Construction and OMR of nuclear power plants

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Note
In this document the references are coded by Q-numbers (e.g. Q6). Each reference has a unique number in this coding system, which is consistently used throughout all publications by the author. In the list at the back of the document the references are sorted by Q-number. The resulting sequence is not necessarily the same order in which the references appear in the text.

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1 Construction cost

Nuclear database of the United States

The construction energy of a nuclear power plant is calculated in this study on the basis of published data of the US nuclear power plants, for several reasons:

- The USA has the largest set (more than 100, see Figures 1 and 2) of nuclear power plants, which have been built under similar economic conditions.
- The situation in the USA came closest to a free market with several independent vendors and a large number of customers.
- The USA was the country with the least government interference, so the published cost figures probably came closest to the real costs for the economy as a whole: the costs paid by the consumer and taxpayer, directly and indirectly.
- The USA has the most extensive published database on cost figures and technical details of nuclear power plants built up to now. Data relevant for energy analysis are extremely scarce, even in the relatively open situation of the USA.
- By far the most studies on nuclear construction are based on the American situation.

Even in the USA there was some talk of hidden subsidies. [Proops 2001] Q125 mentioned three 'hidden subsidies' to the nuclear industry in the USA:

– subsidies from the military nuclear industry,
– subsidies from the government,
– absence of adequate insurance against third-party damage (Price-Anderson law).

In other countries (e.g. Canada, France, Germany, UK, Japan, former USSR) the government interference was (and still is) very strong. Often both the supplier of nuclear power stations and the customer were (are) state enterprises.

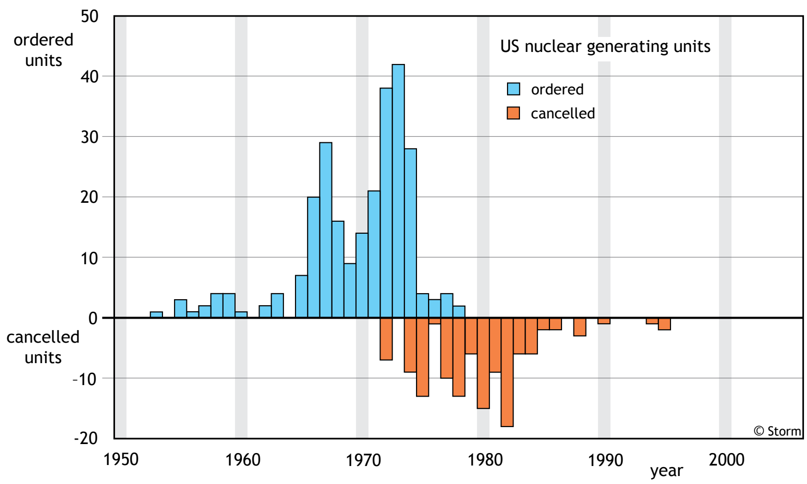

Figure 1

Historical numbers of construction orders and cancellations of commercial nuclear power plants in the United States. The total number of ordered units is 259, and of cancelled units 124. The construction of three units have been stopped indefinitely. Source: [EIA-DOE9.1 2003] Q52.

All LWR power plants connected to the grid in the USA have been ordered before 1974 [Wald 2003] Q220. The last two orders were in 1978, but these units have not been finished. The last cancellations were in 1995, and in 1996 came the last unit on line.

The history of the nuclear generating capacity in the United States is illustrated by Figures 1 and 2.

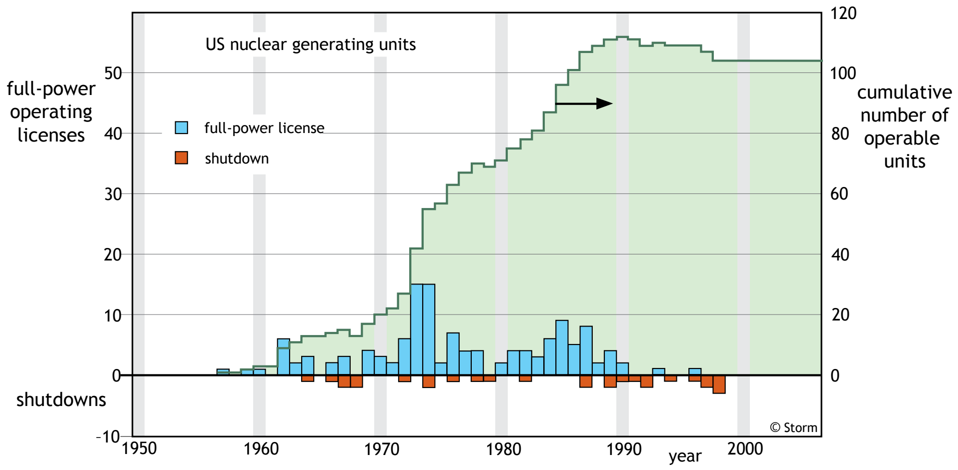

Figure 2
History of the nuclear generating capacity in the United States. The numbers of full-power operating licenses, of closed down units and the cumulative number of operable units. Note that the left and right scales are different. The total number of full-power licenses is 132, and of closed down units 28. From 1999 on 104 units were operable. Source: [EIA-DOE9.1 2003] Q52.

Historical construction costs

The historical costs of nuclear power plants in the USA are represented in Figure 3, with data from [McLain 1964] Q203, [Roddis & Ward 1971] Q60, [Mooz 1981] Q129, [Diaz 2001] Q56 and numerous reports in *Nuclear News*, *Nucleonics Week* and *Nuclear Engineering International*. Probably not all finished nuclear power plants of the USA are represented in the diagram. Some plants may be represented more than once, due to cost overruns and delays before start of construction or during the construction.

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 in the USA, the unit costs fell to a low in 1970. This may be (partly) due to economy of scale. During the first decadeof the nuclear era, the mean power rating increased with a factor of more than 20: from about 50 to about 1200 megawatts electric power. The scaling-up may have contributed to the rapid cost escalations, although a lowering of cost by economy of scale might be expected.
After 1970 the reported costs ($(2000)/W) rised at an increasing rate. The spread of the published unit costs increased as well. For example, in 1983 the highest reported unit cost was nearly 6.0 G$(1982)/GW and the lowest about 1.3 G$(1982)/GWe, a factor of 4.6.
A striking contrast shows up between the forecasts of the Atomic Energy Commission (AEC, the predecessor of the Nuclear Regulatory Commission NRC) in 1964 and the real costs.

During the 1980's, a number of 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 the costs of plants under construction. The decrease in the high end of the cost range in the 1980's is not caused by cheaper construction, but by cancelling plants with the highest costs. During the 1970's and 1980's 124 plants has been cancelled.
Significant is the steep rising trend in the lower limit of the cost range.

Usually, after the introduction of a new technology the unit cost decrease over 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 power plant industry. See also references quoted in [Tyner, Constanza &

Fowler 1988] Q124. Apparently, no real costs became visible during the first decade after introduction of the program "Atoms for Peace" in 1956.

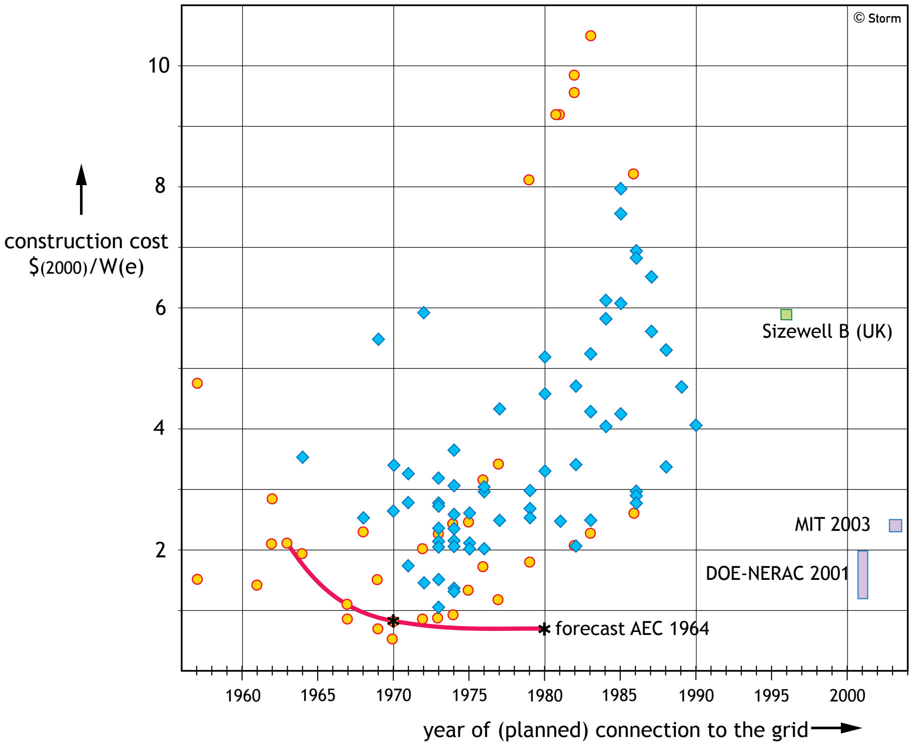

Figure 3

Historical construction costs of LWR power plants in the USA. The circles represent costs in a given year from various sources: [McLain 1964] Q203, [Roddis & Ward 1971] Q60, [Mooz 1981] Q129, [Diaz 2001] Q56 and numerous reports in *Nuclear News*, *Nucleonics Week* and *Nuclear Engineering International*. The diamonds are data from [Diaz 2001] Q56. The value of the Sizewell B cost in the UK comes from [Thomas 2005] Q328.

AEC (Atomic Energy Commission) is the predecessor to the NRC (Nuclear Regulatory Commission). The values indicated by [DOE-NERAC 2001] Q283 and [MIT 2003] Q280 are estimates for future nuclear power plants.

Cost overruns

The escalation in the construction costs have been examined by various authors. [Mooz & Siegel 1979] Q228 found a trend in the cost increase of 141 $(1976)/kWe per year. They concluded:

> " The data available give no clue as to how or when these cost increase might cease, and without such information, projections of LWR capital costs must rely on assumptions about future conditions that affect these costs."
>
> and: " Increased scope is often cited as the prime cause of cost increases experienced by LWR."

[Mooz 1981] Q129 found:

- no economies of scale,
- no cost economies with duplicate units,
- no change of trend in increasing construction times and costs,
- no clear connection between delays and increased costs; lengthened construction time was not related to higher costs,
- construction costs and times increase linearly with time, with 140 $/kWe per year and 4 months per year respectively,
- learning curve in cost and construction time fairly flat, its effects are dwarfed by opposing temporal aspects.

