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First-Order Effects of a Nuclear Moratorium in Central Europe

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Foreword

Following the accident at the Chernobyl nuclear reactor in spring 1986, the long-standing debate on safety and the nuclear power cycle was revived. One of the questions that arose was, what would the relative economic and other consequences of a discontinuation of nuclear programs amount to.

Since IIASA has a long tradition in energy modeling, it can use its accumulated expertise and existing models – depicting the Central European energy supply system – to derive such estimates.

The results resemble those of most of the other modeling groups that undertook similar efforts for individual countries. The main difference between the results of the IIASA investigation and others is that this study suggests that natural gas, and not coal, could well be the most important fuel in filling the gap that a nuclear phase-out strategy would leave in the energy supply system of Central Europe.

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T.H. Lee
Director

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Background

The growing public opposition to the use of nuclear power in Western Europe and a generally higher public interest in energy-related matters are stimulating a reevaluation of future options in energy supply. The need for such an undertaking is stressed by the fact that today – in contrast to the 1970s – political parties are also taking a strong position pro or contra nuclear power. Whereas during the nuclear debate at the end of the 1970s, conflict arose between policymakers from all parties and the public, today the discussion occurs between the parties – including the electorate. This may easily lead to a situation in which it is extremely difficult to find a common basis for decisions in energy planning or even one in which policies are changed in each period between elections.

In the present heated political climate, such a common basis cannot be developed during discussions between supporters and opponents of nuclear power – it can only be built upon a sound scientific base, which has to be trusted by all parties. However, this is a difficult task. In the Federal Republic of Germany, such an undertaking was launched in 1979, when two consecutive Parliamentary *Enquetes* on the Future Uses of Nuclear Power were initiated. However, this effort was discontinued after a change in the composition of parliamentary power.

Since the mid-1980s the situation has changed drastically. After the nuclear accident at Chernobyl in the USSR, public concern about and resistance against nuclear energy rose considerably. A preliminary decision was made not to put on-line the fast breeder reactor at Kalkar, FRG. A final decision on that subject will certainly affect plans concerning the nuclear reprocessing plant at Wackersdorf, FRG. If these two projects do not go on-line in the near future, a decision similar to that in Sweden – a nuclear phase out – is conceivable in the FRG.

In various European countries the situation differs substantially from that in the FRG. In some countries, like France, discussions ended shortly after an initial public opposition, while in the UK public resistance seems to have little effect. Others, like Austria and Sweden, decided to ban the use or construction of nuclear power plants.

Decisions on the future utilization of nuclear power will certainly be taken on a national basis, but they can easily lead to political dissent – as recently seen in the conflict between Austria and Bavaria, FRG, concerning the planned nuclear reprocessing plant at Wackersdorf, and also in that between the Saarland, FRG, and France because of the new nuclear power station Cattenom 1.

Current Status of Nuclear Power in Europe

This report focuses on the first-order effects of a discontinuation of the use of nuclear energy in Central Europe. The region Central Europe comprises Austria, Belgium, Denmark, France, FRG, Ireland, Luxembourg, the Netherlands, Switzerland, and the UK. It is a geographically and economically homogeneous region with relatively well developed economies, but varying utilization of nuclear energy. Table 1 shows electricity generation from nuclear reactors in these countries, together with the total electricity generation for 1980 and 1985. France has an extreme position: in 1985 almost 65% of its electricity was generated from nuclear energy, and between 1980 and 1985 the growth rate of this energy source in France was 28% per year. Currently, a total of 115 reactors are being operated in Central Europe, 43 of them in France. Other countries with large nuclear shares are Belgium, Switzerland, the FRG, and the UK.

Up to 1990 France plans to increase its nuclear capacity drastically, from 37.5 GW in 1985 to 58.5 GW in 1990 – an increase of 21 GW (or 56%), while all the other West European nations together will add 8 GW [1]. The second largest increase is currently foreseen for the FRG with 6.5 GW; the remaining 1.5 GW are to be built in the UK. Currently, only France has reactors under construction, which would add another 4 GW after 1990.

The Approach

This short analysis is based on a model developed for the International Gas Study at the International Institute for Applied Systems Analysis (IIASA); an outline of the study is given in Nakicenovic and Strubegger (1984), and preliminary results are described briefly in Messner *et al.* (1986). The main goal of that study was to

Table 1: Electricity production from nuclear power stations in Central Europe, 1980 and 1985, in TWh and share (%) of total electricity generation (IAEA, 1986).

