The net power balance of nuclear power plants in the Federal Republic of Germany

Die Nettoleistungsbilanz von Kernkraftwerken in der Bundesrepublik Deutschland

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Abstract

It has been speculated that if the build-up of a nuclear program proceeds too rapidly, then it might consume more energy than it ever produces. This argument is examined with respect to the rapidly expanding German nuclear program and is shown to be inapplicable, although the actual results do depend critically on a number of assumptions. The conclusions are not as optimistic as in previous treatments of the subject in Germany.

1. Introduction

Dr. *P. Chapman* has shown that if the build-up of a nuclear program proceeds too rapidly, then it can consume more energy than it produces [1]. The argument is by now well known: the construction of a single nuclear power plant takes place over several years, during which time energy must be invested; this energy is only paid back after the plant goes into operation to produce power. In the meantime, however, depending on the growth rate, more and more plants come under construction, requiring an ever greater total energy investment in plant construction. If this growth rate is large enough the net power output never becomes positive, i.e., the total output from nuclear plants never catches up and becomes larger than the necessary yearly investment in new plant construction. An essential feature here is that the argument goes beyond previous static arguments relating to how well a single reactor "pays" for itself and considers the dynamics of an entire reactor program.

The validity of this argument, as applied to the nuclear program of the Federal Republic of Germany, has been called into question recently in a paper from the Jülich Nuclear Research Facility [2]. In the present paper the net power balance will be examined and the major factors which lead to the large differences between the *Chapman* and Jülich results will be clarified.

The first step in the analysis is the determination of the power output P_0 and input power P_I for a single reactor, where P_0 is the annual energy production minus annual energy costs of operation and P_I is the initial energy investment in construction divided by the number of years required for construction. One obvious source of difficulty here is that while the construction energy inputs are primarily thermal, the output is electrical--for many applications electrical energy is "worth" several times more than thermal energy.

A convenient index of performance for a single reactor is the energy ratio

$$E_r = \frac{\text{Lifetime energy output}}{\text{Initial energy investment in construction}}$$

With a nominal plant life of 25 years and a 5 year construction time, one has $E_r = 5\,P_0/P_I$.

The dynamic aspect of the analysis then involves the use of the information on power inputs and outputs for a single reactor to calculate the power performance of the total nuclear system. This is essentially given by the number of reactors in operation times P_0 minus the number under construction times P_I.

Part of the ambiguity in previous calculations of net power balances can be traced back to the use of different conventions. *Chapman* on the one hand makes a direct comparison of the electrical outputs with the fossil inputs to the nuclear program (albeit with a 1 : 1 ratio in the comparison of electrical and fossil energies), while Jülich examines instead the fossil requirements which would be necessary in order to provide the same electrical power output as from the nuclear program but using conventional (coal) power plants. Now all calculations (including those of *Chapman*, for appropriate parameter values) show that the cumulative fossil fuel consumption of the conventional plants is greater than that of the nuclear program; the Jülich report essentially labels this difference the fossil fuel "savings" due to nuclear power. With this, the energetic argument for nuclear power is ostensibly established.

However, the demonstration that conventional plants are worse in their consumption of fossil fuels does not establish that nuclear power plants are energetically good. Implicit in such comparisons is the assumption that the growth rate in electricity production must remain the same as in the past. Now if this were the case, then the above type of comparison would be adequate--but it is not. Since there are other technological possibilities, it is altogether reasonable to examine what the growth rates in electricity production should be in the future.

Thus we come to the issue addressed by *Chapman*: is the fossil fuel consumption due to a nuclear program for production of electricity, although possibly lower than if conventional power plants were used, itself within acceptible bounds? If not, then perhaps the growth rates in electricity production should be lowered from their traditional values.

To answer the above question one does need to look at the inputs and outputs of the nuclear program itself, in which the relative value of electrical and thermal energies can only be determined with respect to the use to which the electricity is put. We follow this latter procedure in the present paper. It will turn out that the quantitative results, while not as favorable as those of Jülich, do not support the contention of a net negative power balance for nuclear plants in Germany.

2. The conventions and main assumptions

In some cases the influence of an assumption or convention on the quantitative results for the net power balance is fairly obvious, such as in the comparison of thermal and electrical energies. In other cases a sensitivity analysis is required in order to determine the relative importance of the various assumptions.

