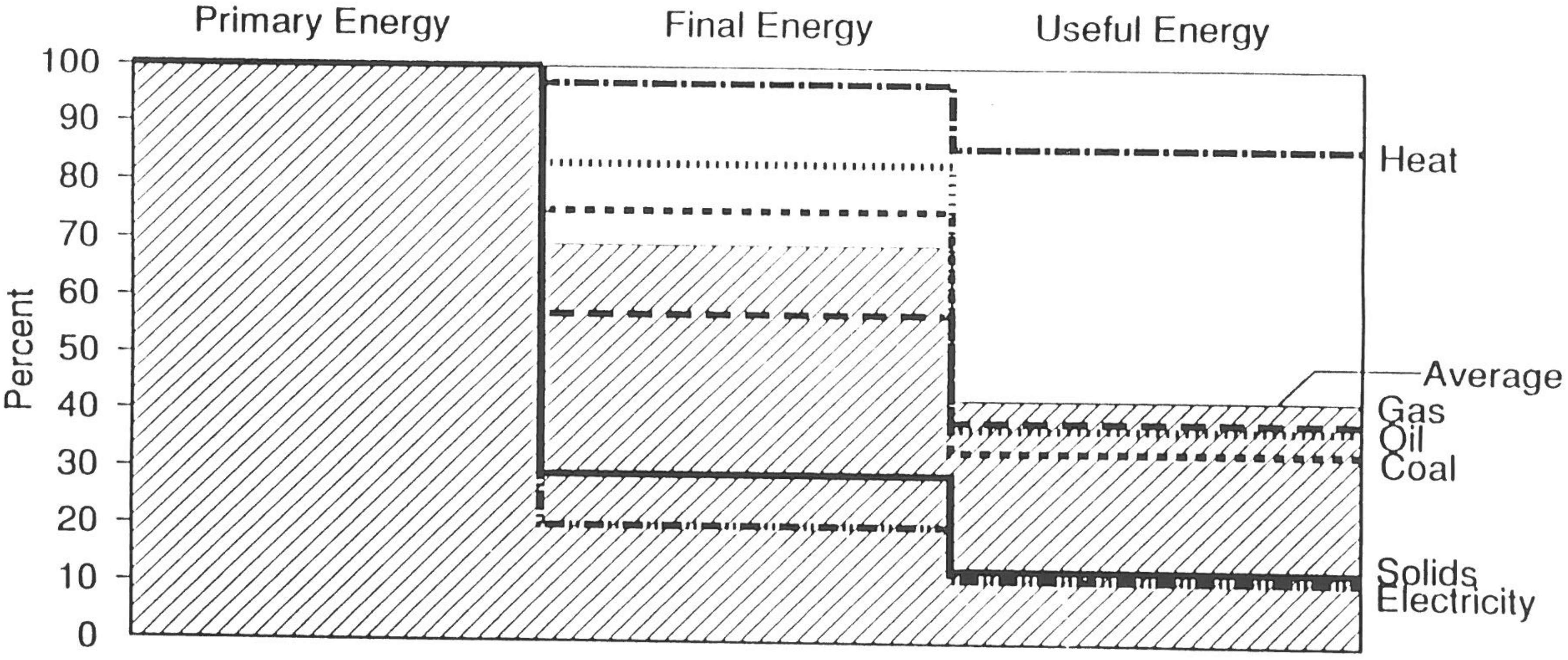


* Vector specific efficiencies exclude cogeneration; average includes district heat and cogeneration

CHART 16

ENERGY EFFICIENCY IN PERCENT OF PRIMARY ENERGY*

Reforming Economies



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

CHART 17

ENERGY EFFICIENCY IN PERCENT OF PRIMARY ENERGY

World

(best available technologies)