	1980		1985	
	TWh	Share (%)	TWh	Share (%)
Austria	0.0	0.0	0.0	0.0
Belgium	12.5	23.4	32.4	59.8
Denmark	0.0	0.0	0.0	0.0
France	61.3	23.7	213.1	64.8
FRG	43.7	11.9	119.8	31.2
Ireland	0.0	0.0	0.0	0.0
Luxembourg	0.0	0.0	0.0	0.0
Netherlands	4.2	6.5	3.7	6.1
Switzerland	14.4	29.1	21.3	39.8
UK	37.0	13.0	53.8	19.3
TOTAL	173.07	14.91	444.1	37.3

analyze the possibilities of using more natural gas in Europe, for which energy models for five net gas-importing regions [2] were developed. The study focused on the balanced development of natural gas imports from various exporting regions [3] to those net importers. In order to obtain a realistic picture, the study covered all energy carriers and dealt with the complete energy system, from extraction to the various end-uses of energy for domestic, industrial, and transportation applications. Thus, one of the competing energy sources is electricity produced from nuclear power plants. This allowed the immediate use of the models to check the implications of a changed nuclear strategy on the restructuring of the energy supply system.

The basis of our investigations was the assumption that no new nuclear power plants will be built after 1990 in Central Europe, but that the existing ones will be used for their planned life times of 25 years. The model results, however, cannot be interpreted as such. The comparative effects of different measures have to be evaluated in comparison with a Reference Case (RC), in which nuclear power plants are built beyond 1990.

The investigations performed with this purely energy-related and regionally aggregated model cannot shed much light on the economic problems faced by the different nations. However, we can examine the following aspects of a discontinuation of nuclear energy:

(1) What are the *energy-specific* consequences?

(2) What are the consequences on *import dependence* and trade balance?

(3) What are the consequences for *emissions* without consideration of stronger measures concerning emissions standards, and what would the consequences be if more stringent measures were enforced?

(4) What effects on the economy could changes in *energy prices* and in *investments* from the energy sector have?

The Energy Supply Model

The model developed for the IIASA International Gas Study for Central Europe utilizes MESSAGE II (Messner, 1984; Strubegger, 1984), a dynamic linear programming model. The application for Central Europe includes 178 technologies, representing extraction, central conversion, transport and distribution, and utilization of energy. It covers the time horizon from 1980 to 2030, with 1980 being strictly and 1985 loosely calibrated with the actual situation.

The energy sources considered are lignite, hard coal, crude oil, natural gas (gaseous or liquefied as LNG), hydropower, nuclear energy, waste incineration and industrial wastes, on-site solar systems, and conservation investments. Secondary energy carriers are lignite, brown coal briquettes, hard coal, coke, fuel oil, gas oil, gasoline, natural gas, compressed natural gas (CNG), electricity, district heat, and methanol in motor fuels (up to 10%). Various types of power plants, including cogeneration of electricity and district heat in pass-out or back-pressure turbines, are represented. The annual and daily load variations and storage requirements of electricity, district heat, and natural gas are accounted for by representing the demand load curves as step functions with varying power requirements.

The model calculates – for the defined objective function – the optimal energy supply development over the time horizon, taking into account technical, economic, and ecological features, such as availability, technical plant lifes, efficiencies, investment costs, and SO_2 and NO_x emissions, as well as additional constraints imposed on the system, such as those on the extraction of domestic coal (reflecting political considerations) or the possibility of introducing district heat grids (with costs depending on the energy densities and building structures in question). The objective function contains, for this application, a mixture of economic and ecological objectives that reflect economic realities and the growing concern about the effects of pollutant emissions.

The Energy-Specific Consequences

Analysis of the possible consequences of a discontinuation of nuclear power is based on the RC of the IIASA Gas Study, which serves as a reference to evaluate the results of the Nuclear Phase-Out Case (NPC). The basic assumptions for the RC are a slight decline in final energy consumption (0.26% per year) up to the year 2000 and stabilization thereafter. The world market price of oil is assumed to increase from the present 15$/bbl with an annual average rate of 2% per year (in real terms). In the following energy analysis we focus on the development of the primary energy mix and the differences in the fuels used for electricity production.

Primary Energy Supply

For a comparison of energy supply in the RC and the NPC, we chose the years 1990, 2000, and 2030 to show the short, medium, and long-term consequences. The structure of primary energy supply will remain essentially unchanged in 1990 [4] (see Table 2).

Table 2: Sources of primary energy in Central Europe, RC and NPC, 1990 to 2030, in shares (%); the total is given in EJ.

