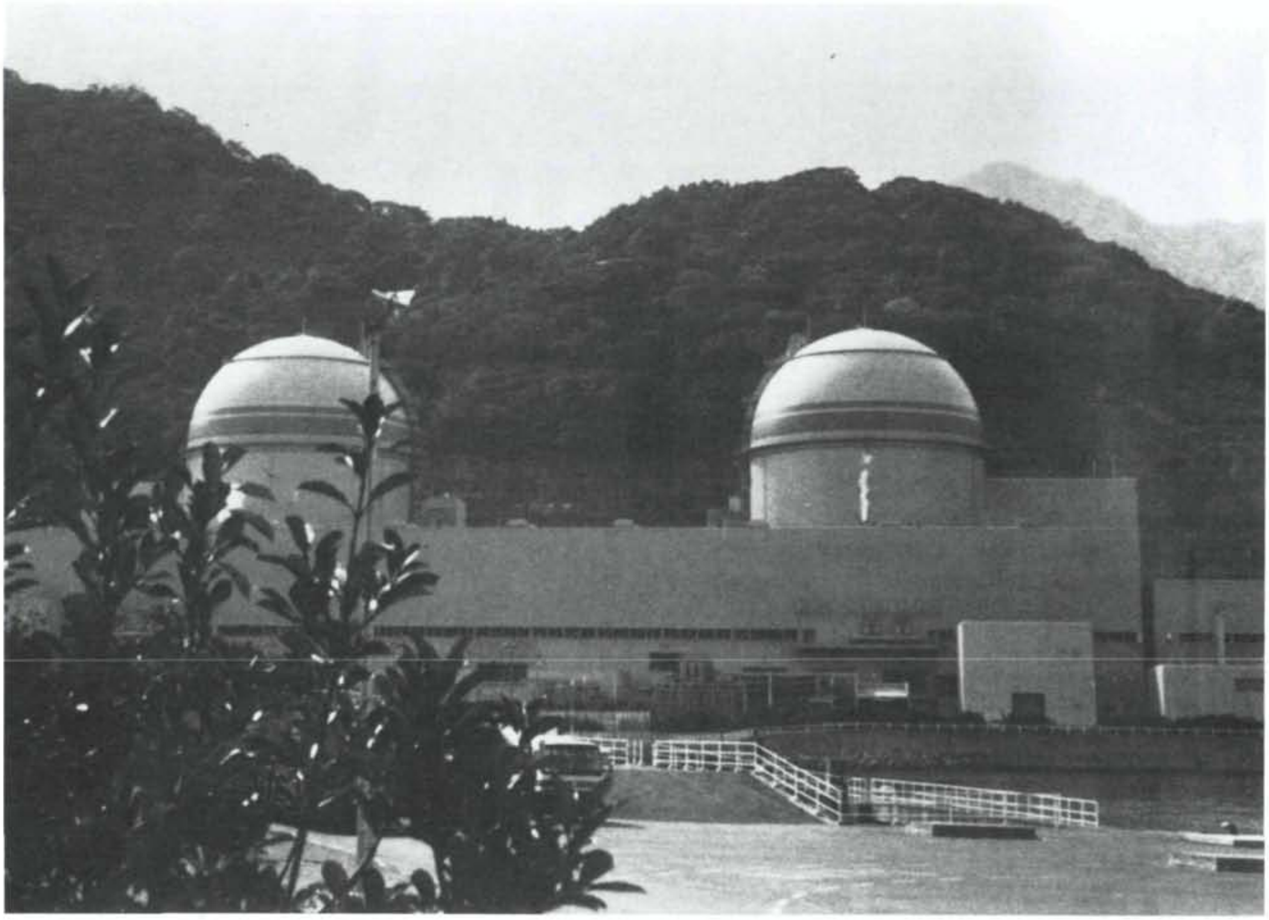

The world's reliance on nuclear power for electricity generation is assuming added importance in the face of environmental concerns over air pollution and emissions of gases linked to global warming. Shown above is part of the Takahama nuclear power station in Japan, where about one-fourth of all the electricity is generated by nuclear plants. At left, a technician visually inspects the welds on fuel pins for the Superphénix fast-breeder reactor in France, where about 70% of total electricity is nuclear generated. (Credits: Yoshida for IAEA; CEA, France)

Energy systems in transition under the conditions of supply and environment

The problem is not one of energy resources, but of energy waste products

by W. Häfele

The current discussion about future energy supplies is characterized by remarkable compartmentalizations and contradictions. The various conflicting positions, challenges, and mutually exclusive assertions can only be sketched broadly here. Basically, they reflect the complex nature of energy systems and their multiple interactions, as well as the fact that certain individual aspects are emphasized by some observers, while others, which may be equally deserving of concern, are not acknowledged at all. In each case, one must understand the relationship of the various aspects. This is true especially in the area of energy policy.

