# Nuclear Energy, the Energy Balance

## Chapter 3

## The Power Plant

fourth revision

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# Part 1: Construction

This analysis is based on Pressurized Water Reactors (PWRs) (Light Water Reactors, LWRs) in the USA because of the availability of data on a large number of nuclear power plants built and operating under the same economic conditions.

*# svl eerste alinea beetje gewijzigd: onderstreept, nieuwe figuur,nieuw caption. verder geen wijzigingen in dit hoofdstuk. aanvullende referenties apart bestand*

### Historical overview of construction costs

All PWR power plants connected to the grid in the USA are of 1980 vintage or older. Since 1978, no new plants have been ordered. In 1973 the last plant was ordered that has been completed. The historical costs of nuclear power plants up to 1986 in the USA are represented in Figure 13, with data from [Roddis & Ward 1971], [Mooz 1981], [Diaz 2001] and numerous reports in Nuclear News, Nucleonics Week and Nuclear Engineering International.

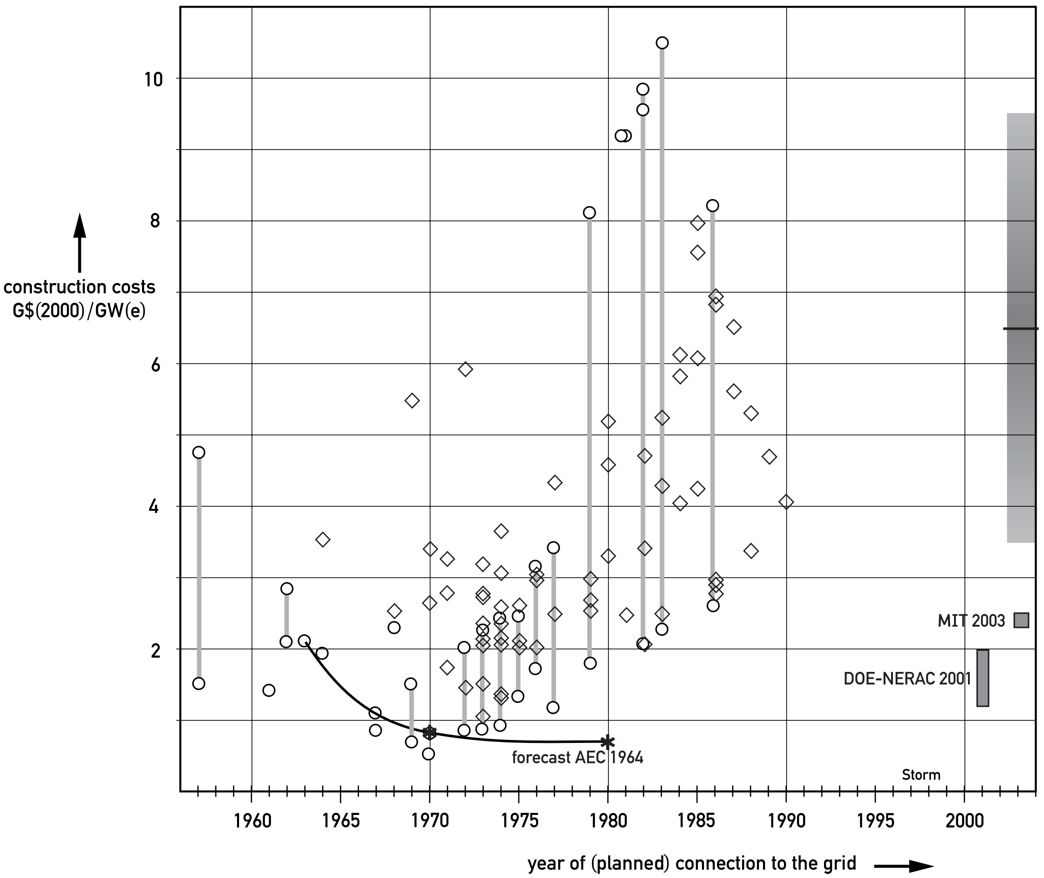


**Figure 13**

Historical construction costs of LWR power plants in the USA. The circles with the thin grey bars represent cost ranges in a given year from various sources: McLain 1964, Roddis & Ward 1971, Mooz 1981, and numerous reports in Nuclear News, Nucleonics Week and Nuclear Engineering International. The diamonds are data from Diaz 2001. The gray bar at right represents the cost range used in this study: 3.5 - 9.5 G$(2000)/GW(e), with an average of 6.5 G$(2000)/GW(e).
AEC (Atomic Energy Commission) is the predecessor to NRC (Nuclear Regulatory Commission).
The values indicated by DOE-NERAC 2001 and MIT 2003 are estimates for near future nuclear power plants.