Mooz cited the construction costs of an average plant coming on line in 1978-1979 at more than 1200 $(1978)/kWe. If these costs are converted to dollars of 2000 and a linear cost escalation of 140 $/kWe is applied, the construction costs in 2000 would be of the order of 6300 $(2000)/kWe. This agrees fairly well with the average value derived from the diagram in Figure 3: 6500 $(2000)/kWe.

[Komanoff & Van Loon 1982] Q231 found a clear relationship between rising construction costs (after elimination of inflation) and labour, materials and standard equipment costs. The costs of nuclear power plants completed in the period 1971-1978 experienced an increase of 142%, and coal-fired plants with scrubbers an increase of 68% in the same period.

The bulk of the cost increase resulted from increases in materials and equipment to meet safety requirements. During the 1970's the amounts doubled per unit nuclear capacity and accounted for about two thirds of the real (inflation adjusted) cost increase. Highly trained labour and engineering costs also ballooned, constituting most of the remaining cost increase.

Komanoff & Van Loon disprove, among others, positions often taken in discussions on economics of nuclear energy, namely that nuclear costs increased because of pressure of environmental groups and because of construction time lost due to unpredictable regulations and general licensing instability.
Operating experience brought forth an unexpected high rate of problems. Utilities began starting construction well before plant design was complete. The typical archtectural-engineering firm completed only about 15% of the reactor design before starting construction.

[Shaw 1979] Q230 observed a cost escalation (adjusted to inflation) of about 16%/yr in the USA, a similar cost growth in Germany and 8%/yr internationally. About 3% of the average cost growth of US LWR's of about 16%/yr was due to 'construction inflation exceeding GNP average', the remainder was due to quality and quantity increases for unit components.
This may correspond with the findings of [Komanoff & Van Loon 1982] Q231 above.
See also next section 'Materials'.

A common phenomenon

Large cost escalations are intrinsic to new energy technology projects, as [RAND 1981] Q126 reports:

- Severe underestimation of capital costs is the norm for all (italics by RAND) 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.
- 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 development.

According to [RAND 1979] Q127, escalations in cost estimates of energy process plants by factors of 2-5 are not uncommon. The nuclear industry itself provides many examples of these observations and those of [RAND 1981] Q126.
The history of the US nuclear power plants shows the great risks of starting large-scale construction programmes with an immature technology. Once again, upscaling of complex technical systems proved to be not so simple as it might look at the start. Starting a billion-plus construction project with only 15% of the engineering finished, is tantamount to asking for cost escalations. The above mentioned RAND reports blame cost escalations mainly to this effect, which is not unique for the nuclear industry anyway.

Another viewpoint on the economics of nuclear power is taken by Proops 2001 [Q125]. 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 third-party damage.

The Near Term Deployment Roadmap [DOE-NERAC 2001] Q283 states:

> " The extended hiatus in new plant construction is due primarely to economic factors. Nuclear plants are capital intensive, and many of the US nuclear construction projects in the late 1970s and 80s were hampered by expensive delays, caused by engineering and management problems, a cumbersome regulatory process and in some cases by public opposition.
> . . . Deregulation of electricity supply in the US has added a level of economic uncertainty that temporarily discourages the major capital investment and long-term commitment required for new nuclear plant construction."

In our view the nuclear industry demonstrates a unscientific and even misleading attitude by stating new nuclear build will be signifantly cheaper than the historical construction cost and will show the learning curve effect, as long as the causes of the cost escalations and the absence of the learning curve are not publicly known. There are no empirical facts underpinning the assertions of the nuclear industry in this respect.

The wide range in the reported construction costs, in 1983 by a factor of more than four, may be due to:

- variations in material and craft labour requirements, roughly by a factor of two, as discussed below,
- different ways of calculating the pubished cost figures and/or different bookkeeping practices. The published cost fgures may or may not include, for example:
  - Sum of all costs paid for.
  - Costs excluding IDC (interest during construction).
  - Overnight costs, without escalation and IDC.
  - Construction costs without start-up costs.
  - Construction costs without first core.
  - The contract sum at the moment of the CP (construction permit).
  - Sum with or without inflation correction.
  - Use of different definitions.

Prospects

Forecasts of nuclear costs and performance are made generally by those with a vested interest in nuclear power, such as plant vendors, promotional bodies and utilities committed to nuclear power, have invariably been overoptimistic and must be viewed with skepticism. Prices quoted by international agencies, such as the Nuclear Energy Agency NEA, also must be treated with care. Often their figures are based on indicative rather than empiric costs. Generally, these costs are provided by national governments, who may have their own reasons to show nuclear power in a good light, and who generally do not base their figures on actual experience [Thomas 2005] Q328.
Most utilities are not required to publish properly audited construction costs and have little incentive to present their performance in anything other than a good light.

There are no indications that the mechanisms described in the RAND studies would not apply to new new nuclear build in 2006. New nuclear build will be of the Generation III or III+ designs, all of which are unproven.

Very litte real data on construction and operating costs has been published so far.
The construction costs of nuclear power plants are underestimated systematically. During the 1980s and 1990s the reported construction costs of nuclear power plants in the USA escalated into the range of 4000-10000 \$(2000)/kW(e), see Figure 3. The final construction cost of Sizewell B, about 5400 \$/kW(e) or about

5900 $(2000)/kW(e), fits within the range of the US NPPs.
US utilities were required to publish reliable accounts of the construction costs of their nuclear power plants for the economic regulator, who only allowed cost recovery from customers for properly audited costs. The cost of Sizewell B is also reasonably well documented because the company building it had few other activities in which the construction cost could be 'disguised' (Thomas 2005 [Q328]).

The nuclear power plant being built at Olkiluoto in Finland, the first unit of the EPR design to be built, is often heralded as an example of the new, cheap and safe generation of nuclear power plants. The cost of Olkiluoto-3 was reported to be 3 G€, or 2000 €/kW(e). [NEA 2000] Q329 cites an EPR cost figure of 4.56 G€, 3000 €/kW(e). One year after the start of the construction, the project was already one year behind schedule and the delay is increasing. The final construction cost of Olkiluoto-3 likely will be much higher than the reported figure. Areva, the vendor of the Olkiluoto power plant, has an off-balance-sheet commitment on the Olkiluoto-3 contract in the range of 1.5-2 G€ [Thomas 2005] Q328.

Absence of a learning effect

The expectations with most technologies is that successive generations of design will be cheaper and better than their predecessors because of factors such as learning, economies of scale, and technological change. The historical costs of nuclear power plants in the USA (see Figure 4) clearly do not show falling costs and a learning effect. As pointed out above, the costs of the USA plants and Sizewell B are the most reliable and best-documented.

The paucity of orders for current generations of nuclear reactors, especially with properly documented costs, makes it difficult to known wether costs have stabilised yet, let alone begun to fall.
No reports have been published making plausible that much lower construction costs of new nuclear build could be expected, especially not after 9/11. It seems extremely unlikely that large batches (say, tens to hundreds) of identical, completely factory-built nuclear power plants would be ordered in the future. Such mass production conditions might be prerequisite to achieve the cost reductions envisioned by [MIT 2003] Q280 and [DOE-NERAC 2001] Q283.
A Nuclear Energy Agency report [NEA) 2000] Q329 states:

> 'The standardisation effect for more than two units of identical design is expected to be negligibly low.'

In Figure 3 two values of construction costs from recent studies are indicated:
1200-2000 G$/GWe, from [DOE-NERAC 2001] Q28] and
2557 G$(2002)/GWe, or about 2420 G$(2000)/GWe, from [MIT 2003] Q280.
Both studies failed to explain on which grounds the US nuclear industry is confident of building new nuclear power plants at costs that are a factor 4 lower than the actual construction costs in the 1980s, when the last NPP's came on line.

The estimates by MIT and DOE-NERAC are beset by ambiguities and uncertainties, to name a few:

- It is not clear which costs are and which are not included in the cited construction costs. As discussed above costs can be booked and presented in many ways.
- The estimated costs concern new reactor concepts, yet unproven, so it is not sure the specifications as advertised will be met in practice. History shows this is far from self-evident, especially in cases of applications of immature technology.
- Corporate policies directed at short-term profit may conflict with programs with very long-term investments, with the first (and unsure) revenues to be expected after about 10 or more years.
- Would the technical and intellectual infrastructure in the near future be of sufficient quality to warrant a production, construction and operating structure, needed to meet the technical and financial promises of the ambitious programs proposed in the above mentioned studies?

Apparently MIT and DOE-NERAC assume construction of standardized power plants, ordered in large batches, to keep costs low.
In our view such an approach may narrow the spread in the construction costs. Reductions by standardization of the average construction costs may be expected if a large batch of new power plants of a proven design will be built and such a design would be a 1980s vintage system.
Such cost reductions may easily and amply be offset by escalations during the constructing of power plants of an unproven design (inherently safe, very high burnup, very long operational lifetime), as MIT proposes.

It may be prudent to build in some margins when new concepts of nuclear power plants are advertised as an option for the future electricity supply. Firstly, performance shortfalls have to be anticipated. Secondly, the final costs may be much higher than agreed on at the moment of the construction contract.
It would be wise to avoid the mistakes and pitfalls of the 1970s and 1980s and to take to heart the results of above mentioned RAND studies.

Construction cost range used in this study

A range of 3.5 - 9.5 $(2000)/We, with an average value of 6.5 $(2000)/We, is taken as starting point of the calculations in this study. For purposes of energy analysis, the full cost range is significant. Cancelling the construction of power plants before completion, when the costs rise into the high end of the range, does not change the real average construction costs or real material and energy requirements.
The lower value of 3.5 $(2000)/We seems not very likely for future power plants, in view of the rising trend of the lower limit, the absence of a learning effect (see diagram of Figure 3), and the inconsistence of the reported cost figures (see remarks above). If the rising trend were to continue through 2000, the lower value of the cost range to be expected in 2000 would come out at about 5 $(2000)/We and the higher value at some 13 $(2000)/We. No further cost escalations are assumed in this study, notwithstanding the expectation that the construction regulations after 9/11 might be more stringent than in the 1980's and 1990's.

The average value of 6.5 $(2000)/We seems a plausible starting point for the calculation of the energy requirements and for forecasts for the next decades. The cost figure from MIT of 2.4 $(2000)/We may be been taken as the lower limit of the cost range to be expected in a new construction program. The empirical facts point to significantly higher actual construction costs.