Arguments and viewpoints

A comparison of typical positions and controversies in the current energy scene may be quite informative. There is, for instance, the demand for increase in the use of coal, which is logical for countries with economically attractive coal deposits. The USA, the Soviet Union, and China have very large coal deposits at their disposal. The Soviet Union, for example, is developing in Siberia, in the Kansk-Achinsk region of Krasnoyarsk, a giant coal field with an energy content as large as the oil reserves in the Persian Gulf. Today, 40 million tons of coal per year are produced there and plans are to increase annual production to one billion (10^9) tons. Such a production level will also affect the accompanying infrastructure, including the construction of large cities. The supply potential of coal in China can be viewed in a similar way. The call for coal is heard even in the Federal Republic of Germany, although the conditions for increasing its use there as in other industrialized nations are not all favourable. Any coal option, however, is drastically affected by the carbon dioxide problem. I refer to the threat of overloading of the earth's atmosphere with carbon dioxide, a combustion product of coal. The carbon dioxide problem is the basis for an opposing argument, which advises a strategy of abandoning coal.

Another group raises the demand for immediate abandonment of nuclear energy. Apparently the opinion is that nuclear energy today does not yet play an economic role, but there is no indication of what the alternative should be. The counter argument would point to the fact that, even today, nuclear energy constitutes a considerable part of electricity production and there is no short-term substitute.

From a third viewpoint, it is sometimes glibly asserted that nuclear energy is only a transitional solution. Here we have to ask about the end goal of this transition. To answer this, one should keep in mind that there are, in practical terms, only three inexhaustible, carbon-free energy sources. They are nuclear energy based on the fast-breeder reactor, large scale use of solar energy, and nuclear energy based on fusion. Those are the principal possibilities of any long-term strategy. So far, the only technical reality is the breeder. One cannot foresee at this point if and when a commercially competitive, significant use of solar energy and fusion can become reality in the present state of development research.

The position of a fourth group appears especially extreme: it sees conservation as the key to the solution of all energy problems and wants to supply the remaining energy needs only from so-called "alternative energy" sources. By this are meant such options as the local use of solar energy and the use of renewable energy sources of the natural environment, such as wind and water, as well as biomass. In addition, there is a special accent on decentralizing the sources of energy supplies. One should realize, of course, that conservation has always been a law of economics and, therefore, the main goal of all energy technology. At best, one could expect that conservation can facilitate the solution of

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energy problems, but it is not the perfect solution. Rational arguments also negate exaggerated expectations for the potential of renewable energy sources. In practice, these are rather limited, except for the large-scale use of solar energy in arid zones.

World energy consumption

In this picture full of contradictions, which are the key points to remember when one tries to gain perspectives for formulating goal-oriented strategies? A look at actual energy supply data and their developmental trends can set some practical limits. In this context, a basic unit of energy, the terawatt year (TWa), is very useful. One TWa (or 10^9 kilowatt years) is equivalent to one billion tons of coal; OPEC produced and sold about 1 TWa of petroleum in 1987, and the lignite open pit at Hambach, located in the vicinity of Jülich, should produce about 1 TWa over the next 50 years.