	Reference Case (%)			Nuclear Phase-Out Case (%)		
Sources	1990	2000	2030	1990	2000	2030
Primary Energy [EJ]	37.71	37.28	39.67	37.68	37.14	38.52
Lignite	3.36	3.72	3.50	3.34	3.74	3.60
Hard coal	17.77	17.68	18.57	17.86	18.09	28.91
Crude oil	42.46	38.26	27.05	42.43	38.75	29.68
Oil production	0.37	0.45	0.77	0.37	0.45	0.79
Gas	20.80	21.53	24.63	20.77	24.97	30.87
Nuclear	10.47	13.06	19.60	10.47	8.69	0.00
Hydro	3.71	3.76	3.68	3.72	3.77	3.87
Solar	0.17	0.41	0.84	0.17	0.41	0.87
Waste	0.88	1.11	1.36	0.88	1.12	1.40

For the NPC, in 2000 nuclear energy will be reduced by one third compared with the RC, the effect being mainly in the use of gas. Only after 2000 will coal consumption start to grow significantly, while the use of oil will be less than 10% higher. The reaction to a phase out of nuclear energy stems from the historic development and present structure of the energy system in Central Europe. After the two oil price hikes in 1973 and 1979 the oil-importing countries, specifically those in Western Europe, undertook major efforts to reduce their dependence on oil exporters. During the economic stagnation at the beginning of the 1980s, the use of gas also started to stagnate and even decline. In a dynamic economic environment natural gas could, to some extent, take over from crude oil as a swing supplier.

The supply picture of natural gas is also very relaxed currently. The USSR has some free capacity in its pipeline system from Siberia to Europe, and Algeria has a tremendous overcapacity for LNG production and shipping. Additional supplies are secured by the decision to develop the Sleipner and Troll gas fields in the North Sea (Quinlan, 1986). If there is a shortage of any energy carrier – like, in our considerations, nuclear energy – gas can supply the shortfall. Crude oil has (mostly political) problems due to supply security considerations, while coal imports need the construction of new harbors and rail transport. Significant increases in the use of coal, other than in large power plants, would also create environmental problems or the necessity to apply very advanced, clean technologies, like fluidized bed combustion.

Electricity Generation and Final Energy Use

Electricity generation in the Central European region, according to the RC, nearly doubles in the period from 1980 to 2030, supplying then 2000 TWh, or 25% of the total final energy. This relatively low growth of 1.2% per year is a reflection of our assumptions on the development of energy utilization in the domestic heating market. The use of electricity for heating will be limited because insulation standards improve over time and new technologies – like heat pumps or highly efficient gas burners – are being introduced. Additionally, the production and use of district heat will increase over time, again reducing the growth potential of electricity in that sector. Similar arguments hold for other low-temperature heat markets in the commercial and industrial sectors.

In the RC electricity production is mainly based on coal and nuclear, which together supply about 80% of the electricity up to the year 2000. After the turn of the century natural gas will gain some importance, delivering 20% of electricity by the end of the study period. This high share of electricity produced from natural gas is a result of the introduction of highly efficient gas turbines and gas-fired combined cycles. Additionally, the required reduction of SO_2 emissions favors natural gas. But not only is gas supported by technological progress; by the end of the time horizon half of the coal-based power plants will use fluidized bed combustion, the rest being equipped according to present standards. Around 2030 coal-based power plants will supply 27% of electricity, while the share of nuclear energy will be 38%. Figure 1 shows the development of the electricity generation structure in the RC and NPC.