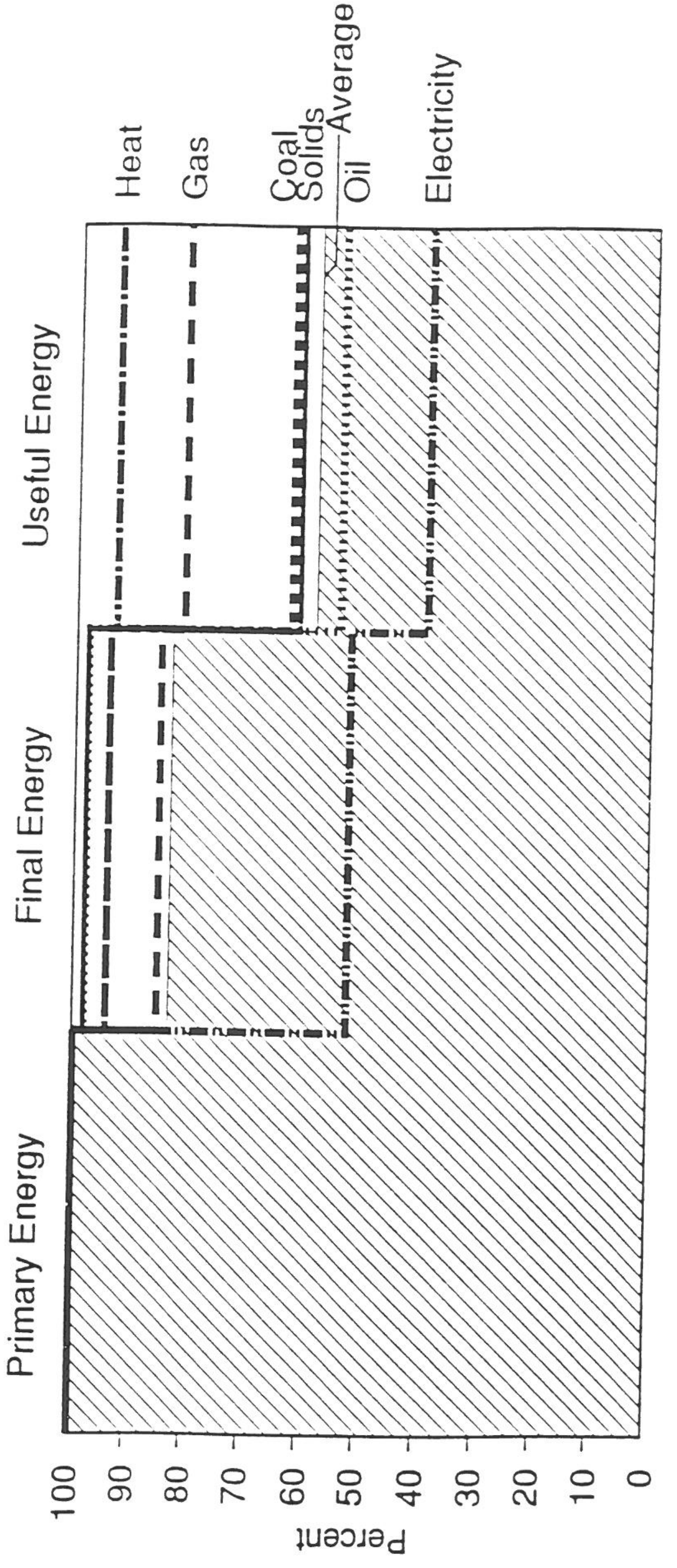


CHART 18

OECD EXERGY EFFICIENCY, 1986 IN PERCENT OF PRIMARY EXERGY

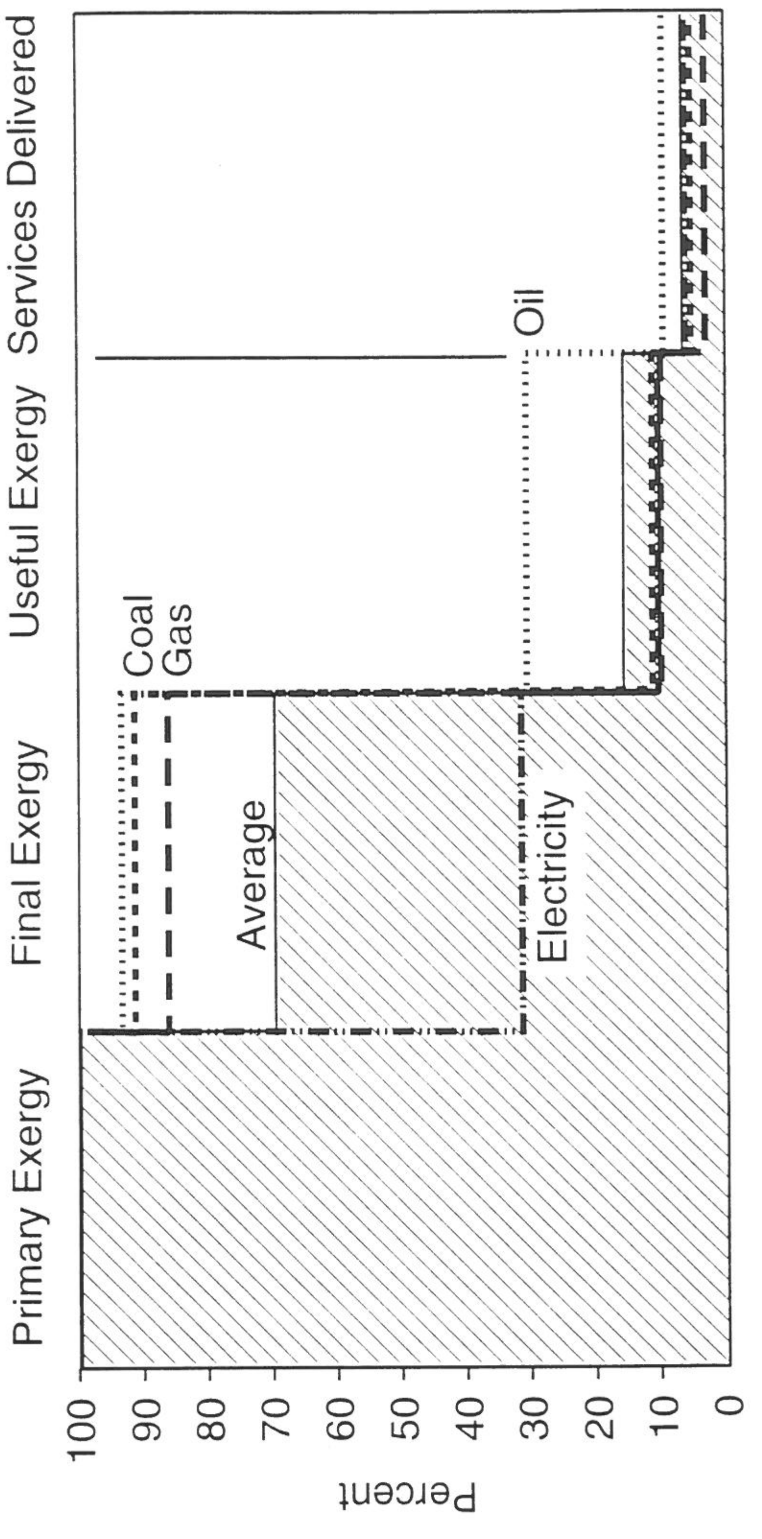


CHART 19

USA - Time and Energy Consumption

	Time*	Final Energy	Density
	10⁹ hr	10⁹ kgoe	kgoe/hr
At home*	835.5*	236.6	0.28
At work	291.1	660.0†	2.27
Services	183.5	152.0	0.83
Travel**	107.6	279.0‡	2.59
Total	1417.7	1328.4	0.94
		10⁹ kg C	kg C/hr
Carbon Emissions		1201.6	0.85

*Excluding sleep

†Including industry transportation, industrial energy use, agriculture, feedstocks