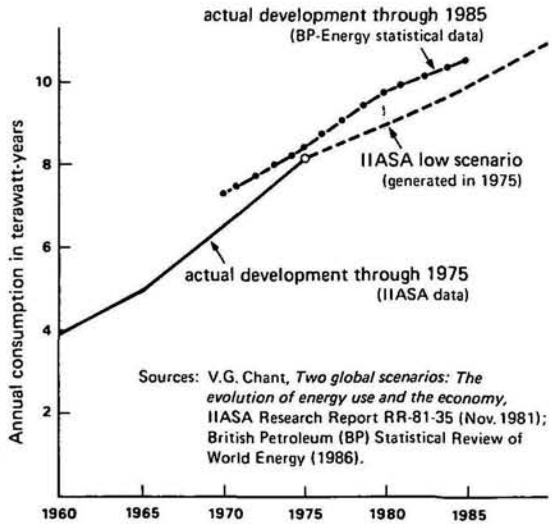
In 1985, the global use of primary energy ran to about 10 TWa, that of the Federal Republic of Germany 358 gigawatt years. The global figure should be increased slightly by the contribution of non-commercial energy, primarily the use of firewood and organic waste for energy in the poor regions of the earth. The contribution of non-commercial energy is estimated by the Conservation Commission of the World Energy Conference at 1.1 TWa per year. Given a world population of 5 billion people in 1985, this results in an average annual energy consumption per person of slightly more than 2 kilowatt years. However, the actual annual *per capita* consumption is distributed rather unevenly over the world population. In the Federal Republic of Germany, it lies at 6 kilowatt years, in North America it reaches values around 11 kilowatt years. More than 40% of the world's people, however, have to get along annually with 0.3 kilowatt years of commercial energy.

One aspect of the problem of energy supply is definitely the increasing growth of world population. Over foreseeable time one can predict quite accurately the age distribution and the birth and death rates of the population living today. In the year 2030, there will be a global population of about eight billion people. Using this number, and an average annual *per capita* consumption of 2 kilowatt years, one arrives at an annual energy use of 16 TWa for the year 2030. This figure should be considered the lower limit. If one assumes levels of energy use that would bring the developing countries to the same standard of living as Western Europe, the resulting variants can delineate a range of predictions from one and a half times to four times today's world energy consumption, depending on the assumptions made for the *per capita* use.

Energy scenarios

One can refine such predictions by considering other variables of energy consumption, that is, numerous technical, economic, and social factors. Additional assumptions have to be included, not randomly, but such that the results are consistent views of the various assumed social/technical scenarios. The technical term for this is "scenario construction". Scenarios are not predictions, but designs of possible futures, orientations, and perspectives from today's viewpoint using the best possible knowledge and insight with a broad field of view. The construction of a slightly ambitious energy scenario requires extremely intensive efforts because the interactions of the energy systems range from the economic circumstances in various sectors, deep into the special characteristics of the structure of society and living patterns. As part of an extensive study in the area of energy at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, near Vienna, two global energy scenarios were worked out during the 1970s for the period 1975 to 2030; a low and a high variant as a theoretical continuation of the actual development until the year 2030. In the meantime, more than 10 years have passed and it has been revealed that the IIASA "low" scenario development of energy consumption represents at least a good lower approximation of the data that have accumulated since then. *(See accompanying graph.)* In addition, there are some newer projections. Among them are those of the World Petroleum Institute in New York and the World Energy Conference, which are fairly close to the projections of the IIASA "low" scenario. Thus, the "low" scenario may, in this connection, contribute a fairly useful orientation for the perspectives of future supply and waste disposal.

Comparison of actual and projected world primary energy consumption (commercial energy)



A comparison of actual trends in world energy consumption with projections of IIASA prepared in 1975 shows that actual use has been fairly close to the "low" scenario.

Potential supplies of fossil fuels

The question of the potential supply of fossil fuels, especially in the long run, has to be considered in a sophisticated way. Simple listings of discovered and estimated energy reserves are not sufficient to characterize the situation of resources, because natural occurrences vary in quality. For instance, the type and concentration of raw materials, the yield of a deposit, and the infrastructure of its use, are all factors which affect the potential economic use of a resource. Of immediate interest for the energy economy are those supplies which can be used or produced according to present technical and economic criteria. They are called *reserves* if they have been proven with certainty or have been developed already. New reserves can result from new discoveries, but also through redevelopment of less economic resources. In the customary view of our energy supplies, the presently available reserves are in the foreground. However, these represent, at present, only a very small percentage of the proven as well as estimated fossil energy supplies.