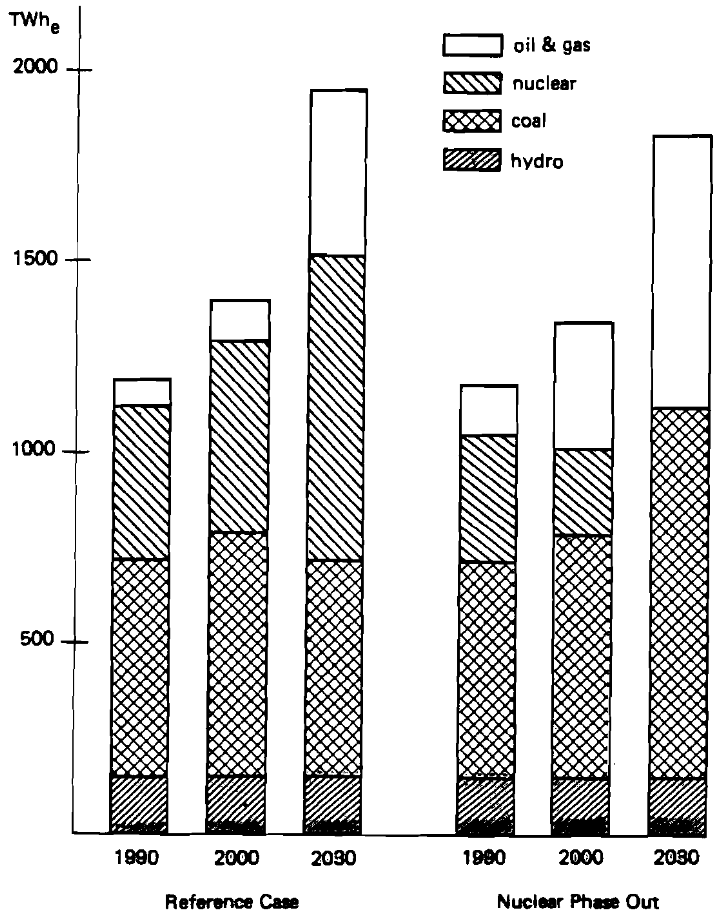

Figure 1: Electricity generation in the RC and the NPC, 1990, 2000, and 2030, in TWh.

For the case in which no new nuclear power plants are constructed after 1990, the contribution of nuclear power to electricity production will be reduced by 170 TWh or one third in 2000, which constitutes 12% of generated electricity. By 2010 nuclear power will be phased out completely, leaving a gap of 610 (in 2010) to 800 (in 2030) TWh to be filled by other energy sources. Also, electricity use will be, due to the increased production cost, reduced by 140 TWh, thus constituting 23.3% of the final energy use in 2030 – compared with 25.5% in the RC. Gas-based power plants will produce 260 TWh more electricity and coal power plants will be stepped up by 400 TWh (see Figure 1).

Table 3: Final energy consumption per energy carrier, RC and NPC, 1990 to 2030, in shares (%); the total is given in EJ.

Carrier	Reference Case (%)			Nuclear Phase-Out Case (%)		
	1990	2000	2030	1990	2000	2030
Final Energy [EJ]	27.82	27.15	27.53	27.84	27.45	28.04
Lignite	0.50	0.00	0.00	0.50	0.00	0.00
Hard coal	6.52	5.59	8.37	6.58	5.62	8.21
Fuel oil	10.30	10.23	7.16	10.33	10.09	6.75
Gas oil	27.76	25.15	19.05	27.73	25.27	19.12
Gasoline	14.53	13.05	10.70	14.52	13.07	10.99
Gas	23.09	23.93	21.78	23.07	24.39	22.17
Electricity	15.46	18.46	25.51	15.43	17.86	23.26
District heat	1.61	3.03	6.21	1.61	3.14	8.42
Solar	0.23	0.56	1.21	0.23	0.56	1.19

The reduction of electricity in final energy use will be balanced by an increase in district heat consumption of nearly 40% compared with the RC. The use of other final energy carriers will change only marginally: the use of gas will increase by 220 PJ ($5.9 \times 10^9 m^3$) , and the consumption of refinery products by 174 PJ (4 million toe [5]) in 2030. Table 3 summarizes final energy use in the two scenarios for the years 1990, 2000, and 2030.

Import Dependence and Trade Balance

Substantial changes in domestic energy production in Central Europe can only be achieved in hard coal extraction. In the RC hard coal mining is reduced from 230 million tce [5] in 1980 to 150 million tce in 2000 and 95 million tce in 2030, whereas in the NPC there will be a nearly constant production of hard coal after 2000 at a level of 140 million tce/yr. This higher production level requires significantly higher investments than currently needed for the production of hard coal, because virtually all the coal that is relatively inexpensive will have been exploited after the turn of the century. The assumed ban of nuclear power will allow the operation of mines otherwise uneconomic. Additionally, coal represents the only opportunity to substitute for nuclear energy without increasing the dependence on energy imports even further. Thus, also for political reasons, a higher level of domestic coal extraction would be desirable [6]. The joint effect of the 45% higher extraction of hard coal within the region – corresponding to an increase of 30% of total coal extraction, including lignite – and the abolition of nuclear reactors will be a 33% lower availability of domestic energy in 2030 [7] (see Table 4).

Table 4: Primary energy imports per energy carrier, RC and NPC, 1990 to 2030, (EJ).