A detailed analysis based on the information given in the Tables later results in a rough ordering, in decreasing order of importance, of the assumptions as applied to the German program as follows:

1. The present energy costs of a nuclear power plant including the first core fuel inventory;
2. The growth rate in the installed nuclear capacity;
3. The plant load factor (normal base-load operation);
4. The convention used in comparing thermal inputs with electrical outputs;

Table 1: Calculation of fuel-cycle energy requirements for a 1000 MW plant (represents an average of typical BWR and PWR characteristics)

First Core [1] (units 10^6 kWh (th) / 1000 MW(e))			
Mining & Milling	0.2% ore	180.3	
	0.02% ore	2953.6	
Conversion		50.3	
Enrichment	Diffusion	2269.4	
	Centrifuge	365.6	
Fabrication		19.2	
Totals, First Core:	0.2% ore	Diffusion	2519
		Centrifuge	616
	0.02%	Diffusion	5293
		Centrifuge	3389

Yearly Requirements (units 10^6 kWh/1000 MW(e) · year [2])		
.2% ore	Diffusion	92 (th) + 314 (e)
	Centrifuge	99 (th) + 30 (e)
.02% ore	Diffusion	1102 (th) + 314 (e)
	Centrifuge	1109 (th) + 30 (e)

[1] Based on converting all electrical requirements to thermal units using a system efficiency of 28%. This includes investment energy costs, amounting to slightly less than 1%, distribution losses, and consumption by the electricity industry itself.

[2] Here the thermal and electric units are kept separate.

5. Changes in fuel-cycle energy costs during the transition to lower grade uranium ores, and the associated problem of whether to count the energy inputs to the nuclear program which occur outside Germany;
6. Fuel enrichment techniques;
7. Additional infrastructure energy costs which are incurred such as in the associated build-up of the electrical distribution network.

These assumptions will be discussed in the following.

1. The (fossil) primary energies consumed in the construction of a nuclear power plant are conveniently calculated through use of an input-output analysis [3], which relates energy intensities with final demands (in monetary units) of various economic sectors. The individual cost contributions to the total cost of the power plant are then multiplied with their respective energy intensities and summed to yield the total energy costs of the plant; the energy costs of the first core are calculated similarly. These calculations are summarized in Tables 1 and 2 and show an energy cost of a light water power plant including first core of about 5230 kWh(th)/kW(e) at the present time (based on diffusion enrichment and ore concentrations of 0.2 %). More details on the calculations can be obtained elsewhere [4].

2. The planned installed nuclear capacity to the year 2000 is given in Table 3; the growth rate between 1972 and 1976 is a huge 43 % per year, corresponding to a doubling time of slightly under 2 years. Continuation of this level of growth through 1985 would result in 238 GW installed nuclear capacity by 1985. Such a large growth rate cannot be sustained indefinitely; in fact after 1976–1977 the growth rate drops to about 23 % annually (and decreases further after 1985), which results in the planned nuclear capacity of 50 GW by 1985. Of all the various factors affecting the net power balance it is this drop-off in the growth rate of installed capacity which will be seen to lead to the tremendous increase in the net power balance which starts about 1975. This is the case since the nuclear plants already on stream are no longer loaded down by the energy sink due to new construction. For the critical time period from 1970 to 1985 this effect effectively swamps all other effects.

Such an effect is not present in Chapman's calculations for Great Britain since constant growth rates corresponding to doubling times of about three to four years were taken to be appropriate.

3. It is difficult to separate fact from fancy in the choice of an effective load factor. An average of the best 33 BWR's and PWR's in the world yields a load factor of 60.4 % for the year 1972 (yearly running average), and this average remained the same in 1973 [5]. The yearly running average is generally taken to be indicative of future plant operation, since the poor load factors which often occur during initial years of operation of nuclear plant carry little weight in the running average. In the case of Germany the numbers for LWR's are 45 % for 1972, 62 % for 1973, and 40 % for 1974; the average for these three years is 50 % [6]. In the calculation a 50 % load factor has been used through 1975, and it is assumed that the load factor then increases linearly to reach the value 0.70 by 1985, and from 1985 to 1990 it again increases linearly to reach the value 0.75; thereafter it is assumed to remain at 0.75.