A recent re-valuation of reserves and resources of liquid and gas hydrocarbons was presented by C.D. Masters at the 12th World Petroleum Congress in Houston, USA, in April 1987. *(See accompanying table.)* This representation differentiates, on one hand, between economical and not yet economical ones. Conventional oil and gas is shown as proven and as probable reserves. Non-conventional resources include heavy oils and tars, natural bitumens and tar sands, as well as oil shales. Representative examples are the Orinoco area in Venezuela, as well as the Athabasca tar sands in Canada, and the Colorado oil shales in the USA. They differ from the conventional oil resources in that they are much lower quality, contain considerable waste and toxic material, and are directly usable only after technically expensive processing. Without doubt, there are a number of technical, economic, and ecologic complications which have to be overcome if energy resources that today are considered of low value should at some point be used on a large scale. However, if one considers the relative amounts, it becomes clear that even if the reserves available today are used up, this does not at all mean the end of fossil fuel use. On the contrary, the practice of the energy industry, of creating new reserves by enhancing unfavourable resources and investing new capital, suggests trends for the possibility of a gradual transition to non-conventional fossil energy resources.

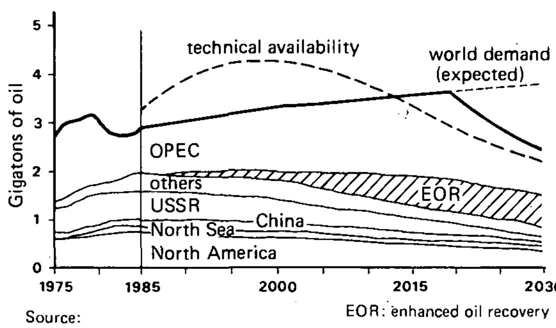
The economic and technological conditions for such a transition have been investigated in detail in the Kernforschungsanlage (KFA) Jülich, especially also the question of how such a transition could be accomplished over time. On the whole, one can state that the increasing world demand for liquid hydrocarbons could be met very well with conventionally produced oil until shortly before the year 2000. However, in the process, one can expect a shift in the regional distribution of world oil production. This is because the limited production capacity, or the decreasing production potential of some areas, must be more than compensated for by the increase of production in other areas. In this respect, the rich deposits in the Persian Gulf will be of increasing significance. Naturally, this also implies weaknesses with respect to the security of supply which, in turn, demands timely precautions for the design of energy strategy and technology. In KFA's base scenario, a continuous improvement of the production efficiency that can be achieved through technological advances is included: for instance, enhanced oil recovery (EOR). Around 2010, the world demand for liquid hydrocarbons cannot be met by conventional oil, so that non-conventional sources will have to be increasingly developed in the years immediately following. Considering the bottleneck situation on the horizon, one can expect even earlier substitute measures after about the year 2000. *(See accompanying graph.)* These dates are not to

World reserves and resources of oil/gas and non-conventional energy

	Conventional		Non-conventional	
	Oil ($10^9 m^3$)	Gas ($10^{12} m^3$)	Heavy oil, shale oil, natural bitumen) ($10^9 m^3$)	
Cumulative production	83.3	33.2	5.5	economical
Discovered reserves	126.5	110.7	10.0	
Not yet discovered	86.1	119.0	—	
Discovered resources	—	—	656.7	not yet economical
Not yet discovered	—	—	1700.1	
Total	296	263	2372	
Still available	≈500 terawatt-years		≈3000 terawatt-years	

Source: C.D. Masters, 12th World Petroleum Congress, Houston, USA, 1987.

Regional distribution of expected world oil production



Source: EOR: enhanced oil recovery
H.C. Runge, Kernforschungsanlage (KFA), Jülich, Fed. Rep. of Germany

be considered firm but, rather, a quantitive expression of a qualitative situation. The development described could just as well start 5 years earlier or later.

Qualitatively similar is the development over time of demand and production of conventional gas. The point in time after which the production is not able to meet the increasing demand, and will show a decreasing trend, should lie somewhat later than for the case of oil, perhaps around the year 2020, because of the particularities of the gas market and reserve situation. Of course, the same cautions as for oil apply to these dates.

A transition to new conditions

From these dates, we can conclude that the present period of intensive use of high-quality natural hydrocarbon deposits at low development costs is coming to an end, probably in the period 2010 to 2030. It is also safe to say that the need for high-quality hydrocarbons can be met long beyond this time from abundantly available sources which are today considered of low value. The energy system is in a transition to new conditions.