	Reference Case			Nuclear Phase-Out Case		
	1990	2000	2030	1990	2000	2030
Hard coal	1.71	2.30	4.60	1.73	2.43	7.13
Oil	11.00	10.27	7.90	11.00	10.39	8.60
Gas	2.44	3.59	6.70	2.42	4.71	8.82
TOTAL	15.15	16.16	19.20	15.15	17.53	24.55

In 2000 energy imports will be 8% higher in the NPC than in the RC, in 2030 they will be 27% higher. The constituents of this substantial increase in energy imports will be 55% hard coal (87 million tce), 9% oil and oil products (16 million toe), and 32% gas (57×10^9 m^3). Import dependence will increase from 44% and 48% in the RC and NPC, respectively, in 2000 to 50% and to 65%, respectively, in 2030 (see Table 5).

Table 5: Comparison of import dependence for NPC and RC.

	Reference Case (%)			Nuclear Phase-Out Case (%)		
	1990	2000	2030	1990	2000	2030
$\frac{\text{Imported fossils}}{\text{total fossils}}$	47.79	53.63	66.01	47.77	55.41	68.77
$\frac{\text{Imported energy}}{\text{primary energy}}$	40.58	43.97	49.61	40.56	47.85	65.11

On the basis of the import price assumptions (an annual increase in the real oil price of 2%, starting from 15$/toe in 1985/1986, and gas and coal prices at 75% and 43% of the oil price, respectively), the effects on the trade balance of the region as a whole can be assessed. In 2000 the payments for energy imports will be 7.2% higher in the NPC than in the RC. By 2030 this figure will increase to 22.2%. In absolute values, this will amount to 144×10^9 US$ (1980) in 2000 and 860×10^9 US$ (1980) in 2030.

One must note here that exchange rate fluctuations, as experienced over the last couple of years between the US$ and the European currencies, would affect the import bills of the Central European nations by a similar order of magnitude.

Consequences for the Environmental Situation

In the RC, SO_2 emissions will decrease from 12 million tons [8] in 1980 to 7.3 million tons in 2000 and to 5.7 million tons by 2030 (see Table 6). This reduction will be achieved by concerted reductions in all energy consuming and conversion sectors. In electricity generation this will occur because of the increased introduction of nuclear energy, the use of gas as fuel, and the application of fluidized bed combustion for coal burning. In the residential and commercial sectors district heat, natural gas, and electric heat pumps will be used to substitute for heavy oil and coal.

Table 6: SO_2 emissions in the RC and the NPC, as percentage of the total, which is given in million tons.

Emission Source	1980	Reference Case(%) 1990	2000	2030	Nuclear Phase-Out Case (%) 1990	2000	2030
TOTAL [10^6 t]	12.10	9.76	7.29	5.71	9.74	7.42	7.04
Central conversion	60.31	61.99	58.71	62.90	61.78	58.62	69.14
Industry	24.19	21.62	22.22	24.72	21.84	22.37	20.13
Residential & commercial	12.62	12.60	13.72	6.51	12.60	13.75	6.07
Transport	2.88	3.79	5.35	5.81	3.78	5.26	4.66

The only market that will have (temporarily) increasing SO_2 emissions is the transport sector, due to the increased use of diesel oil for which no decrease in sulfur content is foreseen in the model. However, the transport sector contributed only 3% of the SO_2 emissions in 1980 in Central Europe. Thus, although some countries have legislation to decrease standards, the additional modeling effort to reflect this situation was not made.

In the industrial sector, similarly to the space heating market, increased amounts of natural gas, some district heat for low- to medium-temperature process heat, and the utilization of electricity for high-temperature markets, as well as gas and electric heat pumps for space heat and low-temperature process heat production, will result in a reduction of SO_2 emissions of 50% between 1980 and 2030 (see Table 7).

In the NPC, SO_2 emissions will be virtually unchanged in comparison with the RC for industry and transport. In the household sector, more light oil and fuel oil will be used for space heating, resulting in slightly higher emissions. The main effect will be, as could be expected, in central conversion, i.e., electricity and district heat generation. The amount of district heat produced will be considerably

Table 7: Development of SO_2 emissions in the RC and the NPC (1980=100).

Emission Source	Reference Case			Nuclear Phase-Out Case		
	1990	2000	2030	1990	2000	2030
Central conversion	82.88	58.63	49.18	82.47	59.59	66.71
Industry	72.01	55.29	48.12	72.70	56.66	48.46
Residential & commercial	80.39	65.36	24.18	80.39	66.67	28.10
Transport	105.71	111.43	94.29	105.71	111.43	94.29
TOTAL	80.66	60.25	47.19	80.50	61.32	58.18

higher, and the fuel mix for electricity generation will contain, after 2000, considerably more coal. By 2030, 75% of this coal will be burnt in fluidized beds; the remaining 200 TWh(e) produced will be used in conventional coal power plants (with back-pressure turbines to utilize the waste heat for district heat production) and so will still produce SO_2 according to the average environmental standards valid in 1985. Nevertheless, the total SO_2 emissions in the year 2030 under the NPC scenario will be 42% lower than in 1980, which is in line with the 30% reduction commitments made by the countries considered under the Convention of Long Range Transboundary Air Pollution (July 1985, Helsinki). Reductions achieved in the RC amount to 53%.