2 Construction material requirements

Historical data

Reliable data on the amounts of construction materials in the open literature are notably scarce. In Table 1 four of the very few available are compiled. [IAEA 1988] Q36 and [ORNL-TM-4515 1974] Q345 seem to refer to the same reference reactor. Only one of the reported specifications [Lako 1995] refers to actual nuclear power plants.
The values given by [Lako 1995] Q23-7 are related to a Swiss nuclear power plant (Leibstadt, a PWR completed in 1984) and undisclosed Japanese PWR power plants. The data of reference [IAEA-293 1988] Q36 are taken from NUREG reports from 1978 and refer to 1971 vintage USA nuclear power plants.
The energy analysis from [White & Kulcinski 1999] Q299 has been based on the data from [ORNL-TM-4515 1974] Q345 and refers to a virtual 1 GW reference reactor of 1971 design.
The data from [Rombough & Koen 1974] Q96 refer to the (then) proposed US Braidwood station in 1974 (figures corrected for 1 GWe) and therefore are not based on actual experience either. Besides data on the concrete construction are missing.

Table 1

Some data on material requirements for construction of an 1 GW(e) LWR, in Mg.

Sources: [Lako 1995] Q23-7 , [IAEA-293 1988] Q36, [Rombough & Koen 1974] Q96 and [ORNL-TM-4515 1974] Q345.

	Lako 1995 Q23-7 (9)	IAEA 1988 Q36	R&K 1974 Q96	ORNL 1974 Q345 composite	constituent
reference year	1984	1971	1974	1971	
reinforcement steel	40 000	33000	–		
other steel	25 000	(3)	10000		
carbon steel	–	–	–	32731	
iron	–	–	–		34662
stainless steel	(1)	2100	(2)	2080	
galvanized iron	–	1300	–	1257	
copper/copper alloy	1200	740	2000	694	726
brass + bronze	–	–	–	35	
aluminium	200	20	45	18	18
chromium	–	–	150		415
inconel	–	100	–	124	
lead	–	50	8	46	47
nickel	–	1	100	1	484
manganese	–	–	400		467
molybdenum	–	–	–		164
tin	–	–	–		2
zinc	–	–	100		2
other metals	–	–	6		
sum metals	66400	37311	12809	36986	36987
insolation	–	–	–	922	
asbestos	–	–	45		138
magnesia	–	–	–		783
paint	–	–	–	730 (4)	
wood	–	–	–	5600 (5)	
concrete	450 000	180000	–	180000 (6)	
cement					30133
aggegate (coarse)					90361
aggegate (fine)					45855
total mass	516 400	217311	–	217908 (7) 224238 (8)	204257

(1) may be included in 'other steel'

(2) probably constuents separately listed

(3) no distinction made between rebar and other construction steel

(4) reported: 17500 gal => 662.4 m^3 => ~730 Mg (assumed density 1.1 Mg/m^3)

(5) reported: $4.8 \bullet 10^6$ bd ft => 11330 m^3 => ~ 5600 Mg (assumed density 0.5 Mg/m^3)

(6) reported: 98130 yd^3 => 75025 m^3 => 180000 Mg (assumed density 2.4 Mg/m^3)

(7) excluding paint and wood
(8) including paint and wood
(9) [Ecoinvent 2003] Q333 cites higher figures for the nuclear power plant Leibstadt.

The early dates of the figures (1971) illustrate the absence of empirical construction data in the open nuclear literature.
The differences between the sources are unexplained. They illustrate the large uncertainties, due to the seemingly inherent inconsistency of nuclear data and the secrecy of vital data, hampering the LCA and energy analysis of the nuclear system.
Another source of inconsistency and ambiguity is the usage of non-SI units, making the already scarce published databases unnecessarily opaque. For example: in the Handbook of Chemistry and Physics are 6 different definitions of the British thermal unit (Btu) and 6 different ones of the unit horsepower (hp).

Escalation of material requirements

An important cause of the cost escalation of LWR's in the USA is formed by the increased material requirements. [Shaw 1979] Q230 observed a growth in material requirements as illustrated by Table 2.

[Crowley & Griffith 1982] Q229 analyzed data on eight PWR's expected to come on line in the 1982-1985 period in the USA, with an average power of about 1150 MW(e). Their findings are summarized in Table 3.
They noted that the amount of craft manhours increased faster than the construction material requirements.

Table 2
Escalation of material requirements for construction of US LWR power plants. Source: [Shaw 1979] Q230

	increase %/yr	value in 1977 Imperial units		value in 1977 SI units	
building volume	6	13	ft^3/kWe	.268	m^3/kWe
structural steel	14	20	lb/kWe	9.07	kg/kWe
reinforcing steel	13	39	lb/kWe	17.69	kg/kWe
structural concrete	9	0.14	yd^3/kWe	0.107	m^3/kWe
farmwork	9	1.90	ft^3/kWe	0.0538	m^3/kWe
piping	17	0.3	ft/kWe	0.091	m/kWe
conductors and cables	12	3.7	ft/kWe	1.13	m/kWe

Extrapolating the figures of Shaw to 1982-1985 results in a concrete volume of 165000 m^3 in 1982 and 196000 m^3 in 1985. The 1982 value is well below the lowest observed volume by Crowley & Griffith and the 1985 value is below the average. This may imply that the escalation in material requirements increased even faster after the investigation of Shaw.
Extrapolating the figures of [Shaw 1979] Q230 to 1990, when about the last US LWR came on line, gives the figures of the third column in Table 4.
If the extrapolation is started with the average concrete volume given by Crowley & Griffith the total mass of the 1990 plant would be about 1187 Gg, close to the figure given by [Uchiyama 2002] Q205: 1291 Gg (1 Gg = 10^9 g = 1000 metric tons).
The concrete/steel ratio is assumed to remain constant (5.77 in the extrapolation of the Shaw figures). Judging by Table 2, the concrete/steel ratio tends to decrease, so the figure of 1187 Gg may not be overrated.

Table 3

Material requirements for construction of actual US LWR power plants in 1982. Source: [Crowley & Griffith 1982] Q229

	low	average	high	unit	high/low ratio
concrete	238000	276000	331000	yd^3	1.4
	182000	211000	253000	m^3	
piping	273000	391000	655000	ft	2.4
	83.2	119.2	199.6	km	
cable	3820000	562200	8422000	ft	2.2
	1164	1714	2567	km	
craft labour	15	22	33	manhours/kWe	2.2

Table 4

Material requirements for construction extrapolated to 1990

	volume m^3 (year #)	volume m^3 (1990)	mass (Shaw) Gg	mass(Crowley & Griffith) Gg
structural steel			49.8	67.3 (2)
reinforcing steel			86.6	111 (2)
concrete	107000 (1977)	328000	787 (1)	
	211000 (1982)	420400		1009 (1)
total mass (excl piping and cables)			923.4	1187.3
craft labour (million manhours) (3)			15-33	15-33

Based on [Shaw 1979] Q230 and Crowley & Griffith 1982] Q229]

(1) reinforcing steel (rebar) not included

(2) same concrete/steel ratio as Shaw 1979 (= 5.77)

(3) assumed no escalation after 1982, but likely the craft labour escalated as well.

The decreasing trend of the concrete/steel ratio is confirmed by the figures from [MPR-2776 2005] Q346, which come out to a ratio of 4.3 (see Table 5). Moreover, the concrete volume as starting point of the calculation is an average, so a significant number of plants may contain more concrete (and rebar).

In addition to the figures in Table 5 a Gen III+ nuclear power plants contains some 7000 Mg high quality steel and alloys contained in the reactor pressure vessel and reactor pressure vessel head, steam generators, turbines and generators. In addition to these figures and the amounts of piping and cabling, a large number of pumps (about 130, of wich more than 20 with power > 3 MW(e), and valves (9000-18000). The authors give no figures on the power consumption of the pumps (except some vague indications) nor on the total mass contained in the piping, cables and auxiliary equipment.

The figures from Table 5 seem to endorse the extrapolation in Table 4, the more so as the figures from Table 5 may be considered to be a lower limit. Figures of this kind from the nuclear industry are never overstated. The number of craft labour manhours refer only to the on-site construction activities and is based on a construction time of 4 years and on partially unproven techniques. The off-site manufacture of equipment, materials and components of the construction will contribute a significant number of required manhours. In view of the historical developments and the recent experience with the construction of Olkiluoto 3 in Finland, significantly higher figures than in Table 5 may be expected.

Table 5

Material requirements for construction of a Gen III+ nuclear power plant, according to [MPR-2776 2005] Q346

	volume yd³	volume m³	mass Gg	length ft	length km
structural steel			25		
reinforcing steel			46		
concrete	460000 (1)	351700	844		
large bore pipe				260000	79
small bore pipe				430000	131
cable tray				220000	67
conduit				1200000	366
power cable				1400000	427
control wire				5400000	1646
process and instrument tubing				740000	226
mass excl. piping & cables and site prep.			915 (1)		
craft labour, on-site only, 8 million manhours					

(1) excluding concrete for site preparation

Reference nuclear power plant

The reference reactor in this study, a 1 GWe LWR to be constructed after 2000, has an average construction mass of 1000 Gg ± 20%, excluding piping and cables. These assumptions are based on the studies of [Shaw 1979] Q230, [Crowley & Griffith 1982] Q229 and [Uchiyama 2002] Q205. With a concrete/steel ratio of about 5.7 (see remarks above) this mass constitutes of about 150 Gg steel and 850 Gg concrete. Assumed the ratio structural steel/reinforcing steel (rebar) will remain constant as given by Shaw, the reference plant will contain 54.7 Gg structural steel and 95.3 Gg rebar.

In Table 6, which is based on Table 4, some figures on the reference reactor in this study are summarized. In view of the relationship between construction costs and material requirements, the lowest costs are associated with the lowest construction mass and the highest costs wth the highest construction mass. For comparison: [Uchiyama 2002] Q205 cites a total construction mass of 1291 Gg.

The requirements of other metals (e.g. aluminium, copper, inconel), contained in the reactor vessel and other equipment, are set at 7 Gg. Non-metal materials may amount to a few Gg. These amounts are not separately listed and are considered to be included in the total mass

We assume the figures of Table 6 are valid for the average nuclear power plant of the year 2000 and that after 2000 no escalations in materials and energy requirements and cost would occur.

Table 6
Steel and concrete requirements and costs of construction of the reference reactor. Mass figures based on [Shaw 1979] Q230 and [Crowley & Griffith 1982] Q229.

	unit	low	mean	high
structural steel	Gg	43.6	54.7	65.4
reinforcing steel (rebar)	Gg	75.8	95.3	113.7
total steel mass (rounded)	Gg	120	150	180
concrete mass (rounded)	Gg	680	850	1020
total mass (excl piping and cables)	Gg	800	1000	1200
concrete/steel ratio	–	5.7	5.7	5.7
cost (in $ of 2000)	G$	3.5	6.5	9.5
specific cost	$/kg	4.4	6.5	7.9

3 Construction energy – other studies

Results from other studies

Different methods to estimate the construction energy have been used in energy analyses. The results of the published energy analyses of nuclear power plants are summed up in Table 7.