To meet the new criteria of resource utilization and evaluation, quite different technological, economical, and geopolitical interactions must be considered. This becomes clear, not only in the case of supply, but also of waste disposal. We are still used to burning relatively high quality and clean fuels. However, we are already using techniques of emission control, for instance, during the cleaning of stack gases in power stations to keep environmental pollution within limits. Yet, increasing energy demand and the transition towards lower quality fuels imply a quantitative increase of wastes. This is especially true of the amount of carbon dioxide released during the use of fossil fuels. According to the IIASA "low" scenario, the cumulative consumption of fossil fuels will increase to 633 TWa by the year 2030. Part of this energy, or about 400 TWa, derives from the combustion of the carbon bound chemically in oil and gas. The amount of carbon dioxide resulting from this approaches the natural content of carbon dioxide in the atmosphere. In other words, 633 TWa of fossil fuel use means an approximate doubling of the atmospheric content of carbon dioxide. For some time there have been reasons to expect that such a doubling will produce a rise in the mean temperature of the earth of about 3 degrees Celsius, with an uncertainty of plus or minus 1.5 degrees. At the poles, this temperature increase would be considerably higher, so that wide-ranging melting of the continental ice in the Arctic and Greenland would lead to a rise of sea level in the range of metres. A noticeable increase of climatic variability is rarely mentioned as an early symptom. There are, however, meteorologists who occasionally express opinions that climatic anomalies recorded during this decade can be interpreted as first signals of a critical overloading of the atmosphere.

Carbon dioxide levels

The "greenhouse" effect of carbon dioxide is physically due to the increased atmospheric absorption of infrared radiation. A number of cause, effect, and feedback mechanisms enter into the geophysical process, which makes an exhaustive treatment of the phenomena, in a strict scientific sense, extremely difficult. Therefore, the doubling of the atmospheric content of carbon dioxide was arrived at in a very simplified way by using the cumulative consumption values of the IIASA "low" scenario. One part of the anthropogenic emission of carbon dioxide into the atmosphere, about half of it, is absorbed fairly rapidly: that is, within 10–20 years, by the upper layers of the ocean. On the other hand, the potential greenhouse effect of the remaining carbon dioxide is considerably increased by anthropogenic trace gases (including chlorinated fluorocarbons, methane, and laughing gas).

The buffer effect of the upper ocean layers is limited by the residence time constants of the exchange processes with the deep sea. Thus, the excess carbon dioxide in the atmosphere can be reduced only slowly. According to new studies, one has to expect a transition time of 600–900 years for the precipitation of the carbon dioxide in the form of deep sea carbonates, that is, to its ultimate disposal.* The current method of disposing of carbon dioxide, the predominant product of fossil fuel use, leads to time frames that we are quite familiar with from the nuclear waste disposal situation. The extent of the problems to be solved is somehow similar. An ideal solution which frees us from all problems probably does not exist.

Toronto conference

In 1988, in the context of a remarkable conference in Toronto, opened by the Prime Minister of Canada, the carbon dioxide problem was discussed at great length. Recognizing fully the serious situation, the delegates targeted several challenging goals. Reductions of carbon dioxide emissions of 10% each, on the consumer as well as the producer side, are supposed to be reached by the year 2005, by forced measures. Included in the catalogue of measures are, of course, the efficiency improvements which have long been a challenge for technological development and which are now being put into practice. Also included was a call for more gas and oil instead of coal, which was seldom heard in the 1970s. Measures further included the demand for more non-fossil primary energy, requiring more appropriate and greater use of so-called alternative energy sources, and cautious discussion of a re-evaluation of the use of nuclear energy.

One should not over- or under-estimate these goals. It does not take a great effort to prove that they are

* Assumption: 2 to 3 time constants of an exponential exchange.

perhaps unreachable. What is expressed in these goals — the awareness of the problem growing out of the improved knowledge of geophysical processes — should not be misunderstood.

The question is then obvious. To what degree can carbon dioxide emissions into the atmosphere be considered as benign in the long-term; benign in the sense that the dynamic equilibrium of the climatic processes will not be affected? Even the framing of the problem is difficult to make precise. By what criteria, for instance, should sensitivity be measured? During the course of the earth's history, there were considerable climatic changes. Meteorological science has for a long time tried to find an answer for this special complex of questions. In order to make statements, which naturally have to be conditional and can be made only approximate and with reservations, one has to introduce large coupled atmosphere ocean models, computer programs which only in most recent times could be written and run due to the capability of today's super computers.