For NO_x the case is different. The introduction of natural gas, a fuel with varying but low nitrogen content, will improve the situation, but some NO_x is formed in the combustion process. In the scenarios, new technological developments allow the specific emissions from gas burners to be further reduced by some 40%. In the RC the emissions of NO_x will be reduced by 30% up to 2000, and by 45% up to 2030. In the NPC, no significant change will occur by 2000, but up to 2030 the emissions will be 16% higher than in the RC (see Tables 8 and 9). The higher increase in NO_x emissions, when compared to SO_2, is a result of the increased use of natural gas for electricity production.

However, both the SO_2 and the NO_x emissions can be expected to be even lower in reality, as most probably environmental standards will be more stringent than assumed in the model runs. Additionally, technological improvements and the utilization of combined cycle power plants for coal combustion will act in the same direction.

Table 8: NO_x emissions in the RC and the NPC as a percentage of total, which is given in million tons.

Emission Source		Reference Case			Nuclear Phase-Out Case		
	1980	1990	2000	2030	1990	2000	2030
TOTAL [10^6 t]	10.59	9.15	7.42	5.85	9.13	7.59	6.79
Central conversion	33.52	34.21	31.27	36.92	34.06	32.28	45.07
Industry	10.76	9.95	10.51	12.82	10.08	10.67	11.63
Residential & commercial	4.63	4.70	4.58	3.76	4.71	4.61	3.24
Transport	51.18	51.15	53.50	46.50	51.26	52.31	40.06

Table 9: Development of NO_x emissions in the RC and the NPC (1980 = 100).

Emission Source	Reference Case			Nuclear Phase-Out Case		
	1990	2000	2030	1990	2000	2030
Central conversion	88.17	65.35	60.85	87.61	69.01	86.20
Industry	79.82	68.42	65.79	80.70	71.05	69.30
Residential & commercial	87.76	69.39	44.90	87.76	71.43	44.90
Transport	86.35	73.25	50.18	86.35	73.25	50.18
TOTAL	86.40	70.07	55.24	86.21	71.67	64.12

Energy Prices and Investments of the Energy Sector

Nuclear power plants are the energy conversion technologies with the highest capital requirements per unit of energy produced. This high capital intensity is offset by the relatively low fuel costs involved. Owing to the reduction in total electricity generation in the NPC compared with that in the RC, and to the discontinuation of nuclear power, the investments for electricity generation in the NPC will be 21% lower than those in the RC in 2000, which amounts to 1.9 billion US$ (1980). In 2030 the investments will be reduced by 39%, corresponding to 7.2 billion US$ (1980).

Consequently, the structure of the energy-related expenditures differs between the two scenarios. In the NPC the expenditures for imported energy will be 7.2% higher in 2000, constituting 17.7% of the total expenditure for energy supply instead of 16.2% in the RC. In 2030, the gap will be considerably larger: import costs increase from 25% in the RC to 30% of the overall expenditures in the NCP. Note that these expenditures contain all the costs related to extraction, transportation, conversion, and utilization of energy. Thus, domestic space heating systems are included as well as industrial burners and power plants.

Up to 2000 the shadow prices (marginal costs) of electricity will change only in the summer, when base-load power plants supply the major share of the electricity, and nuclear plants have to be substituted for. The increase is roughly 20%, from 3 cents (1980) per kWh to 3.6 cents (1980). Peak power will cost 17 cents per kWh in both cases. By 2030 the marginal cost of electricity will, depending on the load, be higher in the NPC throughout the year. In summer the increase will amount to 45 to 50%, while in winter it will be between 24 and 11%. The marginal cost of peak power electricity will then be 25 cents per kWh in the NPC, compared with 20 cents in the RC.

Nuclear Phase Out and Low Emissions

Beside the composition of energy supply the most striking difference between the RC and the NPC is in the NO_x and SO_2 emissions. The obvious question in this context is: What are the implications of abandoning the use of nuclear energy and still have emissions as low as in the RC? Since the energy model for Central Europe includes NO_x and SO_2 emission reduction measures for central conversion and industrial applications, we tried to answer this question by limiting the emissions of these two pollutants to the values of the RC. The basic setup for this model run is like that in the NPC.