Table 7
Estimates of energy input of nuclear power plant construction in other studies

reference	Q	E_{prim} PJ	$E_{th}+E_e$ PJ	*R*	meth	mass Gg	cost M$	base year	ratio MJ/$
Franklin et al.1971	Q111	n.a.	–	–	–	–	–	–	–
Romb&Koen1974	Q96	0.68	–	–	D	12.9	–	1974	–
Romb&Koen1974	Q96	14.50	12.69	14.7	B	–	211.5	1970	68.56
Romb&Koen1975	Q120	14.5	–	–	B	–	211.5	1970	68.56
Rotty etal.1975	Q95	–	10.848	13.70	C	–	–	1971	–
Perry et al.1977	Q114	–	10.848	13.70	C	–	–	1971	–
SRI 1975	Q110	n.a.	–	–	–	–	–	–	–
Kolb et al.1975	Q144	9.486	–	–	?	–	600	1974	15.8
Chapman 1975	Q113	14.602	11.683	11.0	A	–	211.2	1973	55.32
ERDA-76-1 1976	Q109	–	20.80 (1)	11.52	C (1)	–	–	1971	–
Mortimer 1977	Q98	–	5.305-9.230	8.0-7.5	C	253-351	–	1972	–
Held et al.1977 Moraw et al.1977	Q117 Q121	14.76	–	–	F	–	–	1971	–

Lako 1995	Q23-7	25.5± 9.5	–	–	A ?	516	2471	1984	10.3± 3.8
Orita 1995	Q23-14	n.a.	–	–	–	–	–	–	–
White 1998	Q299	20.07	16.88	8.06	D ?	217	–	1971	–
Uchiyama 1995 Uchiyama 2002	Q23-1 Q205	–	5.50	9.88	D	1291	–	?	–
Ecoinvent 2003	Q333	–	–	1.07	E	573	–	1984	–
Vattenfall 2005	Q152 Q309	4.057 (2)	–	–	E	–	–	1980-1985	–
WNA 2007	Q155	–	24.69 (3)	11.52	C	–	–	1971	–
ISA 2006	Q325	14.8	13.8	27	?	–	–	?	–
this study 2007		–	80	4.8	A/G	1000	6500	2000	12.31

n.a. Not available: not included in the analysis.
(1) Construction + operation. Figures from [Rotty et al. 1975].
Operational lifetime T_{100} = 18.67 FPY (full-power year).
Figures of Rotty et al. 1975 are based on data from the WASH-1230 report from 1971.
(2) Includes decommissioning. Only electricity from off-site sources.
(3) Construction + operation. Figures from [ERDA-76-1] Q109, based on [Rotty et al. 1975] Q95, corrected for a longer operational lifetime: T_{100} = 24 FPY.
Method: A = applying general energy/gnp ratio
B = applying energy/$ ratio corrected for sector new construction
C = direct energy + embodied energy in materials
D = energy embodied in materials only
E = direct energy consumption on-site only
F = I/O analysis
G = based on energy/mass ratio
All reported costs are converted into dollars, with 1 GBP = 1.60 US$, 2 DM = 1.00 US$.

Table 7 shows that most studies refer to LWR power plant designs from the early 1970's, at the time of the lowest published specific costs and material requirements. This implies that the technical developments during the 1970s, 1980s and 1990s are not incorporated. Some energy analyses did not include construction energy at all.
Since 1970 the capacity of a generic LWR power plant evolved from 20-100 MW(e) to 1000-1600 MW(e) in 2000 . The mass of construction materials evolved from some 100-200 Gg in 1970 to 800-1300 Gg in the 1990s.

Table 7 illustrates also the scarcity of independent data on nuclear power plant construction, not to speak of the scarcity of data based on actual experiences. Once again the secrecy of the nuclear industry shows up. One may wonder how democratic the decision process in the civil society is with regard to civil nuclear power.

It may be useful to create a calibration point for Table 7, by calculating the embodied energy in only the steel and concrete of the nuclear power plant. The embodied energy in the raw materials can be calculated with the specific values of steel and concrete, taken from [IAEA-TecDoc-753 1994] Q148, and the material construction masses in 1990 from Table 6.The results are presented in Table 8.

Table 8
Embodied energy in the steel and concrete of the reference reactor. All energy units are primary energy units.

reference	specific energy MJ/kg	estimate					
		low		average		high	
		mass Gg	energy PJ	mass Gg	energy PJ	mass Gg	energy PJ
steel	29.54	120	3.545	150	4.431	180	5.317
concrete	1.83	680	1.244	850	1.556	1020	1.867
sum steel + concrete		800	4.8	1000	6.0	1200	7.2
direct energy (Vattenfall)	(1)		4.1		4.1		4.1
total E, direct + embodied			8.9		10.1		11.3

(1) Assumed the direct energy requirements do not depend on the mass of construction materials, but likely they do.

The figures presented in Table 8 certainly are far below the total values of the total construction energy requirements, because solely the embodied energy in the raw materials steel and concrete is accounted for. Ignored are the energy consumed in the processing of the raw materials to produce the construction materials complying with the extremely high quality specifications necessary for safe nuclear power plants. Also the manufacture of components and structures are not included. The basic figures from Table 8 evidently show the need for looking critically at the figures in Table 7.

The sums from Table 8 are used in Approach 4 in the next section to estimate the total energy requirement for construction of the reference NPP in this study.

Most studies happen to be based on a 1971 vintage reference reactor, as Table 7 shows. Since 1971, a year of very optimistic views on the future of nuclear power, the complexity of nuclear power plants increased and the construction mass went up at least fivefold.

Vattenfall

The often quoted publications of Vattenfall AB, a Swedish utility (see Q151, Q152, Q153, Q154, Q155 and Q309) is an evironmental analysis, called an EPD (Environmental Product Declaration).The EPD is made to comply with certain Swedish regulations and is, after certification, valid for a limited number of years.

The Vattenfall EPD is not an scientific energy analysis to be published in a peer reviewed journal and cannot be compared with the analysis of this study. An energy analysis comprises all energy flows related to the investigated object: not only the direct energy consumption at the site, but indirect and embodied energy inputs as well.
This becomes clear by reading the document thoroughly and is confirmed by Birgit Bodlund (Senior Adviser Environmental Affairs, Vattenfall and one of the authors of the EPD) in a personal communication (email 17 December 2001).

The EPD report states that some data are missing from the processes needed to fabricate nuclear fuel from uranium, such as greenhouse gas emissions, because the suppliers did not provide those data. Vattenfall estimated the underestimation of the emissions, caused by the absence of the data, at a few percents, but failed to explain how the estimate was made.

The energy figures in the EPD report refer to the direct electricity consumption by the mentioned processes of the nuclear chain, as far as not provided by the nuclear power plant itself. The electricity consumption is converted into primary energy units, according to the fuel mix of the electricity generation at the site of each process. So the amounts of fossil fuels and CO_2 emissions stated refer only to the direct electricity consumption.

As the electricity consumption in most processes are a minor part of the total direct energy consumption, the total amounts of fossil fuel burnt and hence the CO_2 emission are much larger than stated in the Vattenfall EPD. This 'omission' is not the fault of Vattenfall: apparently these data did not need to be included in the EPD.

Figures of some processes not yet in existence (e.g. deep repository) are not included in the Vattenfall EPD. However, figures of the direct electricity usage of dismantling of the nuclear power plant and of a waste facility do. Vattenfall failed to explain how these estimates were made.

Some figures given in the EPD of Vattenfall are not as solid as they may seem, for Vattenfall assumed a lifetime of 40 years with an average load factor of 0.85, corresponding with 34 full-power years (FPY). Through 2002 the three Forsmark nuclear power plants (connected to the grid in 1980-1985) together reached an operational lifetime of 16.1 FPY. Up until today only a few nuclear plants in the world reached more than 24 FPY, so an expected lifetime of 34 FPY is not based on any practical experience with nuclear power plants in the world.

Certification

The EPD by Vattenfall of June 2004 is certified by the accredited certification body BVQI Svenska AB. 'Certified' means that the Certifier found the Vattenfall EPD to comply with the normative documents from the Swedish Environmental Council. The certification is valid until June 2007.

'Certified' does not mean 'peer reviewed' in the scientific sense. Which peer review has an expiration date?

4 Construction energy estimation – methodology

Construction as a process

The total energy requirements for construction of a nuclear power plant cannot be measured directly, due to the complexity, scale and diversity of the materials, activities and equipment involved. Therefore, the construction energy has to be estimated using indirect methods that will be discussed below.

Any industrial process has an input of direct energy (fuels and/or electricity), services, processed materials, capital goods (machines, transport) and sometimes also raw materials, as found in nature. The output comprises the wanted for product, material waste (gaseous and liquid effluents and solid waste) and low temperature waste heat, released into the biosphere.

Tnis methodology has been explained in report m06 *Energy analysis, the method*.

The nuclear system is no exception to this outline. The construction of the nuclear power plant is just one of the constituting processes of the nuclear system.

The energy inputs of the construction of a nuclear power plant comprise:

- The energy consumed at the construction site, including transport; this component can be measured directly.
- The energy embodied in services: not only the craft labour needed during the construction of the system, but also research laboratories and institutional services from institutes like IAEA, WNA, UIC, NEI and NEA, and quality inspectors.

- The energy embodied in the construction materials, such as concrete, steel and copper, but also in chemicals and other auxiliary materials: that is, the energy consumed in the processes to prepare these materials from the raw resources as found in nature.
- The energy embodied in the manufacturing and construction of components and capital goods, e.g. the reactor vessel, turbines, pumps, transport vehicles, etcetera.
- The energy needed to construct and maintain capital goods, such as reactor vessel, steam generators, pumps and turbines. This in addition to the machines and equipment needed for manufacturing and maintaining those components.

The manufacturing of the components of the nuclear power plant and the capital goods required during its lifetime are produced for their part from processed materials, which also require inputs of energy, materials and services.