**During the 1980's, a number of power plants in the high range of costs were cancelled before completion, so the average of the construction costs of actually commissioned plants is lower than the average of costs of plants under construction, as depicted in the figure. Specifically, the cancelling of plants causes a decline in the upper limits of costs after 1984.**

The actual construction costs as function of the year of (planned) commissioning show a striking pattern. After construction of the first commercial nuclear power plants, the unit costs fell to a low in 1970. Probably this is (partly) caused by economy of scale. During the first decade, the mean power rating increased by a factor of more than ten: from a few tens of megawatts (electric) to many hundreds of megawatts.

After 1970 the (reported) costs rose more and more steeply. The scatter of the published costs per unit increased as well. In 1983 the highest reported unit cost was nearly 6 G$/GWe and the lowest about 1.3 G$/GWe. In 1986 the lowest value was about 1.5 G$/GWe and highest about 4.7 G$/GWe (all values in $(1982)). The decrease in the high end of the range was not caused by cheaper construction, but by cancelling further construction on plants with higher costs. A ceiling value may be about 4 G$/GWe. Probably, the escalation of construction costs is part of the reason that no new nuclear power plants have been ordered in the USA since 1978. The cancellation of the construction of power plants before completion, when the costs rose into the high end of the range, does not change the real average construction costs or real energy requirements.

Usually, after introduction of a new technology the unit costs decrease with time, as more experience is built up and more units are produced (learning curve: learning by doing). After 1970 the learning curve effect is completely absent in the nuclear industry, quite the reverse happened. See also references quoted in [Tyner, Constanza & Fowler 1988]. We have no explanation for the large and increasing differences between lowest and highest reported costs. One must bear in mind that it is difficult to get a picture of the real costs of nuclear power during the first decades after the introduction of the program "Atoms for Peace". Government subsidies paid for much of the construction costs and essentially all of the technological development.

Some thoughts concerning the economics of nuclear power from another point of view are expressed in a recent study [Proops 2001]. Proops put the course of the costs of nuclear power down to three factors: subsidies from the military nuclear industry, subsidies from the government, and absence of adequate insurance against damage to third-parties. If the nuclear industry were to be obliged to insure the real risks, commercial operation might not be possible.

### Cost overruns

Large cost escalations are intrinsic to new technology projects, as [RAND 1981] reports:

Severe underestimation of capital costs is the norm for *all* advanced technologies;

The underestimation for energy process technologies mirrored that seen in major weapon systems acquisition, very large advanced construction projects, and major public work activities.

A number of advanced technologies brought to project completion had problems with reliability and performance.

Capital costs are repeatedly underestimated for advanced chemical process facilities, just as they are for advanced energy process plants. Furthermore, the performance of advanced energy process plants consistently falls short of the predictions of designers (and assumed in financial analyses).

Greater than expected capital costs and performance shortfalls not anticipated by conventional estimating techniques can be explained in terms of the characteristics of the particular technology and the amount of information incorporated into estimates at various points in project develop."

According to [RAND 1979], escalations in cost estimates of energy process plants with factors 2 - 5 are not uncommon. The nuclear industry provides amply examples of this rule and of the observations in [RAND 1981].

In this study a range of 1.4-6 G$(1982)/GWe, is taken as starting point of calculations. For purposes of energy analysis, the full cost range is a realistic basis; we have somewhat arbitrarily chosen the average of the highest and the lowest values, 3.7 G$(1982) as the base of our calculations.

## Energy requirements

The energy requirements for construction are not measurable directly, because of the sheer complexity and scale of the activities. Indirect methods to estimate the construction energy are used throughout in the studies carried out in the past, a number of which are summarized in Table 11.

Table 11 Estimates of energy requirements of power plant construction

n.a. not available
* Not included
** Construction + operation. Figures from Rotty et al. 1975. T100 = 18.67 FPY (full-power year).
*** Construction + operation. Figures from ERDA-76-1 and thus from Rotty et al. 1975, corrected for a longer operating time: T100 = 24 FPY.
Jprim = primary energy requirements: electric energy converted into primary thermal energy:
Jprim = f•Je + Jth , with n = variable factor, often f = 3 - 3.2.
Method: A = applying general energy/gnp ratio
B = energy/gnp corrected for the sector new construction (1.16)
C = direct energy + energy in materials
D = only energy in materials.
(gnp – gross national product)
Notes:
Figures of Rotty et al. 1975 are based on data from WASH-1230 (1971).
All costs converted into dollars, with 1 GBP = 1.60 US$, 2 DM = 1.00 US$.
1 Gg = 1 gigagram = 1000 metric tonnes.