Table 2: Plant investment costs and distribution network costs

1. Construction (20%)		164,- DM/kW(e)
2. Machinery (55%)		451,- DM/kW(e)
3. Electrical (25%)		205,- DM/kW(e)
4. Other services related to the nuclear plant		380,- DM/kW(e)
Energy Costs		
1. Construction Energy Costs @ 283 kWh/100 DM	:	464 kWh
2. Machinery Energy Costs @ 227 kWh/100 DM	:	1024 kWh
3. Electrical Equipment @ 228 kWh/100 DM	:	467 kWh
4. Other Services 199 kWh/100 DM	:	756 kWh
Total costs for a nuclear plant, excluding the first core	:	2711 $\frac{kWh(t)}{kW(e)}$
Network Investment Costs: 1300,- DM/kW(e); 2.4 kWh(th)/DM	:	3120 $\frac{kWh(th)}{kW(e)}$

Table 3: Installed nuclear electrical capacity in the Federal Republic of Germany

	GW
1962	0.016
1966	0.32
1970	0.96
1972	2.27
1974	3.49
1976	9.51
1978	12.03
1980	22.94
1985	50.0
1990	89.0
1995	135.0
2000	170.0

In calculating the net electric power output of a plant P_0 the nominal capacity of 1000 MW is multiplied by the load factor times 8760 (the number of hours in a year) to give the annual energy output. A factor of 12 % is then subtracted to account for the energy consumption in the plant and the distribution losses, and the annual energy costs associated with the fuel cycle requirements (Table 1) are also subtracted.

4. Since at the start of the nuclear program one has a fossil-fuel based economy, all of the energy costs for the construction program are initially calculated on the basis of the primary energy inputs. Any electrical energy inputs in the construction are converted to the original thermal inputs by using the system efficiency for converting fossil fuels to electricity (about 28 % for Germany). This procedure is also used in the calculation of the energy requirements for producing the first core.

But now how should the net electric power output P_0 be compared to the original thermal inputs? Any comparison of thermal and electrical energies must be based on the use to which the electrical energy is put. Obviously, if electricity is used for producing low temperature heat such as in homes, then its energy "value" is only slightly better than fossil energies applied for the same purpose (100 % conversion efficiency for electricity, as opposed to 70 to 80 % conversion efficiency of fossil fuels to heat). This case is mentioned here because it appears that a fairly large share of the projected increases in household electric energy demands in Germany may be due to increased use of electric room and water heaters.

On the other hand, for applications where electricity is needed for motive power, then it clearly does have a value roughly 3 times greater than the same quantity of thermal energy (since thermal energy would have to be converted to electricity first before it could be used).

Thus, a comparison of electric with thermal energies requires an average over all end use applications in the sectors industry, household-commercial, and transportation. For the purpose of the present calculation this average is obtained through consideration of the present and future shares of the electricity production which go to industry and to household-commercial, where we note that the electricity share to household-commercial in Germany which should be valued at 3 times is already saturated. In the calculation we have used a multiplication factor which has the value 3.2 in 1970 and gradually decreases to the value 2 in 2000. This decrease is conservative, and occurs too slowly to have a significant influence on the rapid variation of the net power balance which will be seen to occur starting about 1975.

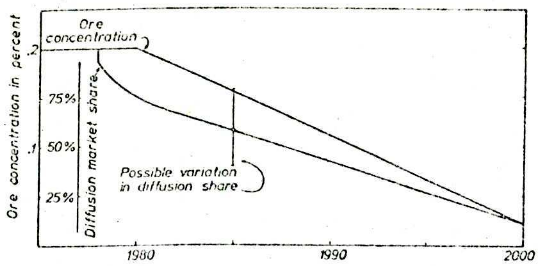

Fig. 1: Assumed time dependence of ore concentrations and of the diffusion share of the enrichment market (inner scale refers to diffusion.market share)

The problem of determining the thermal-to-electric relationship is avoided in the Jülich calculation due to their choice of a different convention (the comparison of fossil fuel consumption by conventional and nuclear programs for the same electrical output).