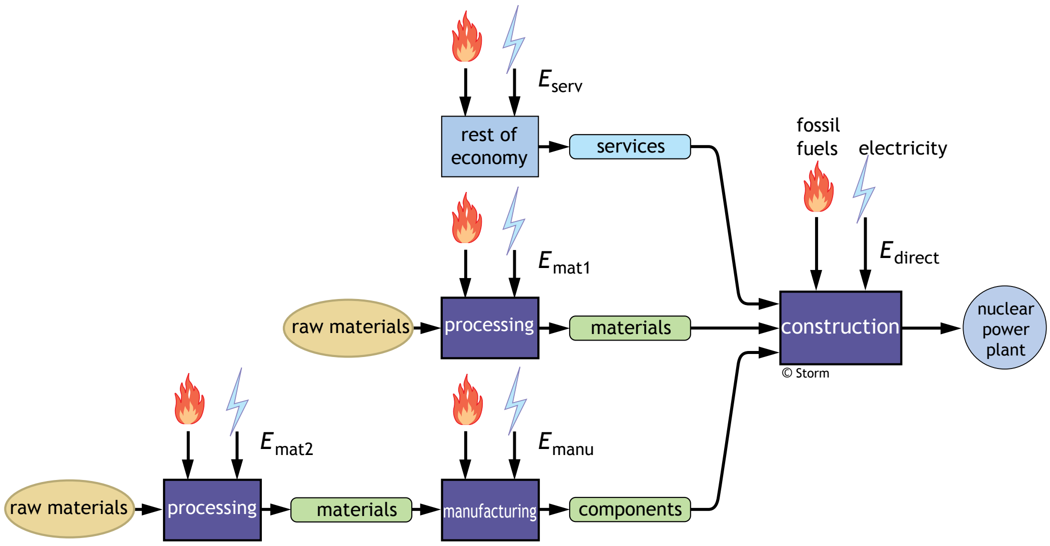

Figure 4
Simplified outline of the process analysis of the construction of anuclear power plant

The energy inputs embodied in the services, processed materials and capital goods make up the *indirect energy input* of the contruction process. The energy requirements of construction is the sum of the direct and indirect energy inputs (see Figure 5):

$$E_{con} = E_{direct} + E_{mat1} + E_{mat2} + E_{manu} + E_{serv} \quad \text{eq 1}$$

The energy input of construction has an electric and a thermal (fossil fuel) component, analogous to the energy input of any process. In this study the electric and thermal (fossil fuel) inputs are kept separate, as pointed out in Part C1 of [Storm&Smith 2008] Q6 and report m06 *Energy analysis, the method*.

$$E_{process} = E_{th} + E_e \qquad R = \frac{E_{th}}{E_e}$$

$E_{process}$ = total energy input of a process J
E_{th} = thermal energy input (fossil fuels) J
E_e = electric energy input J
R = thermal/electric ratio

eq 2

Quality and work

The materials required for the construction of a nuclear power plant have to be of exceedingly high quality, as has to be the craftwork needed to manufacture the components, e.g. the reactor vessel, from those high-quality materials. The safety and the operational lifetime of a nuclear power plant is for a large part determined by the quality of the reactor vessel and associated components. These components cannot be replaced anymore once the reactor is started up.

To achieve a high level of safety and a long lifetime, the properties of the materials and of the components as a whole have to be predictable to an extremely high degree under stressful circumstances, such as high pressures and temperatures, neutron radiation and corrosion processes.
To achieve a high predictability of properties one has to start from very pure materials and the fabrication processes have to occur under tightly controlled conditions. The amounts of rejected materials and components in a production process increase rapidly with increasing quality requirements.

A high predictability of properties translates into a low entropy per unit mass: the lower entropy the higher the predictability. The lowering of the entropy of a given amount of matter is possible by applying work: high-quality usable energy, such as mechanical energy and electricity. The amount of work to be applied per unit mass increases exponentially with decreasing entropy. Consequently, the production of 1 Mg reactor-grade steel requires much more work than 1 Mg steel intended for the construction of a garden fence.

More work implies not only more direct energy input, but also a larger infrastructure of skilled people and facilities to run the process and to perform an adequate quality control.

The minimum amount of work needed to lower the entropy of a given mass to a certain low level, is determined by the Second Law The Second Law is one of the basic thermodynamic laws governing all changes in the observable universe. Advancement of technology only can help coming closer to the thermodynamic minimum of the required work, but the limit never can be surpassed. A thermodynamic efficiency of 30% of an industrial process (e.g. aluminium production) is considered as favourable, most processes reach lower values. An efficiency of 30% means that the actual work done to perform a given process is over three times as high as the thermodynamic minimum of that process.

The materials used in the construction of a nuclear reactor and associated energy conversion components cannot be substituted freely by other materials, for instance when the work intensity of the first choice is considered too high. The materials are carafully chosen for their very specific properties, such as strength at high temperatures and pressures, corrosion resistance and nuclear properties (e.g. deterioration by neutron radiation, generation of radionuclides by neutron capture.
Some important implications of the Second Law for nuclear technology are discussed in reports m21 *Nuclear safety* and m38 *Nuclear power and the Second Law*.

Above considerations bring the conclusion that the construction of a nuclear power plant requires more work per unit electricity production capacity than non-nuclear power plants, which have lower safety and predictability requirements than nuclear power plants.

5 Input/output analysis

During the 1970's and 1980's the methodology of energy analysis has been developed, maturing to a useful tool to calculate the energy requirements of a good or economic activity with reasonable accuracy.

Process analysis, discussed in report m06 *Energy analysis, the method*, leads to a large underestimation of the total construction energy requirements, when labour and supporting activities of the construction are discounted, see e.g. [Rombough & Koen 1978] Q120 and [Bullard, Penner & Pilati 1978] Q102. This is the case in a number of energy analyses published in the past (see Table 7). Input/output (I/O) analysis is well suited to large aggregated activities, like the construction of a nuclear power plant. [Chapman 1975] Q106 concluded:

> "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."

Chapman was member of the IFIAS workshops [IFIAS 1974] Q99 and [IFIAS 1975] Q100. His methodology has been peer reviewed by a large group of scientists, all experts on energy analysis, from a number of countries.

The I/O analysis may be simplified by using the general energy/gdp ratio of a particular year in a particular country to calculate the net energy requirement of a complex activity. The general energy/gdp ratio (or energy intensity) *e* is defined as the quotient of the total primary energy consumption of a country (in joules) and gross domestic product GDP (often in US dollars) of a given year *i*, see equation 3.

$$e_i = \frac{E_{\mathrm{prim}\,(i)}}{\mathrm{GDP}_i}$$

e_i	=	energy/GDP ratio of year i	J/$\$_i$
$E_{\mathrm{prim}(i)}$	=	primary energy consumption in year i	J
GDP_i	=	gross domestic product of year i	$\$_i$

eq 3

In case of the construction of a nuclear power plant, estimation of the construction energy using the energy intensity *e* from the monetary costs in the same year, according to equation 4, does not introduce a large error. The spread in the capital cost, 6500 USD(2000) ± 50%, is about as large or larger than the uncertainty introduced by this simplification.

$$E_{\mathrm{con}} = C_{\mathrm{con}(i)} \cdot e_i$$

E_{con}	=	primary energy requirements of construction	J
$C_{\mathrm{con}(i)}$	=	construction cost in year i	$\$_i$
e_i	=	energy/GDP ratio of year i	J/$\$_i$

eq 4

This simplification gives a fairly reliable value of the energy embodied in that activity, including energy costs of craft labour, services, subsidies, etcetera, according to [Tyner, Constanza & Fowler 1988] Q124. This conclusion endorses the conclusions of other studies, e.g. [Rombough & Koen 1978] Q120, [Roberts PC 1982] Q103, [Bullard, Penner & Pilati 1978] Q102, [Constanza & Herendeen 1984] Q119.
As Constanza & Herendeen 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 may considered being high-tech, on top of an extensive industrial and economic infrastructure

of other high-tech production processes, as pointed out in the previous section *Quality and work*.
The studies of Rombough & Koen 1975] and Bullard, Penner & Pilati 1978 showed that the value calculated via a detailed I/O analysis is somewhat higher than the value found via the simplified method. Both studies concluded that construction of a (coal-fired) power plant is more energy-intensive than the average economic activity.

A more accurate estimation of the construction energy can be found by multiplying the construction costs of a plant (in year *i*) with the energy/cost ratio (in J/$) of the sector 'new construction of utilities', in the same year *i*. This can be done as in equation 5, by multiplying the result of equation 4 with a factor *a*, derived from the publication of Bullard, Penner & Pilati.

$$E_{con} = C_{con(i)} \bullet e_i \bullet a_i \tag{eq 5}$$

E_{con}	=	primary energy requirements of construction	J
$C_{con(i)}$	=	construction cost in year i	$\$_i$
e_i	=	energy/GDP ratio of year i	$J/\$_i$
a_i	=	multiplier in year i	

In this study a constant value of $a = 1.16$ is assumed (valid for the year 1967), although it is slightly increasing with time and getting more electric energy-intensive. In view of the considerations in the section *Quality and work* the multiplicator might by higher for nuclear power plant construction.

Basic concept

The concept of the energy/gdp ratio is based on the notion that in a given year the economy consumes a measured amount of energy units and produces a measured amount of units of economic transactions or changes by human action: the gross domestic product GDP. The energy input is measured in joules J and the GDP is usually measured in USD.

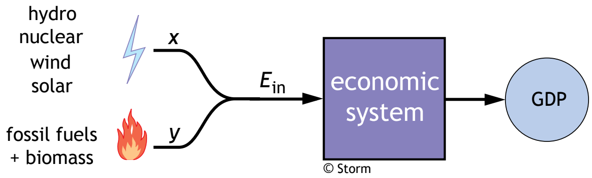

Figure 5
The economic system from an energy point of view. The virtual product of the system in given year is an amount of economic transactions, measured in monetary units, and can be seen as a measure of changes by human action.

The basic energy input of the economy E_{in} consists of:
- the energy generated by hydro power, nuclear power, wind and solar (x), which is supplied to society as electricity, plus
- the energy supplied in the as fossil fuels and biomass (y), which comes available as combustion heat.

See also Figure 4. In this study the electric energy input x is not converted into 'primary energy units' for reasons explained in report m06 *Energy analysis, the method*. So:

$$E_{in} = x + y \tag{eq 6}$$

The average energy intensity of one unit of economic transactions in a given year i is:

$$e_i = \frac{E_{\text{in}\,(i)}}{\text{GDP}_i} = \frac{x_i + y_i}{\text{GDP}_i}$$

e_i	=	energy/GDP ratio of year i	J/$\$_i$
$E_{\text{in}\,(i)}$	=	energy consumption in year i	J
GDP_i	=	gross domestic product of year i	$\$_i$
x_i	=	primary electric energy in year i	
y_i	=	thermal energy (fuels) in year i	

eq 7

Note that this definition is different from equation 3. In this study the definition of equation 7 is used.

Every change in the universe is accompanied by an energy conversion and the changes (transactions) in the economic system are no exception. Every human activity consumes energy, that is, converts high-quality energy into low-quality energy (degradation of energy quality). In one place at a certain moment an activity may seem to do the reverse, e.g. the generation of electricity by a battery, but on another place and/or at another moment more energy degradation has to take place, to fabricate the battery. The sum of all human activities which are powered by mineral energy sources – which come from within the biosphere – always is degradation of energy, according to the Second Law of thermodynamics. One of the more popular names of the Second Law is: the law of the irretrievable loss.