| reference | $J_{prim}$ PJ | $J_e + J_{th}$ PJ | R $J_{th}/J_e$ | method | mass Gg | cost G$ | year | MJ/$ |
|---|---|---|---|---|---|---|---|---|
| Franklin et al. 1971 | - * | - | | | | | | |
| Rombough & Koen 1978 | 1.37 | n.a. | n.a. | D | 25.7 | 0.21 | 1974 | |
| *idem* | 16.8 | 12.69 | 14.7 | B | | 0.21 | 1970 | 79.31 |
| *idem* | 15.4 | - | n.a. | A | | 0.21 | 1970 | 73.17 |
| *idem* | 16.8 | | 14.7 | B | | 0.21 | 1970 | 79.69 |
| Rotty et al. 1975 | | 10.85 | 13.7 | C | n.a. | | 1971 | |
| Perry et al. 1977 | | 10.85 | 13.7 | C | n.a. | | 1971 | |
| SRI 1975 | - * | - | | | | | | |
| Kolb et al. 1975 | 9.49 | | n.a. | B? | | 0.6 | 1974 | n.a. |
| Chapman 1975 | 14.6 | 11.7 | 11 | A | | 0.21 | 1973 | 55.32 |
| ERDA-76-1 1976 | | 20.8 ** | 11.5 | C ** | n.a. | | 1971 | |
| Mortimer 1977 | | 5.3-9.2 | 8.0-7.5 | C | 253-351 | | | |
| Lako 1995 | 25.5±9.5 | n.a. | n.a. | B | 516 | 2471 | 1993 | 10.32 |
| Orita 1995 | - * | - | | | | | | |
| Vattenfall 2000 | n.a. | n.a. | | | | | | |
| WNA 2001 | 24.7 *** | n.a. | n.a. | C *** | n.a. | | 1971 | |
| Uchiyama | | 5.5 | 9.88 | D | 1291 | | n.a. | |

## Methodology

The construction of a nuclear power plant is an extensive and very complex activity. During the 1970's and 1980's the methodology of energy analysis was developed, maturing to a useful tool to calculate the energy requirements of goods or economic activity with reasonable accuracy, see for example [Constanza & Herendeen 1984], [Bullard, Penner & Pilati 1978], [IFIAS 1974], [IFIAS 1975], [Reister 1977], [Roberts 1975], [Roberts PC 1982], [Chapman 1975].

The energy requirements for a process or economic activity can be determined by either of two general methods: process analysis or input/output (I/O) analysis (Approach 1, below). For reasons which will be explained below (Approach 2, below) we also use an approximation to I/O analysis. In addition a variant based on the weight of materials is applied (Approach 3, below). These three widely divergent approaches deliver quite similar values for the construction energy.

Process analysis measures the direct energy consumed in the process plus the energy embodied in the process chemicals and/or construction materials. This method is suited to specific, relative simple processes and products, for which physical flows are easy to trace. Process analysis leads to a large underestimation of the total construction energy requirements when labor and supporting activities of the construction are not included, see e.g. [Rombough & Koen 1978]. The results are therefore not valid for the calculation of the total energy required for a process, although surprisingly enough it has been used in a number of energy analyses of nuclear power.

Estimating the energy embodied in capital goods and services besides the direct energy requirements of the process itself requires the use of I/O analysis. This is well suited to large aggregated activities, such as the construction of a nuclear power plant. Chapman [Chapman 1975] made the following comment on the use of this approach:

> "In principle this is an unsatisfactory procedure since the inputs to nuclear systems are likely to be uncharacteristic products of the sectors documented in the input-output tables. However there are grounds for believing that provided a product has a large vector of inputs, i.e. requires inputs from many other sectors of the economy, then the average energy intensity derived from the input-output table is fairly reliable."

The I/O analysis can be simplified by using the ratio of the total energy used by a country to the gross national product in a particular year to calculate the net energy requirement of a (complex) activity, in this case the construction of a nuclear power plant, from the monetary cost in the same year. The energy/gnp ratio must be corrected for the deviation of the energy costs of the 'new construction' sector from the overall ratio. This simplification gives a fairly reliable value of the energy embodied in that activity, including energy costs of labor, services, subsidies, etc. [Tyner, Constanza & Fowler 1988]. This is affirmed by other studies, e.g. [Rombough & Koen 1978], [Roberts PC 1982], [Bullard, Penner & Pilati 1978], [Constanza & Herendeen 1984]. As Constanza & Herendeen who calculated the energy costs in this way, put it:

"Embodied energy (calculated the way we suggest) is a good, non-trivial static correlate of the economic value of the relatively large aggregates of goods and services that make up the entries in the I/O tables."

Certainly, the construction of a nuclear power plant is a large aggregate of goods and services. Nuclear technology is "high-tech", on top of an extensive industrial and economic infrastructure of other "high-tech" production processes.