A first answer is given in a recently published study by Maier-Reimer and Hasselmann.* There they indicate that a carbon dioxide emission of a stoichiometric equivalent of 2.5 gigatons of carbon per year (that is, 9.2 gigatons of carbon dioxide per year for the next 100 years) will only lead to a slight increase in the carbon dioxide content of the atmosphere. However, the effect of the ocean biota has not been considered. This is a preliminary approximation; it is expressed with reservations and should be received with reservations, as it can certainly change. In any case, the present emissions are double this amount. The world's annual use of commercial energy in 1985 of 10 TWa resulted in carbon dioxide emissions corresponding to 5.7 gigatons of carbon. For a typical fuel mix of 1985, 2.5 gigatons of carbon per year would be surpassed with the use of 4.3 TWa, which is 43% of the actual energy consumption of that year. Such limits will have to be considered in any discussion about the expansion or limitation on the use of fossil fuels.

Nuclear energy's contribution

Now for nuclear energy, at this point our most efficient source of non-fossil energy. At the beginning of 1987, there were 165 nuclear power stations in service in countries of the Organisation for Economic Co-operation and Development (OECD), with a capacity of about 222 gigawatts-electric.** Prominent is the high share of the USA. This is also remarkable because among Germans the opinion is spreading that there are hardly any nuclear power stations in the USA. The Americans are bringing on line, one by one, nuclear plants which were long planned or long under construction. France, too, follows a consistent expansion policy, with at least 50% of USA capacity in service. Nuclear energy is a considerable economic reality even here in the Federal Republic of Germany and in other countries. This is even more evident in the contributions which nuclear energy is making to the entire electricity supply, both in the leading industrial nations as well as regionally and worldwide. *(See accompanying table.)* Nuclear power plants contributed 1515 terawatt-hours-electric, or 15.4% in 1986, to the global electricity production of 9849 terawatt-hours-electric. On a global scale, but also in comparison to North America, the high electricity contribution in Western Europe is considerable. It reaches 30%. When, for whatever reasons, the demand to get out of nuclear energy is heard, one has to ask the question: "What can be substituted?" And if this question cannot be answered, then the demand cannot be accepted.

Electricity production from nuclear power plants, 1986

	Nuclear power plants (terawatt-hours electric)	Total production (terawatt-hours electric)	Nuclear share (per cent)
North America	481	3076	15.6
Western Europe	597	1967	30.3
Pacific Region	166	814	20.5
Eastern Europe	198	2134	9.3
Asia	57	962	6.0
Latin America	5.5	509	1.1
Africa and Middle East	8.8	386	2.3
World total	~1515	~9849	15.4
OECD countries' share of world total	1244	5857	21.2

Reprocessing and nuclear fuel supplies

The supply of nuclear fuel is not a problem, first, because there is plenty of uranium and, second, there is the fast-breeder reactor. Difficulties can be seen, however, in disposal of nuclear waste, more precisely in the systematic processing of spent fuel elements. A comparison of the annual output of spent fuel and available reprocessing capacity in the area of OECD shows this

* "Transport and storage of carbon dioxide in the ocean — an inorganic ocean-circulation carbon cycle model", by E. Maier-Reiner and K. Hasselmann, *Climate Dynamics*, 2, 63-90 (1987).

** OECD member countries are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Federal Republic of Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, UK, and USA. Special status: Yugoslavia.

quite distinctly. In 1986, 5300 tons of spent fuel were produced in the OECD area, including 35 tons of fissionable plutonium that had to be recycled. For the year 2000, we have to expect a corresponding annual production of 8300 tons, or 54 tons respectively. The processing capacity in operation in 1987 in OECD countries ran at 1980 tons per year and will increase by an additional 2800 tons per year to 4780 tons per year if all units which have been planned and under construction are actually in operation. In the most favourable case, 3520 tons of spent fuel will remain unreprocessed in the year 2000; in the worst case, 6320 tons. This means 23 tons or 42 tons of plutonium, respectively. Extrapolating to the year 2030, this would result in several thousand tons of plutonium. They cannot be accumulated in the form of spent fuel, but would have to be burned in the reactor because we could not possibly leave for the following generations the problem of continuously guarding deposits of spent fuel elements.