Suppose a model economy producing 225 units of GDP in year *i* and that the construction of nuclear power plant in that year requires 15 units of GDP. These 15 units are directly related to the construction and cannot be attributed to other activities in the economic system.

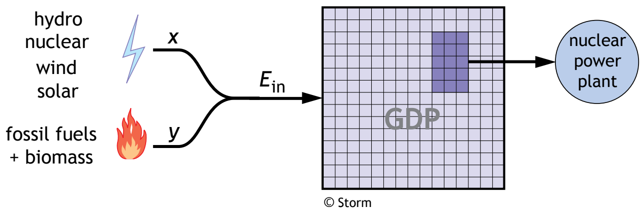

Figure 6

Basic concept of the input/output analysis of construction. A part of the economic activities in a given year, 15 out of 225 units in this simple example, is required to construct a nuclear power plant.

In a first approximation it seems reasonable to assign 15/225 of the total energy input of the economic system to the construction of the nuclear power plant. Based on this concept the approximate construction energy in the simplified example would be:

$$E_{\text{con}} = \frac{15}{225} \bullet E_{\text{in}\,(i)} = \frac{15}{225} \bullet (x_i + y_i)$$

$E_{\text{in}\,(i)}$	=	total energy consumption in year i	J
x_i	=	primary electric energy in year i	J
y_i	=	thermal energy (fuels) in year i	J

eq 8

Note that in equation 8 thermal and electric energy input are differentiated in another way than in equation 2, which is used throughout this study.

Activities involving nuclear technology certainly are more work intensive (more usable energy required per mass unit product) than the average activity, as is explained in the section above 'Quality and work'. Above way to approximate the construction energy of a nuclear power plant likely will not lead to overrating.

6 Four approaches

In this study the construction energy requirements are estimated in four more or less different ways, here called approaches 1-4.

Approach 1

Approach 1 is based on equation 5. The historical construction costs are deflated to the year 1967 and multiplied by the ratio *e* and the multiplier *a* of 1967.

Advantage of Approach 1 is the availability of the correct energy/cost ratio for construction. However, it implies the assumption that the construction energy requirements remained unchanged during the period 1967 to 2000. This is likely not the case, as the overall energy efficiency of the economy improves by time. Moreover, the average thermal/electric energy ratio *R* (see equation 2) in 2000 is lower than in 1967: the economy is becoming increasingly electricity-intensive. In addition, the history of construction of nuclear power plants features a strong trend of becoming more complex and requiring more materials, energy and manpower in the course of time. This trend may offset an improved energy efficiency in the construction sector.
Considering these arguments, Approach 1 seems to result in a fairly reliable value of the energy requirements for construction.

Approach 2

Approach 2 is also based on equation 5. The historical construction costs are inflated to the year 2000 and multiplied by the ratio *e* of 2000 and multiplier *a* of the year 1967.

In Approach 2 the improved energy efficiency of the economy in 2000 is accounted for. A trouble, however, is wether the multiplier a in the year 2000 and the ratio *R* are the same in 2000 as in 1967. The improvement of the overall energy efficiency of the Western economies is coupled with a relatively rising consumption of electrical energy. So, the overall ratio *R* decreases and most probably the *R* of the construction sector decreases even more, since the construction sector historically is more electricity-intensive than the economy as a whole.

Approach 3

In Approach 3 the energy requirements are approximated on the basis of the total mass of the construction and the monetary costs. This method is based on a publication by Roberts PC 1982 [Q103]. Peter Roberts was member of the IFIAS workshops in 1974 and 1975, [IFIAS 1974] Q99 and [IFIAS 1975] Q100, as were Peter Chapman, Robert Herendeen and Malcolm Slesser, to name a few. Robert's methodology has been peer reviewed by a large group of scientists from a number of countries.

Roberts found a strong, non-linear, relationship between cost of goods in dollars per mass unit and the energy embodied in the goods, measured in energy units per mass unit. From his graphical presentation of this correlation, based on US I/O tables of 1967, the energy requirements for construction of a nuclear power plant in the USA can be deduced.
Unfortunately, all energy values in the paper of Roberts 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.

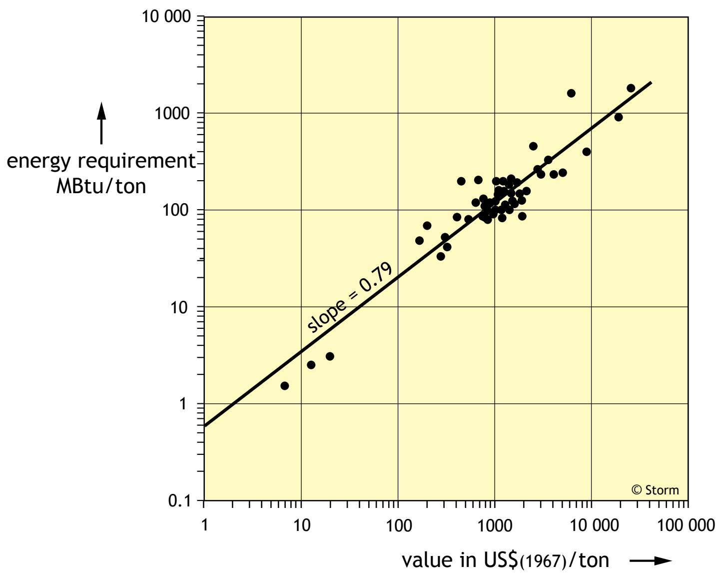

Figure 7

Relationship of specific energy requirement and monetary value (USA 1967). Source: [Roberts PC 1982] Q103 The principles of this method have been discussed and reviewed by a large peer group at the IFIAS workshop 1974 Q99.

From his graphical presentation (Figure 7) we derived the following equation, valid for the USA in the year 1967:

$$\log J_{con} = -0.315 + 0.79 \cdot \log c_{con}$$

J_{con} = primary construction energy per unit mass MBtu per short ton
c_{con} = construction cost per unit mass $(1967) per short ton

eq 9

Handbook of Chemistry and Physics (75th ed. 1994) cites six conversion factors for Btu to joules. In this study the conversion factor 1 Btu = 1.0551 kJ is used, in accordance with BP 2007 [Q91] and the International Tables. Using this energy conversion factor and the mass conversion factor 1 Mg = 0.907185 short ton, equation 9 becomes:

$$\log J_{con} = -0.283 + 0.79 \cdot \log c_{con}$$

J_{con} = primary construction energy per unit mass GJ/Mg
c_{con} = construction cost per unit mass $(1967)/Mg

eq 10

Solving for the primary energy Econ.p needed for construction of a 1 GWe nuclear power plant, we get:

$$E_{con.p} = m_{con} \cdot J_{con} = m_{con} \cdot 10^{(-0.283 + 0.79 \log c_{con})}$$

$E_{con.p}$ = primary construction energy GJ
J_{con} = primary energy per unit mass GJ/Mg
c_{con} = construction cost per unit mass $(1967)/Mg
m_{con} = total mass of the nuclear power plant Mg

eq 11

As explained above we employ for the total energy of construction the sum of the thermal and the electric components, so we must use equation 2 to find the sum of these two components. Combining equations 2 and 11 we find:

$$E_{con} = E_{th} + E_e = \frac{1+R}{R+f} \bullet E_{con.p}$$

E_{con}	=	construction energy	GJ
E_{th}	=	thermal input (fossil fuel)	GJ
E_e	=	electric input	GJ
$E_{con.p}$	=	construction energy, primary units	GJ
R	=	thermal/electric ratio	
f	=	electric to primary energy multiplier	

eq 12

Approach 4

Approach 4 is based on the fact that the embodied energy in the unprocessed construction materials, steel, concrete and other metals and materials, constitutes only a part of the total energy input of construction. If that ratio is known, the total energy input can be approximated.

The ratio embodied/total energy is examined by [Rombough & Koen 1974] Q96 and in1975 Q120. They showed in their studies that the embodied primary energy in the unprocessed materials of a nuclear power plant constitutes 4.7% of the total primary energy requirements of construction, calculated via an elaborate I/O analysis.
They considered in their study only the metal construction components and equipment and ignored the concrete with its reinforcing steel, in calculating the embodied energy in materials as well as in their I/O analysis. Direct energy consumption at the construction site, engineering costs and IDC (interest during construction) are excluded from their analysis. For that reason, the total energy requirements for construction of the reference plant in their study, would be higher.

Underestimation

This study uses the cost figures in the year of completion and connection to the grid of the nuclear power plants. In fact this will lead to underestimation of the real costs, as they should be calculated in constant dollars, and not as 'mixed current' costs (sum of spendings), see [Komanoff 1981] Q227 and [Starr & Braun 1984] Q180. The difference may be significant, due to the long construction times of nuclear power plants (often 10 years or even more). A GDP unit in year 1 represents a higher energy value than a dollar spent in year 10. The construction costs in constant dollars, in the year of completion, are larger than the sum of the expenditures in current dollars during the construction period.
Consequently, the values for construction energy when calculated from the construction cost (Approaches 1 and 2) might be underrated.
The construction of a nuclear power plant belongs to the most energy-intensive activities.

The construction energy of nuclear power plants is assumed to remain constant at the level calculated from the US database. During construction of the US nuclear power plants large cost escalations occurred, which had a direct relationship with increased requirements of energy, materials and craft labour, as pointed out in a previous section. Above assumption implies that no further escalations in costs, energy and materials would occur. This is uncertain, because there are no indications pointing to a stop of the escalating trend at the moment of completion of the last US nuclear power plant, certainly not after 9/11.

The last order of a new US nuclear power plant has been placed in 1978, but none of the plants ordered after 1973 ever reached completion, so the youngest operating design dates from the year 1973. New reactor concepts, most likely variants of the LWR, which may be developed in the future are not expected to lead to significantly less specific consumption of materials and energy, at least, no indications have been reported. On the other hand, the energy/GDP ratio of the OECD economy decreases in time, which would result in a lower construction energy input. However, the specific energy consumption of the sector new construction is relatively increasing, and the economy as a whole is becoming increasingly electricity-intensive.

The net result of above mentioned effects together is hard to estimate. Keeping the value at the level of the presently operating US plants may be prudent.

7 Energy/GDP ratio or energy intensity

An important parameter in energy analysis is the general energy/GDP ratio, also called the energy intensity, of a country, *e*, defined as the ratio of the total domestic primary energy consumption in year *i* and the gross domestic product in year *i*, given in energy units per USdollar of year *i*, $J/\$_i$, see equation 3.

When this study started in spring 2000, a value of the general energy/GDP ratio *e* in the year 2000 was not yet available. We extrapolated a value from the statistics in Europe Energy Scenario's 1996 [Q20]:

energy/GDP ratio = *e* = 10.64 MJ/$(2000)

This value would be valid for the whole OECD and virtually equal to the value for the USA.