The studies of [Rombough & Koen 1975] and [Bullard, Penner & Pilati 1978] showed that the energy costs calculated via a detailed I/O analysis of the sector "new construction of utilities" is approximately 1.16 times the value found via the simplified method: costs x total energy/gnp (Method A in Table 11). Both studies concluded that an accurate estimation of the construction energy of a power plant can be found by multiplying the construction costs of a plant in a given year with the energy/cost ratio (in MJ/$) of this sector.

Roberts [Roberts PC 1982] [Q103] found a strong, non-linear, correlation between costs of a product in dollars per mass unit and the energy embodied in that good, in energy units per mass unit. From his graphical presentation of this correlation, based on UK and US I/O tables of 1967, the energy requirements for construction of a nuclear power plant can also be deduced.

**The energy cost of constructing a nuclear power plant in the year 2000**

The overall energy/gnp ratio is given in primary energy units per dollar gross national product. In published energy statistics, e.g. [BP 2001], electrical energy is usually converted to primary energy by multiplying it by a factor $f$: $J_{\mathrm{prim}} = J_{th} + f \bullet J_e$ The factor $f$ is usually taken to be 3.

The construction energy requirements are here defined as the sum of electric and thermal energy: $J_{con} = J_{\mathrm{e}} + J_{\mathrm{th}}$, with given thermal/electric ratio $R$ ($R = J_{th}/J_e$ ).

Therefore: $J_{con} = (1 + R)/(f + R) \bullet J_{prim}$

Since no recent I/O tables are available, the energy requirements for construction in the year 2000 have to be approximated, using available data. The following three approaches, based on [Bullard, Penner & Pilati 1978] and [Roberts PC 1982], appear to be the most reliable.

**Approach 1**

The energy cost of a nuclear power plant is calculated by multiplying the monetary cost by the energy/$ ratio of the sector 'new construction'. The latter was found by input/output analysis to be 83.8 MJ/$ in 1967 [Bullard, Penner & Pilati 1978]. The energy cost in 1982 is then obtained by deflating the (monetary) construction costs in 1982 dollars to 1967 dollars by multiplying by the Consumers Price Index ratio between these years (0.346).

The advantage of this method is the availability of the correct energy/cost ratio for construction. However, it assumes that the construction energy requirements remained unchanged during the period 1967 to 2000. This is probably not the case, as the overall energy efficiency of economic activity improves with time. Moreover, the average thermal/electric energy ratio R in 2000 is lower than in 1967. On the other hand, construction of nuclear power plants historically has shown a strong trend to become more complex, at least partly due to greatly increased concern for safety, demanding more materials, energy and manpower, all manifested in sharply rising costs. This trend may offset an improved energy efficiency in the construction sector.

Considering these arguments, this method should result in a fairly reliable value of the energy requirements for construction. We take, as discussed above, the base cost of 3.7 G $(1982), for a 1 GWe nuclear power station in 1982. This comes to 1.28 G$ in 1967 dollars using the Consumers Price Index ratio mentioned above to deflate the costs. Using the value of 83.8 MJ/$(1967), the construction energy requirements then are $J_{con} = J_{th} + J_e = 1.28$ G$ • 83.8 MJ/$ = 107 PJ, with $R = 4.8$.

The full uncertainty range is 40 – 174 PJ, as is shown in Table 13.

**Approach 2**

Here, instead of using the input/output value of 1967, we extrapolate from 1982 to the year 2000. There have been no I/O analyses published for the construction sector for this year, however. We therefore use the overall energy/gnp value but correct it with the factor 1.16 to get a good approximation to the construction sector [Bullard, Penner & Pilati 1978]. Since no new nuclear power plants have been ordered we use the values for the 1980s by inflating the costs in $(1982) to $(2000) and use the energy/gnp ratio of 2000.

In this way the improved energy efficiency of the economy in 2000 is accounted for. A trouble, however, is whether the multiplier in the year 2000 and the ratio R are the same in 2000 as in 1967. This problem was discussed under approach 1.

From the statistics in [Europe Energy Scenario’s 1996], [Europe Energy Outlook 1999], [Europe Energy 1999] [Q9], [BP 2001] [Q91] and [WNA-ueg 2001] [Q93], the value of the general energy/gnp ratio in the year 2000 can be deduced: energy/gnp = 10.64 MJ/$(2000), valid for the whole OECD: EU, USA and Japan. Applying the multiplier 1.16 to account for the new utilities construction sector, the energy/$ ratio in 2000 for the sector new utilities construction we have:

12.34 MJ/\$(2000). After correcting this figure through application of the Consumers Price Index factor of 1.78 mentioned above to the 1982 cost of 3.7 G\$ for a 1 GWe power station as we find the construction energy as 3.7 G\$ • 1.78 • 12.34 MJ/\$ = 81 PJ.

The construction energy requirements then are: $J_{con} = J_{th} + J_e = 81$ PJ, with $R = 4.8$.