As we have seen, the disposal of fossil combustion products also presents difficulties, although they are of a different kind. It is certainly true that different kinds of things are difficult to compare. However, we will have to contrast and weigh the respective advantages and disadvantages of various aspects if we are to judge and make decisions based on objective criteria. In the light of such a comparison, it is helpful to look at the disposal quantities.

For the annual production of 10 TWa based purely on nuclear energy, there would be nuclear wastes of 4680 tons per year, a reasonable and technically disposable amount. By comparison, in the case of exclusively fossil energy supply, there would be carbon dioxide emissions of 21 billion (10^9) tons per year, corresponding to a carbon contribution of 5.7 billion tons per year emitted into the atmosphere. The ratio of waste streams, fossil to nuclear is, therefore, one million to one. The guidance of nuclear waste streams requires special care but, as we know, care is also indicated in the case of the carbon dioxide problem.

Energy options

As we have seen, liquid and gaseous hydrocarbons could be continued to be used in the long term but with distinct limitations, perhaps up to an annual contribution of 4 to 5 TWa. We will not have to decrease their use to zero.

From today's viewpoint, there are three — and only three — options for carbon-free primary energy supply in the capacity range of 10 TWa per year and above. They are represented, as mentioned initially, by the fast-breeder reactor, the large-scale use of solar energy, and fusion.

For a carbon-free production of primary energy in the range of 1 TWa per year, "alternative" energy sources like water, wind, and solar energy (locally used) can be considered. Their production potential runs at 10% of the present world energy use and, therefore, they are not truly alternative but, rather, complementary energy sources.

The actual economic significance of renewable energy sources is put into perspective by changes in their evaluation in recent time. The potential that can be realized in the Federal Republic of Germany has been investigated repeatedly and, each time, it was estimated at a lower level. It is not by chance that energy conservation has been raised to a central theme in the most relevant scenarios using alternative energy, but it has to be a specific characteristic of a supply system using alternative energy sources.

The topic of conservation is somewhat biased by the demand for idealistic savings goals on one side and realistically feasible savings potential on the other. Obviously, one must consider the question of what constitutes necessary or sensible energy consumption. Of course, the annual *per capita* consumption values of the world population range over a wide scale: between 0.6 kilowatt-years for the poorest, who have to get along with the minimum for survival (0.3 kilowatt-years of commercial energy plus 0.3 kilowatt-years of firewood), and the 11 kilowatt-years of the North Americans lies a factor of 20.