‡Only passenger travel

CHART 20

CARBON EMISSIONS FROM US PASSENGER CARS

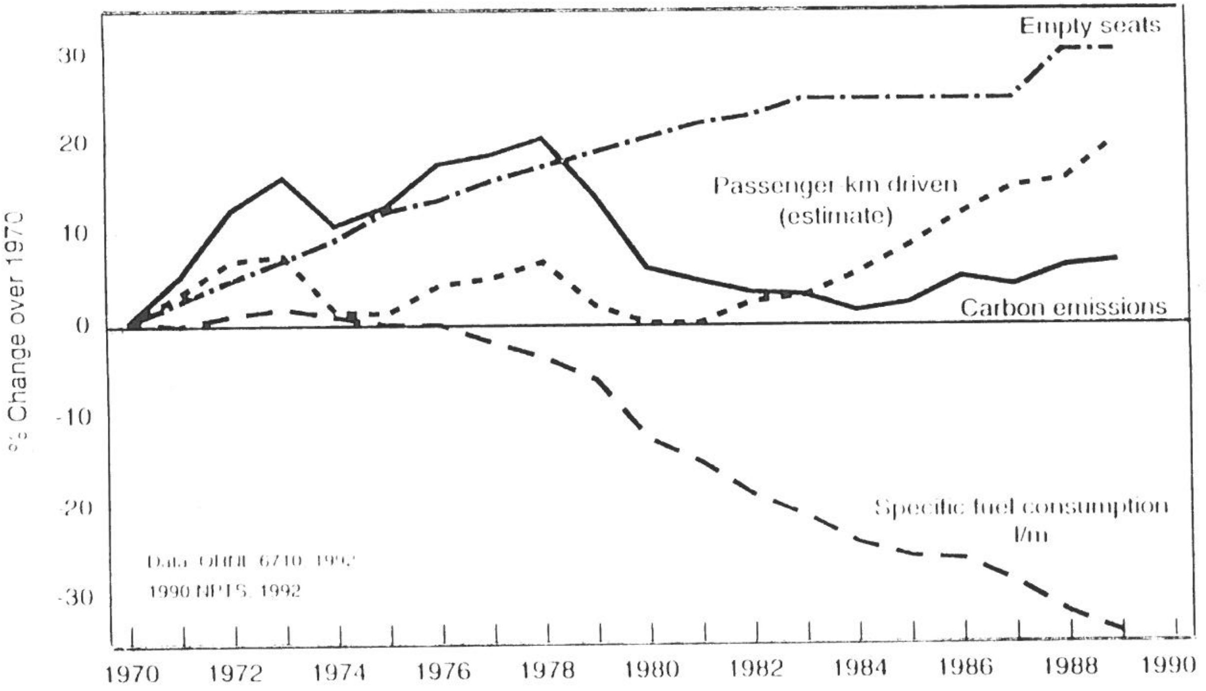
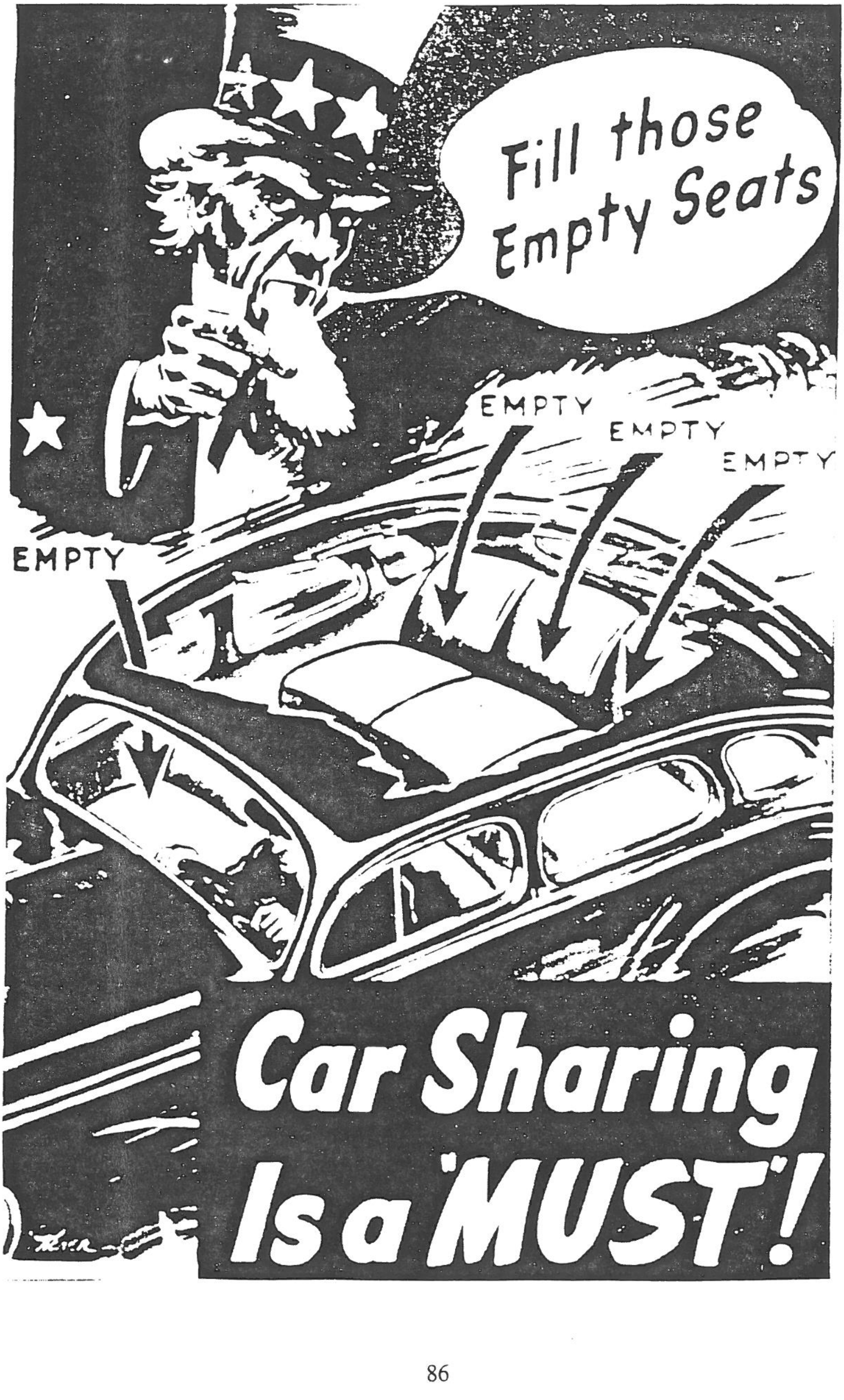


CHART 21


Fill those Empty Seats
EMPTY
EMPTY
EMPTY
EMPTY
Car Sharing Is a "MUST"!