The full uncertainty range is 31 – 132 PJ.

Any real escalations in costs (excluding inflation) and requirements of energy, materials and manpower to construct a PWR power plant of the 2000 vintage (not yet existent), compared to 1978 vintage (in 1978 the last new US nuclear power plant was ordered), are neglected in approach 2 as in approach 1.

**Approach 3**

In this approach the energy costs are approximated on the basis of the total weight of the construction [Roberts PC 1982]. Unfortunately, all energy values in his paper are given in primary energy units and no distinction is made between electric and thermal energy. Extrapolation of Roberts' method to the year 2000 is not possible, so the specific costs have to be deflated to the 1967 level.

From his graphical presentation we derived the following correlation for the year 1967 by curve fitting:

$\log E = -0.315 + 0.79 \log(\boldsymbol{C})$

With: $E$ = energy per unit mass (in MBtu/short ton)
$C$ = cost per unit mass (in \$(1967) per short ton)

Using the conversion factors 1 MBtu = 1.054 GJ and 1 short ton = 0.9072 Mg , we convert $\boldsymbol{E}$ (the symbol, not the number) to GJ/Mg by dividing by 1.054 and multiplying by 0.9072. The left-hand side of the formula becomes then:

$\log E + \log(0.9072/1.054) = \log E + \log 0.861 = \log E - 0.0651$.

Converting the symbol $C$ to \$(1967)/Mg by multiplying by 0.9072, the right-hand side becomes:

$-0.315 + 0.79 \bullet (\log C + \log 0.9072) = -0.315 + 0.79 \log C + 0.79 \bullet (-0.0423)$

$= -0.348 + 0.79 \log C$.

Equating the two sides we find:

$\log E = -0.283 + 0.79 \log C$, which expresses the same relationship as above but with:

$E$ = energy per unit mass (in GJ / Mg) and
$C$ = cost per unit mass (in \$(1967)/Mg)

Solving for the primary energy, $Jcon$ , needed for the construction of a 1 GWe nuclear power plant, we have:

$$J_{con} = \frac{1+R}{f+R} \bullet J_{prim} = \frac{1+R}{f+R} \bullet M \bullet E = \frac{1+R}{f+R} \bullet M \bullet 10^{[-0.283 + 0.79 \bullet \log C]}$$

A recent figure, M = 516 Gg (1 Gg = $10^3$ metric tonnes), is used for the construction mass of a 1GWe nuclear power plant. This (rounded) value is found from a graphical presentation given by [Lako 1995], see Table 12. [Uchiyama 2002] reports a much higher mass: 1291 Gg.

Using the mass of 516 Gg and assuming a cost of the power plant of 3.7 G\$(1982) = 1.28 G\$(1967), the specific cost C = 2480 \$/Mg. Entering these values into the formula with f = 3 and R = 5 we find:

$J_{th} + J_e = 97$ PJ

For the bottom of the range we substitute a cost of 1.4 G$(1982) = 0.484 G$(!967), and find***:***

$J_{th} + J_e =$ 45 PJ.

For the top of the range we substitute a cost of 6 G$(1982) = 2.08 G$(1967), and find:

$J_{th} + J_e =$ 142 PJ

These figures are in reasonable agreement with those found in approach 1 and 2. The fact that three quite different methods of calculating the energy cost of the construction of a nuclear power plant lead to quite comparable results, indicates, in our view, that the values, while estimates, are reliable.

Table 12 Construction materials of a 1 GWe nuclear power plant by mass
Data of Leibstadt PWR and Japanese PWR power plants
Source: [Lako 1995] and Y. Uchiyama, quoted by Lako.

| Construction materials | Reinforced steel | Stainless steel and other steels | concrete and cement | copper &copper alloys | aluminum | approximate total |
|---|---|---|---|---|---|---|
| mass (Mg) | 40,000 | 25,000 | 450,000 | 1,200 | 200 | 516,400 |

Table 13 Construction energy requirements of a 1GWe nuclear power station (in petajoules, PJ)

| Cost in G$(1982) | Energy cost in PJ according to: | | |
|---|---|---|---|
| | Approach 1 | Approach 2 | Approach 3 |
| 1.4 | 40 | 31 | 45 |
| 3.7 | 107 | 81 | 97 |
| 6 | 174 | 132 | 142 |

Given the large scatter in construction costs of a LWR power plant (1.4-6.0) G$(1982)/GWe), a detailed I/O analysis would not be meaningful. In our view the estimates above are as reliable as can be expected. It is highly unlikely that construction costs should have declined in recent years.

In this study we choose the lowest value, $J_{con}$ = 81 PJ, not because this is the most plausible value, but because we want to be sure that we do not exaggerate the energy requirements. In Chapter 4 we will need the cost per unit of weight. This is found by dividing 81 PJ by the weight given in Table 12, i.e. 516,00 Mg, or 157 PJ/Mg, with R = 4.8.