5. The energy requirements for obtaining the necessary uranium is roughly inversely proportional to the ore concentration. Presently mined concentrations are about 0.2 % and do not involve large energy inputs (Table 1). On the other hand, lower grade ores, on the average, will be mined in the future. For simplicity in the calculation we have assumed a linear decrease in the ore concentration, starting from the value 0.2 % in 1980, as shown in Fig. 1. The value 0.02 % in 2000 corresponds to the value used in the Jülich study, although the fall-off begins five years sooner than in the Jülich calculation. The Chapman calculation does not include any assumption on the time dependence of the ore concentration. His study, being the first of this type, makes use of constant, limiting values for the ore concentration (0.3 % and 0.007 %) to illustrate the range of variation in the net power balance due to change in the ore concentration.

In the calculation all energy costs have been included, regardless of whether they are incurred domestically or outside the country. For the purpose of an energy analysis this procedure would seem called for: the energy must be "paid" for in one way or another, and neglect of the energy costs falling outside the country would amount to assuming an indefinite energy subsidy. Both the Jülich and Chapman calculations include both the foreign and domestically incurred energy costs. Other procedures can also be adopted which allow, in one way or another, the energy costs incurred outside the country to be counted at less than the actual value – this of course leads to a more favorable net power balance. The Jülich calculation illustrates this possibility as a deviant to their standard case.

6. The energy requirements of the centrifugal enrichment technique have been estimated to be about a tenth of those for the currently used diffusion technique; at the present time, however, no large centrifuge plants exist. If the centrifuge technology proves to be successful on a large scale, then a considerable improvement in the fuel cycle energy costs will result (Table 1). The phase-in of the centrifuge method used in the present calculation and shown in Fig. 1 is based on current projections [7]. It must be admitted, however, that there is considerable room for variation in the curve, since the capacity of currently planned or already operating facilities falls short of the expected requirements. The possible variation, indicated by error bars in the figure, will depend on the relative success of the centrifuge technology.

It turns out in the calculation that the increased energy costs due to the use of lower grade ores are compensated by the gradual conversion to the centrifuge technology, except during the last decade of the century.

7. The required energy expenditure in building up the distribution network [8], for each 1000 MW of capacity which is added, is actually larger than the energy cost of the nuclear plant itself (Table 2). Should this energy be included in the calculation? If electricity were the only alternative as a secondary energy, then the only comparison would be between nuclear and conventional power plants; since this energy cost is incurred by both technologies, it could then be neglected in the comparison.

But there are alternatives to electricity, depending on the end use application, so it is reasonable to include the distribution network energy costs in the calculation of the net power balance. Of course the alternatives also have distribution network energy investments, such as for pipeline systems in the case of gas; these investments tend to be lower, however. It has been assumed that the construction time for increments to the distribution network is one year.

Neither the Jülich nor the Chapman calculations included the distribution network energy costs, but the effect is in any case not large since we assume the energy is only invested one year in advance as opposed to five years for nuclear plant construction. In quantitative terms the total value for the energy investment for 1000 MW of additional nuclear capacity lies between the values obtained in the Chapman and Jülich calculations.

3. Results

Based upon assumptions outlined above the energy ratio E_r, the electrical output of a plant over its assumed 25 year lifetime divided by the original fossil fuel investment, turns out to be about 32. In obtaining this number the relative value of the electrical output with respect to thermal energies has been taken into account (see the assumptions). A nuclear plant clearly pays for itself. Another way of expressing the results for a single plant is in terms of how long it takes the plant to pay off the original fossil energy investment; it can do this in ten months (based on the load factor of 50 % at present, and including the energy necessary to pay back the increment to the distribution network).

Next we turn to consideration of the overall nuclear program. The total annual thermal input and the electrical output of the program are shown in Fig. 2. Here the electrical output has already been increased from its nominal thermal value through use of the multiplication factor discussed in the assumptions. Even though the energy ratio for a single reactor is quite high, the point to the exercise is to consider the effect of a rapid build-up in new capacity on the overall power balance. It can be seen that in the year 1975 roughly 64 % of the output has to be reinvested in new plant construction, so that only 36 % of the output prepresents a net gain in the conversion of fossil fuels to electricity. However, by 1980 the reinvestment percentage has dropped to 18 %, and by 2000 the value is 10 %. Although during the years up to about 1977 the program consumes a large share of fossil fuels relative to its own electrical output, the net power balance (the difference between the two) does remain positive.