Using data from [Eurostat 2002] Q275a, a value of *e* =11.0 MJ/$(2000) for the USA is found. [IEA 2003] Q274 cites *e* = 0.25 kg oil equivalent/$(1995) for the USA in 2001, which would correspond with about *e* = 9.47 MJ/$(2000) in 2000.
[WETO 2003] Q237 cites a figure from which a value of *e* = 10.7 MJ/$(2000) can be deduced for North America, probably USA plus Canada. As the Canadian economy is more energy-intensive than that of the USA, the value of the US ratio would be slightly less.

Lack of clarity with the ratio *e* may arise by different ways of calculation of both the quantities 'gross domestic primary energy consumption' and 'gross domestic product' in different countries. The various statistical publications are not always consistent in their basic figures from which the ratio is calculated. Sometimes even different conversion ratios are used for the conversion of kWh or joules to kg oil equivalents and vice versa.

From that point of view, the four-digit number of *e* = 10.64 MJ/$(2000) used in this study may suggest more exactiness than strictly can be justified.
The spread in the cost figures, used to calculate the construction energy requirements, is much larger than the contingency in the value of *e*, so the uncertainty in the results calculated by equations 4 or 5 is almost completely determined by the cost figures.
For that reason, in combination with the apparent uncertainties in the definition of the gross inland primary energy consumption/gross domestic product ratio, we choose to maintain the value of

e = 10.64 MJ/$(2000).

The results of the calculations are rounded, because of the large spread in the basic data.

As the costs are based on the US situation, the value for the USA should be used.
Applying the multiplier *a* = 1.16, the energy/$ ratio in 2000 for the sector new construction utilities is:

e = 12.34 MJ/$(2000).

8 Results of this study

Since no recent I/O tables are available, the energy requirements for construction in the year 2000 have to be approximated, using available data. In a previous section four approaches are discussed, which appear to be the most reliable ones. Approaches 1 and 2 are based on [Bullard, Penner & Pilati 1978] Q102, Approach 3 on [Roberts PC 1982] Q103 and Approach 4 on [Rombough & Koen 1974] Q96 and 1975 Q120. The results of the calculations are summarized in Table 10.

Approach 1

In approach 1 construction costs in 2000 dollars are deflated to $(1967) and is the energy/$ ratio for new construction of 1967 used according to eqation 4.
Starting from the baseline costs of 6.5 G$(2000), the costs of a 1 GWe nuclear power station would be 1.28 G$(1967), using the Consumers Price Index to deflate the costs. In 1967 the energy intensity for the sector new construction was 83.8 MJ/$(1967). The average construction energy requirement then is:

$$E_{con} = E_{th} + E_e = 106 \text{ PJ} \qquad R = E_{th}/E_e = 4.8 \qquad \text{eq 13}$$

The full uncertainty range is:
E_{con} = 57 – 155 PJ.

Approach 2

In Approach 2 the costs in current dollars are inflated to $(2000) and is the energy/$ ratio of 2000 used. Applying the energy/$ ratio in 2000 for the sector 'new construction utilities' e = 12.34 MJ/$(2000) – see previous sections – and using the cost figures from Table 6 the energy requirements can be calculated with equation 4. The construction energy requirements of the average nuclear power plant then are:

$$E_{con} = E_{th} + E_e = 80 \text{ PJ} \qquad R = E_{th}/E_e = 4.8 \qquad \text{eq 14}$$

The full uncertainty range is:
E_{con} = 43 – 117 PJ.

Any real escalation in costs (excluding inflation) and in requirements of energy, materials and manpower to construct a PWR power plant of the 2000 vintage (not yet existent), compared to 1970's vintage, are ignored in Approach 2, just as in Approach 1.

Approach 3

In this approach the energy requirements are approximated on the basis of the total mass of the construction and the monetary costs per mass unit, according to the method of Roberts PC 1982 [Q103].
In this study the values R = 4.8, just as in Approaches 1 and 2, and f = 3 are used, the common conversion factor of electricity into primary energy units used in the years before 2001.

Approach 3A
Substituting the masses and specific costs from Table 6 in equations 10 and 11, and R = 4.8 and f = 3 in equation 12, we find for the baseline nuclear power plant:

$$E_{con} = E_{th} + E_e = 109 \text{ PJ} \qquad R = E_{th}/E_e = 4.8 \qquad \text{eq 15}$$

The full uncertainty range is:

E_{con} = 64 - 153 PJ

Approach 3B

If a constant construction mass of 516 Gg is assumed (as in the study of Lako 1996 [Q23-7]), independent of the same construction cost range, the results are:

$E_{con} = E_{th} + E_e$ = 96 PJ $\qquad R = E_{th}/E_e = 4.8$ $\qquad$ eq 16

The full uncertainty range is:

E_{con} = 59 - 130 PJ

Approach 4

Approach 4 is based on the fact that the embodied energy in the unprocessed construction materials, steel, concrete and other metals and materials, constitutes only a part of the total energy expenditure for construction.

Table 9

Construction energy in the steel and concrete of the reference reactor (see also Table 8) and the total construction energy input according to Approach 4.

	low PJ	mean PJ	high PJ	approach
embodied energy steel (primary)	3.545	4.431	5.317	
embodied energy concrete (primary)	1.244	1.556	1.867	
sum steel + concrete (primary units)	4.8	6.0	7.2	
construction energy (primary units)	96	120	144	4A
$E_{th} + E_e$ (R = 4.8, f = 3)	71	89	107	
construction energy (primary units)	71	89	106	4B
$E_{th} + E_e$ (R = 4.8, f = 3)	53	66	79	

In Table 8 the embodied energy of only the main construction materials, steel and concrete, are summarized. Other metals and materials are not accounted for.

If the ratio embodied energy/total energy expenditure for construction of 5% is applied to the figures from Table 8, we get the results in Table 9. Primary energy is converted into electric plus thermal energy according to equation 12, assuming a thermal/electric ratio R = 4.8, the same as in Approaches 1, 2 and 3.

Approach 4A is based on the embodied energy in steel and concrete:

$E_{con} = E_{th} + E_e$ = 89 PJ $\qquad R = E_{th}/E_e = 4.8$ $\qquad$ eq 17

The full uncertainty range is:

E_{con} = 71 - 107 PJ

Approach 4B is based on the embodied energy of steel only:

$$E_{con} = E_{th} + E_e = 66 \text{ PJ} \qquad R = E_{th}/E_e = 4.8 \qquad \text{eq 18}$$

The full uncertainty range is:

E_{con} = 53 – 79 PJ

Approach 4 seems to be quite reliable, but features some uncertainty: it is not sure wether the ratio embodied energy/total energy in 2000 is the same as in the 1970s. On the other hand the results may be low, because only a part of the embodied energy in the construction materials has been accounted for.

Summary of the results

In Table 10 the outcomes of the four approaches are summarized.
The energy equivalent of the reference reactor from [MIT 2003] 280 can be calculated in the same way as above, starting with the construction cost of 2.4 $(2000)/We.
As Approach 4 is independent of the construction costs in 2000, so the same values apply for the MIT plant as for the reference reactor.
The values resulting from the MIT figures, summarized in Table 10, may be taken as the lower limits of the construction energy to be expected.

Table 10
Construction energy requirements E_{th} + E_e of the reference 1 GWe nuclear power plant. Summary of results.
The column MIT is based on the construction costs cited in [MIT 2003] Q280 .

method	MIT PJ	low PJ	mean PJ	high PJ	R
Approach 1	39	57	106	155	4.8
Approach 2	30	43	80	117	4.8
Approach 3A	35	64	109	153	4.8
Approach 3B	44	59	96	130	4.8
Approach 4A	71	71	89	107	4.8
Approach 4B	53	53	66	79	4.8

Discussion of the results

The results of the four Approaches 1-3B may be low estimates, for reasons explained in above sections.
The similarity of the results of Approach 1 and Approach 3, may be attributed partially to the use of the same data base (I/O tables of the USA in 1967). In Approach 1 the energy/cost ratio of the sector new construction has been applied.

The method of Roberts (Approach 3) takes all sectors of the economy and introduces the energy/mass and cost/mass ratios of a great number of products. The fact that the results of both methods are so close, confirm the relationship between energy per mass unit and costs per mass unit in a given year.

Approaches 3 and 4 are based on the total mass of construction materials. It may be expected that 2000 vintage NPP's will have a contruction mass in the higher end of the range introduced in Table F.6 (800 - 1200 Gg), because of more stringent safety regulations. Several proposals for new NPP's, after 9/11, feature a double-walled containment building. This will add to the construction mass and the construction energy.

The differences between the highest and lowest values of construction mass, cost and energy requirements found in this study are not completely caused by statistical scatter or by bookkeeping artefacts. The conditions and locations of the construction of NPP's, may vary widely and so the above parameters. In the future also the construction of a NPP at location A may have different requirements from location B. As this study assesses the global impact of nuclear power, the average values of construction parameters are used.

Given the wide spread in possible construction costs of a LWR power plant (3.5 - 9.5 G$(2000)/GWe), a detailed I/O analysis seems not very meaningful. In our view above approximations (see also Figure F.9) are as reliable as may be expected. There are no signs that construction costs in energy and mass units would have declined significantly during the past 15 years, particularly not after the 9/11 terroristic attacks.

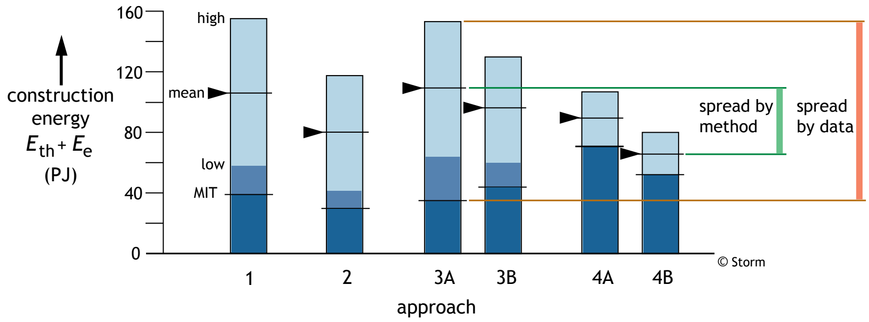

Figure 8

Grafical representation of the construction energy requirements with uncertainty ranges, calculated by four different methods. As Approach 4 is independent of the construction costs, the minimal construction energy based on the MIT 2003 [Q280] study gives the same result as the reference reactor of this study.

The diagram in Figure 8 shows that the range of values caused by the spread in the data is wider than the spread due to different calculation methods.