## Part 2: Performance

As mentioned earlier the facts do not substantiate the nuclear industry's claim concerning the performance of nuclear-power plants. A recent performance compilation shows that, on the average, the maximum full-power lifetime of reactors just barely reaches 22 years. This is shown in Figure 14. The source of the data shown in these figures is a recent compilation of the industry (Knox, 2001), listed in the Chapter *References*. Of the 399 slow-neutron reactors listed only four have ever reached a full-load lifetime of 24 years. The averages that we take are very flattering, since none of the "failed" reactors are listed in the compilation of Knox.

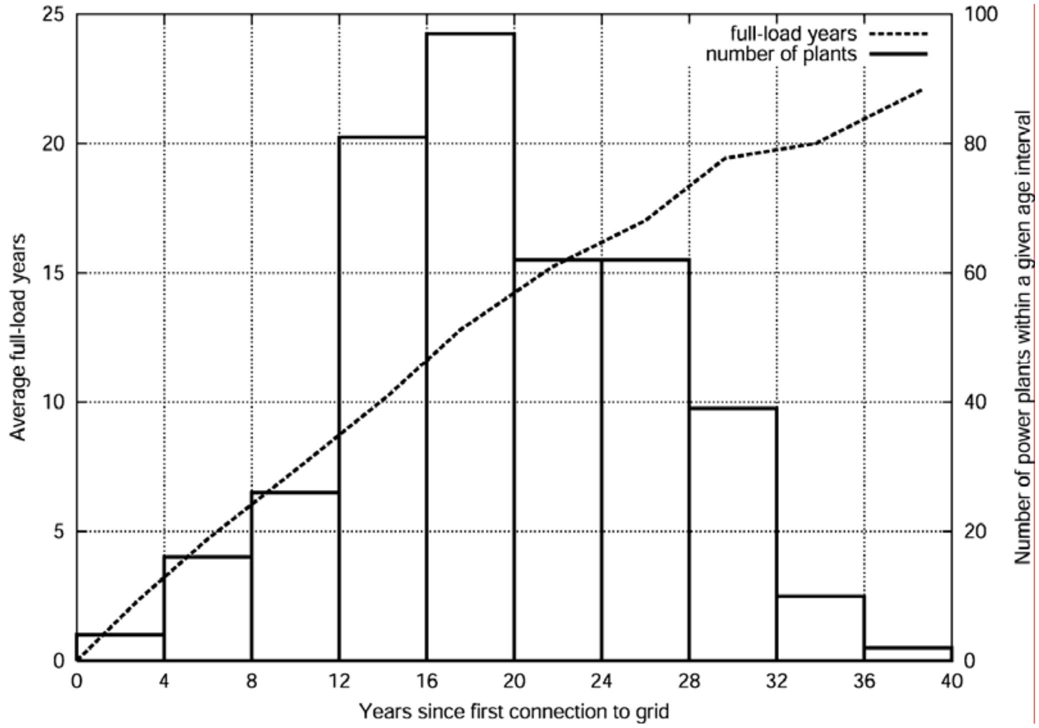
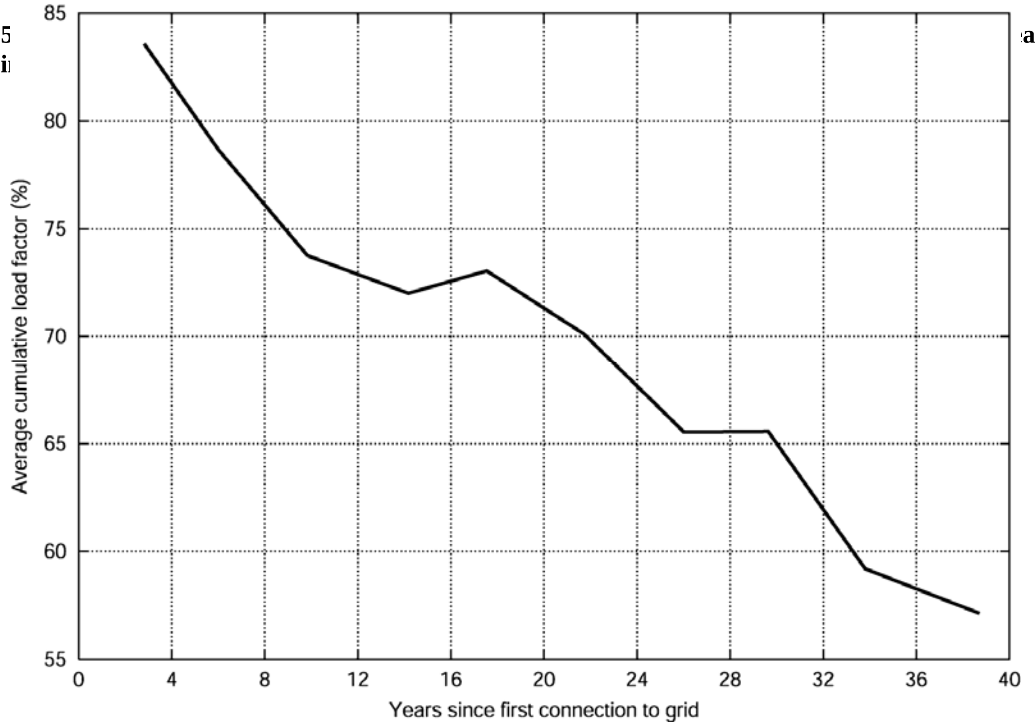