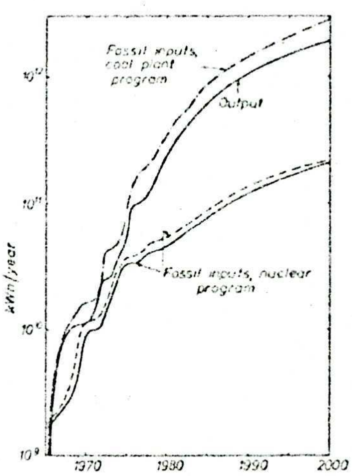

Fig. 2: Comparison of electrical outputs and the fossil inputs for coal and nuclear programs. The dotted line shows the effect of increasing the energy costs of a reactor, exclusive of first core, by 50 %

If the economic costs of nuclear plants used in the present calculation turn out in reality to be higher than those shown in Table 2, then due to the method of calculation – the multiplication of energy intensities with economic costs to obtain the energy costs – the energy costs would then need to be corrected upwards. The dotted line in Fig. 2 shows the nuclear program inputs which result if the individual reactors exclusive of first core require 4100 · 10^6 kWh(th) for their construction, the value obtained by Chapman, instead of the 2711 · 10^6 kWh obtained in the present study. The situation in 1975, for example, is aggravated a bit, since then about 74 % (before: 64 %) of the nuclear output is reinvested in order to build up the program. However, as before the net power balance becomes favorable very rapidly after 1975.

So what leads to the major differences between these results for Germany and those presented by Chapman? First, the energy ratio obtained for Germany is several times larger than Chapman's worst case example $E_r = 5$ (in which he has used a 1 : 1 valuation of thermal and electrical energies).

For the energy ratio obtained in the present paper an extremely large growth rate over an extended time period would be required to make the net power balance negative for very long. It was pointed out earlier that the fall-off in the growth rate leads to the large positive changes in the power balance which begin to occur about 1975, and that other effects are relatively unimportant. This can be illustrated in a round-about way by considering the power balance which would have resulted if the growth rate of 43% during the years 1972–1976 were to be continued indefinitely into the future, with the other parameters such as the ore concentrations shown in Fig. 1 being unaltered (as if this were possible!).

The purely hypothetical result is shown in Fig. 3. Here the net power balance, the difference between output and input, wavers a bit during the beginning years, and finally becomes uniformly positive starting about 1976. After 1976 both input and output display linear behaviour on the log scale, which is roughly what one would expect for an exponential growth rate. Although the power balance is positive and continues to increase in magnitude, the inputs now stay in step with the outputs. In other words, the share of the output which must be reinvested in new plant construction always remains at unacceptibly high levels; this is a direct result of using a constant growth rate instead of the decreasing growth rate appropriate for Germany. Even for somewhat smaller energy ratios these results would hold true.

It was pointed out previously that the Jülich calculation employs a different convention, in which the fossil fuel inputs necessary to support a conventional power plant program with the same electrical output as the nuclear program are examined. One is thus not directly concerned with an input-output comparison or the associated question of how the electrical output is used. The result obtained by Jülich for coal power plants is also shown in Fig. 2. Viewed from this perspective, nuclear plants are better than conventional plants almost from the beginning, since they consume less fossil fuel.

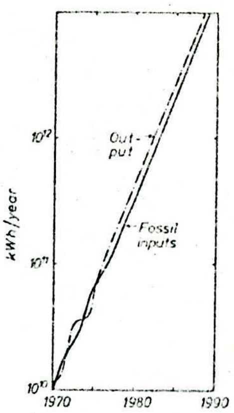

Fig. 3: Hypothetical result for a reactor program if the 43% growth rate during 1972–1976 were continued into the future

The other factors only begin to become important towards the 1990's such as when the phase-in in centrifuge enrichment can no longer compensate for the increased energy costs due to the assumed fall-off in the assumed ore concentrations. Chapman's analysis was limited to the diffusion technology, which however is adequate for the 1970's. Possible changes in the net power balance due to changes in the various other parameters towards the end of the century are probably not worth discussing within the framework of the present assumptions, since other reactor types (high temperature gas reactors, for example) may well be in operation also by that time. This would have to be included in the calculation. Also, other effects should also be considered, such as plant lifetimes of only 15 to 20 years instead of the assumed 25 years. Shorter plant lifetimes would of course make the net power balance less favorable.

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