The results obtained suggest that there are no major problems in reducing the emission levels of the NPC to those of the RC. Up to 2000 the emissions will not differ much anyhow, and thereafter the use of coal is reduced slightly – 6 million tons or 1.6% less hard coal will be used in 2030. The change in the consumption of all other energy carriers will be even lower. The consumption of final energy will also be similar, with more electricity from the combined cycle gas turbines and less gas and district heat in the energy menu.

The increase in the annual expenditures for energy supply and consumption will be below 1%, as will the change in the total discounted costs (objective function value). All these results indicate that a discontinuation of nuclear energy can be performed without incurring major environmental problems, if the proper measures are taken in time to protect our environment.

An important problem concerning the environment, which is not discussed in this analysis, is the question of CO_2 accumulation in the atmosphere. All uses of energy that rely on burning a fuel containing carbon are bound to increase the atmospheric concentration of CO_2. Only energy carriers that are generated without such a source of energy – like nuclear and solar energy – or from sources that recycle atmospheric carbon – like biomass – can help to solve this problem. And only electricity and hydrogen can be used to bring this clean energy to the consumer. Centrally generated heat would also be environmentally benign, but it has a rather limited range of applications.

A Nuclear Moratorium

Another question of some interest concerns the effects of an *immediate discontinuation* of all nuclear power generation. Since the resolution of the model calculations is only five years, the effect of such a decision in all Central European countries within the next five years was analyzed. In the Nuclear Moratorium Case (NMC) no nuclear power station will be put on-line after 1985, and from 1990 on no electricity will be generated from nuclear power.

The major difficulties encountered in an immediate discontinuation concern the availability of power generation capacity. In the RC and the NPC roughly 400 TWh or 34% of the electricity will be generated from nuclear power stations in 1990. Since currently many countries have – due to the too high forecasts used as a basis for the expansion of the system – considerable overcapacities in their electricity systems, the necessity to install new systems is somewhat alleviated. Between 1985 and 1990 2×10^9 US$ will be invested for fossil-fired power plants in the RC, and in the NPC this figure amounts to 2.4×10^9 US$, while the investments for nuclear power plants will be 6.4×10^9 US$ in both cases. The high investments in the NPC are, as mentioned earlier, initiated due to the perfect foresight in the model approach. In the NMC the annual investments between 1985 and 1990 will amount to 12.9×10^9 US$. *Thus, the total investments for electricity generation will be 50% higher over the period 1985 to 1990 in the NMC.*

In terms of total energy use, the 10% primary energy equivalent contributed by nuclear power in 1990 will have to be substituted for. As in the NPC, in the NMC the main additions will come from natural gas. The gas imports will be 34% or $70 \times 10^9 m^3$ higher than in the RC in 1990; compared with 1985 the increase will be $83 \times 10^9 m^3$. In terms of increased export capacity from Algeria or the USSR this seems to be an unrealistically high value; also North Sea production is unlikely to grow at this rate. From this viewpoint higher oil imports seem to be more probable.

Total electricity generation will be reduced by 40 TWh or 3.5% in 1990 – a reduction that will occur mainly in the industrial use of electricity for high-temperature processes. The remaining gap left by nuclear will be substituted by fossil power plants – fueled with either gas or fuel oil, depending on the availability and price on the world market. In the long run the supply menus will be the same in both cases.

Broader Aspects

As already mentioned, in 1985 Central Europe produced 444.1 TWh of electric energy from nuclear power. In terms of ***primary energy equivalent*** [9] 100 million tons of oil or 155 million tons of coal will be required to substitute for nuclear energy in Central Europe. These are, in relation to the global production of those fuels, relatively modest amounts. In 1985 the global production of crude oil amounted to 2790 million toe and for coal to 3500 million tce (2271 million toe). Especially regarding crude oil, the current market situation allows an additional 100 million toe or even larger amounts to be supplied rather easily. Between 1979 and 1985, global production of crude oil fell by 436 million toe and for OPEC even by 713 million toe. But also coal and natural gas extraction can be stepped up in a number of countries, although slower than in the case of crude oil. Thus, in the near term the additional amounts of fossil fuels needed to substitute for nuclear power in Central Europe could be supplied rather easily, and there are no logical reasons why this should lead to drastic price increases for those fuels.

Even in the long run, up to 2030, the additional amounts of fossil fuels needed to fill the gap resulting from a nuclear phase out, as described in this paper, are less than the world 1985 consumption of fossil fuels: 5000 million toe additional demand (cumulative) over the next 45 years compared with 6500 million toe of fossil fuels consumed in 1985. The combustion of these additional fossil fuels will increase the CO_2 emissions by roughly half the global CO_2 emissions of the year 1980.