**Figure 14. The average full-load years of 399 nuclear-power plants, grouped into ten four-year intervals. The left-hand ordinate scale and the dashed curve refer to full-load years. The right-hand ordinate scale and the blocks give the number of power plants found in each of the ten age intervals.**

In Figure 15 the average (cumulative) load factor is shown as function of the actual age of the power plant. It shows a remarkably consistent picture of steadily decreasing reliability with increasing age.

**Figure 15** **ars of**
**service si**



## Part 3: Operation, maintenance and refurbishing (omr)

Operation and maintenance during the active lifetime of PWR power plant cost about 100 M$ a year [Blok & Hendriks 1989], or about 138 M$ in 2000. This is about 2.1% of the average construction costs (6.57 G$(2000)/GWe) a year, or about 2.8% per full-power year. [Rotty, Perry & Reister 1975] used the value of 3.1% per year.

In addition, most plants need one or more large refurbishments during their active lifetime, such as replacing steam generators, implementation of new, updated control systems and updated safety measures. These replacements and updates cost about 20-80% of the original construction costs. Assumed that the refurbishment costs are 50% of the average construction costs and are to be spent over an operating period of 24 full-power years, the average annual costs are about 2% of the construction costs per full-power year.

If operation, maintenance and refurbishments together are taken as an average economic activity in the sector new construction, the total energy expenditure for this part of the nuclear fuel chain can be estimated at 4.8% of the construction energy expenditure per full-power year (FPY):

$J_{\mathbf{omr}}$ = 0.048 • 81 = 3.9 PJ/FPY, with R = 11. For the period of 300 days this becomes 3.2 PJ/(300 full-load days) with R= 11. This is a time-dependent (better: energy- production- dependent) cost and will therefore be subtracted during the reactor's useful life from the energy production (i.e. this is not a "debt", but an operating cost).

### Transportation costs

The energy costs of the necessary transportation are included in the costs of other activities.

## Part 4: Decommissioning and dismantling

### Operation & maintenance after final shutdown

After final shutdown, the reactor must be maintained during an extensive period, ranging from about a decade to perhaps a century, before the actual dismantling of the nuclear part of the plant can be started. This is a question of standard maintenance, not closely connected to radioactivity. In this study an annual energy expenditure of 0.5% of the construction energy expenditure is assumed. So during 10 years about 5% and during 100 years about 50% of the construction energy is needed for this phase.

### Clean-up

After final shutdown, the fuel elements are removed from the reactor and stored in a cooling basin or dry storage building. The nuclear part of the reactor cooling system then is to be cleansed, to remove as much radioactive contamination CRUD (Corrosion Residuals & Unidentified Deposits) as possible. This CRUD material contains activated corrosion products from the reactor and cooling system, fission products and actinides from leaking fuel elements. This procedure produces about 1000 $m^3$ of high-level waste (HLW) and takes several years to complete and may cost as much as 50% of the construction costs.

### Cooling water: the tritium and $^{14}$C problems

The cooling water from the reactor becomes highly tritium-radioactive ($H_3$) and, to a less extent by $^{14}$C and should be stored as well. In present practice the cooling water is discharged into rivers and sea. So large amounts of tritium are being discharged into the environment. Theoretically, tritiated water can be immobilized (e.g. in drying agents or cement) and packed in appropriate containers. If this were done, all the cooling water would be immobilized every time the reactor is refuelled. This procedure would produce very large numbers of containers with tritiated waste, demanding a concomitant immense energy expenditure.

A PWR generates about 743 TBq/GWe.a tritium [IAEA-203, 1981], [NEA, 1980], [Dworschak 1993], of which about 740 TBq/GWe.a remains contained in the spent fuel elements and about 3.3

TBq/GWe.a is discharged during operation of the reactor. If reprocessing is done, the tritium from the spent fuel elements is discharged into the sea at the reprocessing plant. If the spent fuel is not reprocessed, this tritium remains in the elements. However, during the long interim storage period (tens of years) of the spent fuel, before being conditioned for final disposal, part of the remaining tritium will have decayed (eg. after fifty years the radioactivity will have declined by a factor of 16). The rest will diffuse through the Zircalloy cladding into the biosphere. The artificial production of tritium by nuclear power plants surpasses the natural generation by cosmic radiation [Dworschak, 1993].