It is not clear which of the six approaches results in the most reliable value of the construction energy. In our view Approaches 3A, 3B and 4A might be the most reliable methods for estimating.
Looking at Figure 8 a value of 80 PJ appears to be a plausible mean value. This value is used throughout this study.

$$E_{con} = E_{th} + E_e = 80 \text{ PJ} \qquad R = E_{th}/E_e = 4.8 \qquad \text{eq 19}$$

The full uncertainty range is taken at:

$E_{con} = 40 - 120$ PJ.

We use rounded values, for the large spread in possible values and the uncertainties in the calculations make more precision in the numbers meaningless.
An indirect endorsement of the order of magnitude comes from the study [ExternE-UK 1998] Q308. This study calculated a total CO_2 emission by the contruction of Sizewell B, a 1188 MW PWR, of 3740000 Mg CO_2. Assumed the CO_2 is produced by burning fuel oil with a specific CO_2 emission of 75 g/MJ (as a rough average of fossil fuels), the construction would have consumed about 50 PJ.

The average energy intensity of construction is:

$$e_{con} = \frac{E_{con}}{m_{con}} = \frac{80}{1000} = 80 \text{ GJ/Mg}$$

e_{con} = construction energy intensity GJ/Mg
E_{con} = thermal + electric construction energy PJ
m_{con} = total mass of construction materials Gg

eq 20

This value of the energy intensity of an average nuclear process is used to estimate the energy requirements of some other processes of the nuclear chain, discussed in Part E of Storm&Smith 2008 [Q6].

From the study [ExternE 1998] Q308, one of the few published analyses based on an existing nuclear power plant, follows that the construction of the Sizewell B NPP in the UK required some 50 PJ thermal energy. The total CO_2 emission of the construction of Sizewell B has been estimated at 3.15 Tg/GW$_e$.
Nearly all other LCA studies based their estimates on NPP designs from the 1970-1972 era, existing only on paper, and not on actually constructed NPPs.

Table 11
Energy investment and CO_2 of the construction of a nuclear power plant of 1 GW$_e$.

item	low	mean	high	unit
construction cost	3.5	6.5	9.5	USD (2000)/W$_e$
construction mass (1)	0.800	1.000	1.200	million Mg
spread in construction energy estimates (2)	43-71	66-109	79-155	PJ
construction energy investment, baseline (3)	40	80	120	PJ
CO_2 production of construction, baseline	2.5	5.0	7.5	Tg

(1) No evidence is known wether a relationship exists between low cost and low construction mass.
(2) Spread caused by different estimation methods and by spread of input data.
(3) Sum of electric and thermal energy inputs, direct + indirect, ratio $R = E_{th}/E_e = 4.8$.
Baseline values in this study.

In the past numerous other studies, from 1971 on (see Table 7) and [Sovacool 2008] Q372, have estimated the energy investments of the construction of a nuclear power plant, with results ranging from $E_{construct}$ = 5.3 - 17 PJ/GW.

There are several reasons why other studies come to substantially lower estimates than this study, such as:
- not including all indirect energy inputs
- accounting for only the direct energy inputs at the construction site
- basing on a non-existing model nuclear power plant from 1971,
- not using empirical data of actual NPPs
- using very low cost estimates (not actual costs) in an input/output analysis.

This study includes all direct and indirect energy inputs, used empirical data from 2000 (pre-9/11) and applies several methods to estimate the construction energy; see for details Part F4 of Storm & Smith 2008 [Q6]. The spread in the value caused by the spread in available data turns out significantly larger than the spread caused by different estimation methods.

9 Critique

The study of [ISA 2006] Q325, a review of this study from 2005, confirmed on the whole the methodology and results of this study, but disagrees with one point: the value of the construction energy requirements. However, the authors of ISA failed to incorporate in their model basic physical concepts and constraints. In addition the authors failed to explain why the many studies, which our methods are based on would be wrong. The ISA model seems to feature an exclusively economic viewpoint, with little or no connections with the physical aspects of the economy as a system of activities within the biosphere. All human activities together are a partial system of the biosphere and are governed by thermodynamic laws.

Widely different results in other studies

In the literature a number of estimations of the construction energy requirements have been published (see Table 7). The published values vary widely due of different calculation methods. In a number of studies only a part of the energy inputs is included: for example only the direct energy inputs consumed on the construction site, or the only embodied energy in (a part of) the materials, or only the electric component of one ore more of the energy inputs, or various combinations of these partial contributions. In a few studies the construction energy is estimated using the method of cost and energy/GDP ratio, but have been based on very low construction costs, unrelated with empirical costs.

10 Operation, maintenance and refurbishments

Operation and maintenance of the nuclear power plant is not included in every energy analysis, see compilation of figures from other studies in Table 12.

The value given by SRI 1975 is very low, judging by the figures given by Rombough & Koen 1974, Rotty et al. 1975 and Perry et al. 1977. A number of analyses do not take the energy input of operation and maintenance into account.

Operation and maintenance costs during the active lifetime of PWR power plant are about 100 M$ a year [Blok & Hendriks 1989] Q21, or about 138 M$ in 2000. This is about 2.1% of the average construction cost (6.5 G$(2000)/GWe) a year, or about 2.6% per full-power year. [Rotty et al. 1975] Q95 used the value of 3.1% per year.
[Komanoff 1992] Q222 found a figure of 97 M$(1991) per year, about 122 M$(2000)/yr, for operation and maintenance of a 1 GWe plant. or 1.9% of the construction cost per year. At the moment of his study, the O&M costs were escalating at a rate of 4.7% per year, including inflation. Applying that rate, the O&M costs in 2000 would be about 147 M$(2000) per year in 2000, or 2.26% of the average construction costs. Assuming a load factor of 0.82, the O&M costs are about 2.8% of the average construction costs per full-power year (FPY), slightly lower than the value from Rotty et al. 1975.
The average fixed O&M costs (excluding refurbishments) in the USA were 17.2 $/MWh [Thomas 2005] Q328 and [Thomas et al. 2007] Q347, or about 150 M$/GWe.a, 2.3% per FPY. In the UK the reported O&M costs were almost three times as high.
[MIT 2003] Q280]reported fixed O&M costs in 1993 of 96 $/kW/yr with an escalation rate of 1% a year. This corresponds with some 149 M$(2000)/GWe.a, at an assumed load factor of 0.82, or 2.3% per year.
The study [Ecoinvent 2003] Q333 lists a large number of chemicals and auxiliary materials needed to operate a nuclear reactor, with a total mass of some 4000 Mg each year. This would correspond with 0.4% of the construction mass each year. The Ecoinvent study did not perform an energy analysis of these materials.

Table 12

Some estimates of energy requirements of operation, maintenance and refurbishments (OMR)

reference	Q	J_{prim} PJ	$J_{th} + J_e$ PJ	R J_{th} / J_e
Franklin et al.1971	Q111	n.a.	–	–
Rombough & Koen1974	Q96	–	0.141 /yr	7.31
Rotty etal.1975	Q95	–	0.332 /yr	9.77
Perry et al.1977	Q114	–	0.441 /GWe.a	9.73
SRI 1975	Q110	0.0083 /yr (5)	–	–
Kolb et al.1975	Q144	n.a.	–	–
Chapman 1975	Q113	n.a.	–	–
ERDA-76-1 1976	Q109	–	20.80 (1)	11.52
Mortimer 1977	Q98	n.a.	–	–
Held et al.1977	Q117	n.a.	–	–
Lako 1995	Q23-7	n.a.	–	–
Orita 1995	Q23-14	n.a.	–	–
White 1998	Q299	–	0.2406 /GWe.a	12.3
Uchiyama 2002	Q23-1, Q205	–	1.004 /yr	0.27
Vattenfall 2005	Q152, Q309	0.083 /yr (2)	–	–
WNA 2007	Q155	–	0.730 /GWe.a (3)	11.52
ISA 2006	Q325	–	1.008 /GWe.a	27
this study 2007		–	3.44 /GWe.a (4)	4.8

n.a. Not available: not included in the analysis.

(1) Construction + operation. Figures from Rotty et al. 1975, valid for operational lifetime of T_{100} = 18.67 FPY (full-power year). Apparently WNA assumed an energy input of O&M of 0.730 PJ/FPY: see note (3). If so, 18.67 FPY would correspond with 13.63 PJ for omr. Consequently the energy input of construction only would be 20.80 – 13.63 = 7.17 PJ.

(2) 'Fuel', probably primary energy units.

(3) Construction + operation 24.69 PJ. Figures from ERDA-76-1 and so from Rotty et al. 1975, corrected for a longer operating lifetime: T_{100} = 24 FPY. The difference of 5.33 FPY corresponds with 24.69–20.80 = 3.89 PJ. This points to an energy input of 0.730/GWe.a for operation and maintenance.

(4) Includes refurbishments during operational lifetime.

(5) 0.25 PJ for 30 years.

In addition, most plants need one or more large refurbishments during their active lifespan, for example: replacing steam generators, implementation of new, updated control systems and updated safety measures. These replacements and updates may cost about 20-80% of the original construction costs. Assumed that the mean refurbishment costs are 50% of the mean construction costs and are to be spent over an operating period of 25 full-power years (30 reload periods), the annual refurbishment cost are about 2% of the mean construction costs per full-power year.

Only a few reactors in de world reached an operational lifetime of 24 FPY today. Extensive refurbishments are required to reach even this lifetime, corresponding with an age of some 40 years. Extension of the operational lifetime beyond 25 FPY might require even more replacements: most parts of the nuclear power

plants have to be replaced, except the reactor vessel. The reliability of the reactor vessel determines the operational lifetime of a NPP. The quality of the vessel deteriorates over time by corrosion and neutron capture.
It seems plausible to assume the refurbishment efforts will remain about constant, on the average, throughout the operational lifetime of a nuclear power plant, regardless the length of the operational lifetime. Consequently we assume the refurbishment cost will remain 2% of the construction cost, independently of the operational lifetime.

If operation, maintenance and refurbishments together are taken as an average economic activity in de sector new construction, which may be an underestimate, the total energy requirements of this part of the nuclear chain can be approximated at 4.3% of the mean construction energy requirements per full-power year.

J_{omr} = 0.043•80 = 3.44 PJ/GWe.a R = 4.8   eq 17

Per reload period, D = 0.82 FPY, equivalent to 1 calender year at a load factor of 0.82, the operational energy input is:

J_{omr} = 0.82•3.44 = 2.82 PJ/D R = 4.8   eq 18

The value of equation F.18 is used throughout this study.

The specific energy consumption of OMR corresponds with a specific CO_2 emission of:

$\gamma(CO_2)$ = 6.92 $GgCO_2$/PJ = 24.5 gCO_2/kWh   eq 19

A few previous studies include the energy requirements for operation and maintenance, albeit accounting for only the direct energy inputs. No other study included refurbishments each NPP has to undergo. This study does include direct plus indirect energy inputs and refurbishments. A matter of system boundaries.

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