Even if the effects of a nuclear phase out do not show dramatic consequences on the global scale, this should not suggest that a discontinuation of the further development of power generation systems based on nonfossil fuels is trivial. The dependence on imported fuels, and thus the vulnerabilty to price shocks, increases in the countries considered, and we do not know yet how, even comparatively minor, additional CO_2 emissions will affect the earth's climate.

Conclusions

The first-order analysis of the impacts of a discontinuation of nuclear energy in Central Europe described in this paper indicates that the direct effects on the energy system are manageable, and that the effects on the environment can be kept within reasonable limits. The financial consequences – seen from the perspective of the whole energy system – are also moderate.

The most severe problems will obviously occur in France, with its strong nuclear program and the low availability of domestic energy resources. But, to be realistic, it is very unlikely that France, without experiencing a major nuclear accident, will follow the NPC or NMC strategies investigated in our paper. The only countries that might consider such policies are the FRG and Belgium. In the FRG the consequences would be low, due to the large number of currently existing but unused fossil-fired plants. If a nuclear phase out occurs, both countries could switch to coal as the major source of electricity, which could, besides the related costs, have a positive first-order effect on employment. One of the studies performed on this subject in the FRG (by the Institute for Applied Ecology in Berlin) even foresees an innovative push from the necessity to find new solutions (*Wiener Zeitung*, 10. 9. 1986).

However, the conclusions derived from a macro-perspective cannot be translated directly to the micro-level. For a discontinuation of nuclear power the industries affected most will be the electric utilities, which will have to develop new investment strategies, and the companies supplying the investment goods. The consequences could – for single companies – be in the range of the problems that emerged in the 1960s, when the export of large-diameter pipes from members of NATO to the USSR was banned by an embargo. This embargo had been initiated by the USA because the pipes were to be used in the construction of the Friendship oil pipeline from the USSR to its Eastern European Allies, thus possibly assisting Warsaw Pact Maneuvers (Stent, 1982). At that time large German companies, like Mannesmann and Hösch, which were involved in East–West trade, had to cut their production capacity considerably.

Similar measures were necessary in the refinery sector at the beginning of the 1980s. Because of a slump in demand and the bad performance of the Western economies, together with a dramatically different pattern of demand for oil products, capacity had to be cut, and even new refineries had to be closed. In the FRG, refining capacity was reduced from 160×10^6 tonnes in 1978 to 87×10^6 tonnes in 1985, a reduction of 45%, while the average reduction in the EC was roughly 36%. The capacity for upgrading heavy products rose by 30% in the same period (Baum, 1986).

A difference between the nuclear industries and these examples is the special interest of governments in their nuclear industries. Leaving aside defence-related aspects, which have considerable importance in some countries, these industries are viewed as high-technology branches and expected to initiate innovation, technological progress, and improve competitiveness. Most governments would be concerned about a reduction in such operations.

Notes

[1] These figures include only those reactors under construction or with a confirmed construction start in 1986.

[2] Northern Europe (Scandinavia), Central Europe, South West Europe (Iberian Peninsula), South East Europe (Greece, Italy, Yugoslavia, Turkey), and East Europe (CMEA excluding the USSR).

[3] Algeria, the Middle East, Netherlands, Nigeria, Norway, and the USSR.

[4] The reason for the minor differences is, that the supply model has perfect foresight and calculates the optimum for the whole time horizon.

[5] $1000 m^3$ of natural gas = 37.3 GJ.
1 toe (ton of oil equivalent) = 44.8 GJ.
1 tce (ton of coal equivalent) = 29.3 GJ.

[6] The, for a linear programming model, somewhat unexpected result of an increase in both domestic extraction and imports of coal, is a result of a dynamic constraint enforcing that domestic extraction can, at maximum, be kept constant.

[7] Domestic energy in this analysis is all the energy produced in the countries in the region Central Europe. This means that all gas from the Netherlands is included in the domestic sources, as well as the oil and gas produced in the British part of the North Sea.

[8] The IIASA Acid Rain Project (ACI) states a figure of 13.6 million tons of SO_2 emissions for the same region in 1980, with 8% higher emissions in the industrial sector and lower figures for the household/commercial and transportation sectors. This discrepancy was not resolved yet, but due to the relatively small differences the results would only change marginally.

[9] I.e., expressed as the amount of fossil fuels required to generate the same amount of electricity.

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