Besides tritium, large amounts of $^{14}$C are generated in de cooling water of LWR's: about 0.26 TBq/GWe.a [Dodd and Van Hienen, 1996].

The long-term effects of significantly higher tritium and carbon-14 concentrations in the environment are not clearly understood. On global scale, the rise of the concentrations may seem harmless, but on a regional scale, high concentrations in surface waters may occur. In Western Europe, for example, with numerous nuclear power plants, rivers are used as resources for cooling water for nuclear power plants, as well as for resources of drinking water. Probably not all conceivable biochemical reactions of tritium and carbon-14 in living organisms have been investigated thoroughly.

It is not clear how to deal with this problem. The basic principle of this study: that a sustainable energy system should not generate irreversible effects in the environment, would require that all tritium from nuclear reactors be kept out of the biosphere. We have deviated from this principal because of the immense energy costs of sequestering the tritium formed in the cooling water and have therefore not included the energy costs in our accounting. The fact is that we really have no knowledge of the seriousness of the biological dangers involved. This assumption means that all of the tritium generated in the reactor (not in the fuel elements - see above) during its operational lifetime, will be discharged into the environment, as is the present practice. This is a non-sustainable situation in the sense mentioned above, so that the costs of nuclear power given in this study are lower limits. A truly sustainable solution would cost much more.

### Dismantling

After a cooling period of 10-100 years in which the the activation products such as $^{60}$Co and $^{55}$Fe will have decayed considerably, the reactor is then dismantled and cut into small pieces, which can be packed in containers for final disposal. The radioactive inventory of the reactor and connected systems increases with the reactor operation time, by activation and contamination of the construction materials. For most nuclides, but not for long-lived nuclides, equilibrium between activation and decay will be reached after 10-20 full power years.

Dismantling will be increasingly difficult and energy intensive as the radioactive inventory rises. This results from three factors:

1. the inventory of long-lived activation products - $^{63}$Ni and $^{94}$Nb in steels and $^{3}$H, $^{14}$C, $^{41}$Ca, $^{152}$Eu and $^{154}$Eu in concrete - increases with the neutron flux [IAEA-389, 1998];
2. the (cumulative) radiation doses will be higher, so more material has to be removed by remote operations (robots);
3. more auxiliary equipment and materials will be needed. Although tritium ($^{3}$H) has a relatively short half-life of 12.3 years, the inventory can be very large, even several tens of years after shut down.

Based on the meagre data available on actual dismantling of nuclear installations, only a crude estimate of the dismantling energy expenditure is possible.

Even after a few full-power days a reactor becomes so radioactive that dismantling costs rise to as much as about 60% of the construction costs, e.g. the reactor at Niederaichbach [Schwald et al. 1995], [Liebholz 1995], [Komorowski and Meuresch 1995], [NEA 1996].

The very limited experience with dismantling projects completed up to now indicates that the decommissioning and dismantling costs can reach 100 - 220% of the construction costs, depending of the full power operating lifetime [Junker, 1995], [Thierfeldt, 1995], [Dilemma, 1999], [IAEA-293, 1988], [Lako, 1995].

The reader will remember that we have chosen to explore two options for the dismantling phase. In what we would call the environmentally responsible option, we have taken the total of the decommissioning and dismantling costs discussed in this chapter to be 200% of the construction energy costs after about two full-power years. One full-power year corresponds to full-power operation with 1 GW(e) output during one year. The radioactive inventory caused by corrosion products CRUD (Corrosion Residuals & Unidentified Deposits) will, of course, be a function of the full-power operating time, but because of the large uncertainties in the estimation of all of the energy expenditures, this dependency is not considered.

Included in the decommissioning and dismantling energy expenditure are:

- operation and maintenance during safeguarded period after final shutdown;
- clean-up of the nuclear components before dismantling;
- actual demolition of the radioactive components;
- dismantling;
- packaging and permanent disposal of the dismantling wastes (see also Chapter 4)..

We believe that the estimates we have made of the energy "debts" incurred by these operations plus the construction costs (see Part 1, above) are not excessive. This debt is "capitalized" at time zero, i.e. when the reactor starts operating, to a total of 240 PJ. In the *après nous le déluge* option the dismantling as described above does not take place. The reactor is completely isolated from the outside world and left for future generations to be disposed of. The debt, "capitalized", in the same way as just mentioned is taken to be 80PJ, in fact just the construction costs.