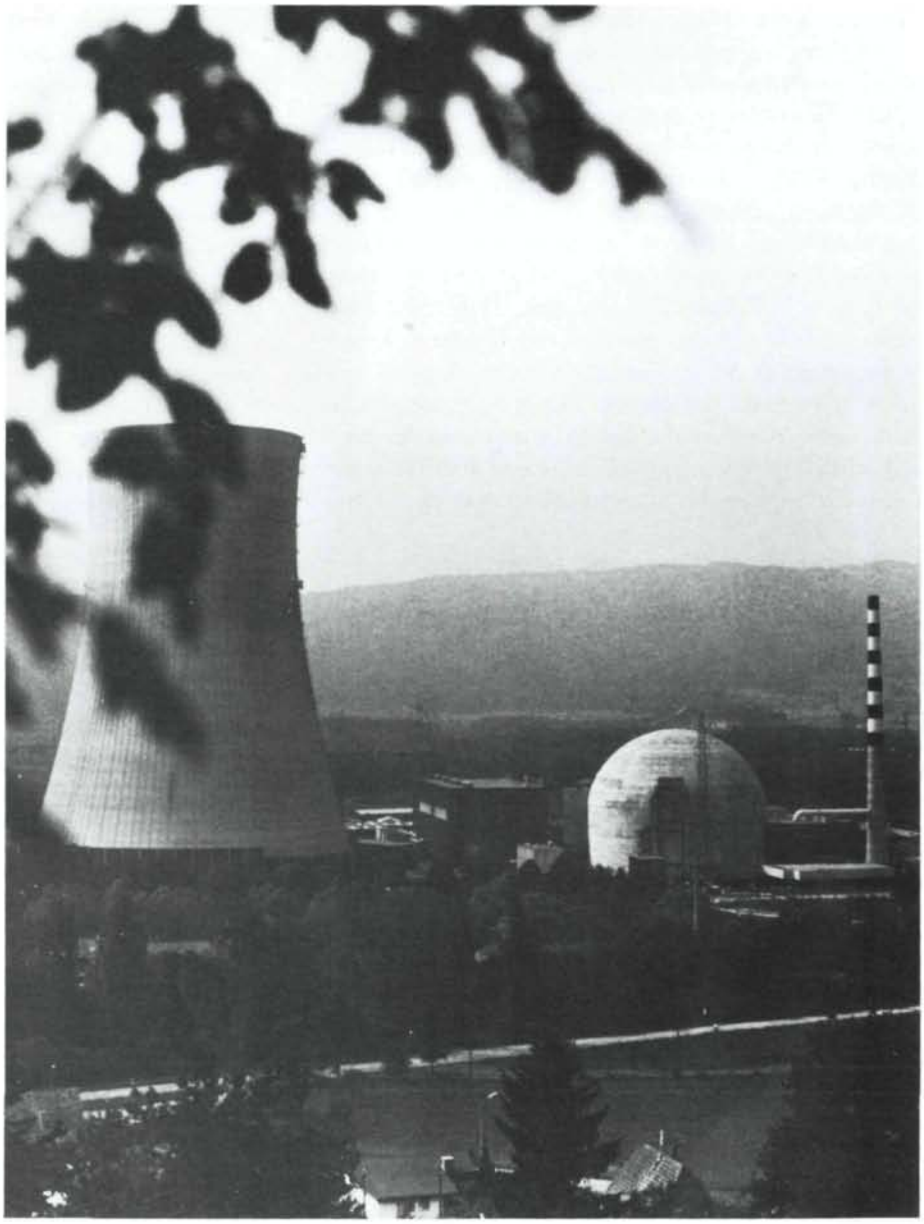
In the context of energy consumption one has to realize that the effect of energy use (that is, energy service) depends on a number of production factors: capital investment, labour, knowledge, and skills. They are partially interchangeable; that is, the same product can be achieved in quite different ways by a proper combination of respective factors. It is possible to achieve the same energy service with a considerably smaller energy input if the amount of capital, labour, and engineering know-how is increased accordingly. This fact is not always generally realized. When we speak today of efficient energy technology, or of conservation potential, we usually mean the substitution of capital for energy. The capital requirement and the question of limited capital applied in the most appropriate way usually becomes less important. Therefore, figures on energy conservation potentials are not a purely physical/technical matter, but a question of interaction between technology, economy, and society. The much discussed topic of energy requirements should be understood in the same context.

Assigning priorities

What are the proper orientations and perspectives when the goal is to overcome the compartmentalizations and contradictions? Is it the sum of the various aspects? The whole is probably greater than the sum of the parts. It requires assigning of priorities and this is given in various time horizons. The energy technology of today has as its most urgent task the reduction of pollution emissions into the environment, especially in the reduction of nitrogen oxides and sulphur dioxide emissions. Below a time horizon of 50 years, the emergence of the carbon dioxide appears. The buildup of critical concentration of carbon dioxide in the atmosphere coincides with the time limit of the supply of conventional oil and gas. We have not mentioned the development of technology of the carbon-poor, environmentally benign energy systems which will take 100–140 years to develop and will require goal-oriented transition strategies. This consists, basically, of the introduction of hydrogen as a secondary energy carrier, as well as electricity, while the primary energy supply will have to be mainly carbon free. The supply of non-conventional fossil fuels should last at least 250 years.

Reduction of the expected carbon dioxide emissions will take about 50 years. Reduction of anthropogenic carbon dioxide content, through the coupling of the upper ocean layers with the deep sea (the final depository for atmospheric carbon dioxide) falls in the time horizon of 500–1000 years — a familiar time frame for typical decay times of radioactive waste. The time horizons of supply on the basis of the breeder or fusion should lie around 15 000 years and that of solar energy at billions of years. Under these conditions, we see that the main problem is not one of resources, as we thought in the 1970s, but is rather the urgent problem of the disposal of fossil fuel products.

I think that this picture, even though dramatic, shows directions which lead beyond compartmentalizations and contradictions. We have to keep these directions in mind if we want to return to sober evaluation of energy relationships which allows rational and responsible action.



Gösgen nuclear plant, Switzerland. (Credit: Siemens)