Nuclear energy economics in India[1]

M.V. Ramana
Centre for Interdisciplinary Studies in Environment and Development (CISED)
Institute for Social and Economic Change Campus, Nagarabhavi, Bangalore-560 072, India
E-mail: ramana@isec.ac.in

Antonette D'Sa and Amulya K.N. Reddy
International Energy Initiative, 25/5, Borebank Road, Benson Town, Bangalore-560 046, India

Using a discounted cash flow methodology, we have performed a detailed analysis of the current costs of electricity from two Indian nuclear reactors. We compare these costs to that from a recently constructed coal-based thermal power plant of similar size. Our results show that for realistic values of the discount rate, electricity from coal-based thermal power stations is cheaper than nuclear energy.

1. Introduction

Nuclear energy has had a long history in India. The Atomic Energy Commission was set up in 1948, barely a few months after the country became independent after two centuries of British colonialism. A few years later, in 1954 the Department of Atomic Energy (DAE) was formed under the direct charge of the Prime Minister, thereby circumventing many standard procurement and funding procedures. Ever since its inception, the DAE has made confident predictions that atomic energy would play an important role in satisfying India's energy needs, but the actual growth of nuclear power in the country has been extremely modest. In April 2005, the total installed nuclear power generation capacity was 2,770 MW, less than 3 % of the total installed electricity generation capacity of over 115,000 MW in the country[2].

The promise offered by the DAE is not only that nuclear power would form an important component of India's electricity supply, but that it would be cheap. As early as 1958, Homi Bhabha, the chief architect of the programme, projected "the contribution of atomic energy to the power production in India during the next 10 to 15 years" and concluded that "the costs of [nuclear] power [would] compare *very favourably* with the cost of power from conventional sources in many areas" (emphases added) [Bhabha and Prasad, 1958]. The "many areas" referred to regions that were remote from coal-fields. In the 1980s the DAE stated that the cost of nuclear power "compares quite favourably with coal-fired stations located 800 km away from the pithead and in the 1990s would be even cheaper than coal-fired stations at pithead" [Srinivasan, 1985b]. This projection was not realised. A more recent Nuclear Power Corporation (NPC) internal study comes to the less optimistic conclusion that the "cost of nuclear electricity generation in India remains competitive with thermal [electricity] for plants located about 1,200 km away from coal pit head, when full credit is given to long term operating cost especially in respect of fuel prices"[3].

Despite its inability to live up to its promises, the DAE has always received high levels of financial support from the government. In the late 1950s, over a quarter of all resources devoted to science and technology development in the country went to the Department of Atomic Energy [Abraham, 1993]. Though it was subsequently overtaken by the Department of Space, the total amount spent on the Department of Atomic Energy, the Defence Research and Development Organisation, and the Department of Space has been increasing as a fraction of all government research and development budgets. In the late 1980s, for example, the proportion was over 60 % of the total. With the nuclear weapon tests conducted in 1998, the DAE's funding has increased dramatically over the last few years (see Table 1)[4]. This government support has once again revived the hopes of the DAE for large-scale expansion; the DAE envisions having a total installed capacity of 20,000 MW of nuclear power by the year 2020 [Joseph, 1999]. The largest component of this would be in the form of pressurised heavy water reactors (PHWR) [Chidambaram, 2001][5].

This expected increase in nuclear power capacity, in particular the focus on PHWRs, makes an assessment of the economics of electricity generation in these reactors particularly relevant and urgent. Over a decade ago, a comparison of energy technologies had concluded that other options such as coal and hydroelectric power were cheaper than nuclear power under realistic assumptions and "even if the projections and scenarios indicate large demand-supply gaps in the future, the most expensive way of bridging these gaps is through nuclear power plants" [Reddy et al., 1990].

The major problem in making independent estimates of the cost of nuclear energy has been the difficulty in getting economic and performance data from the DAE. Like nuclear establishments elsewhere, the DAE has had a history of secrecy [Ramana, 2005]. The present study was undertaken with the hope that over the last decade more information on the expenditures actually incurred would

Table 1. Government outlay for DAE (in millions of rupees)

	1997-1998	1998-1999	1999-2000	2000-2001	2001-2002	2002-2003	2003-2004	2004-2005	2005-2006
Budget estimate	18,365.3	26,080.6	29,620.1	27,505.7	27,793.9	38,689.5	38,000.9	44,699.7	49,958.6
Revised budget	19,963.3	24,181.2	26,820.4	27,452.1	27,685.9	33,516.9	37,387.7	42,404.6	

Source: Government of India budgets 1998-2005 (Plan + Non-plan expenditure)

Table 2. GDP deflator data for India (base year 1993)

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Deflator	36.1	38.9	42.3	45.5	48.7	52.0	56.8	61.6	66.7	73.7	83.9
Year	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Deflator	91.3	100.0	109.7	119.5	128.2	136.5	147.3	153.0	159.9	165.4	172.0

Source: The World Bank database (available on the Internet to subscribers)

have become publicly available, allowing a better and more reliable estimate of the costs of electricity generated in recently constructed and proposed reactors. This hope has been only partially realized. While the total expenditure on various reactors is available, details about operational and maintenance expenditure, the cost of producing heavy water, and so on are not available in the public domain. Nevertheless, using the available current information, and making reasonable assumptions or extrapolations from other countries, we have calculated the "busbar" cost of generating electricity (i.e., not including transmission and distribution costs) that is delivered to the grid (i.e., taking auxiliary or in-plant consumption of electricity into account)[6].

In order to assess the economics of nuclear power, one has to weigh these costs against the corresponding costs of generating power through some roughly comparable technology. For this purpose we follow the DAE's analyses and choose coal-based thermal power plants, which constitute 58 % of India's generation capacity [CEA, 2003]. Like nuclear reactors, these provide base-load electricity.

2. Methodology

We use the discounted cash flow (DCF) approach that is widely used in investment analysis [Brealey and Myers, 2000]. This has been applied to earlier studies of the costs of nuclear power [Reddy et al., 1990], but we have fine-tuned it for this study by taking into account many of the sub-processes involved in nuclear power production.

We will express all costs in 2002 (fixed year) rupees. Our results will therefore be in terms of real discount rates rather than nominal rates. However, the two are equivalent. To convert costs from one year to another, we use the ratio of GDP deflators for the respective years as specified by the World Bank[7]. These are listed for the 22 years from 1981 to 2002 in Table 2.

The cost of generating electricity consists of three main components: the capital cost of constructing the generating facility, the annual fuelling and operations and maintenance (O&M) costs, which must be incurred as long as the facility is running, and the waste management expenses from the running of the facility in an environmentally acceptable manner. One other component in the case of nuclear power is that of decommissioning the reactors. Though this is an expensive process, its discounted cost will be small because it is done only many years into the future. In mathematical terms:

$$PV\,(costs) = \sum_{l=-M}^{0} \frac{C_l}{(1+i)^l} + \sum_{k=1}^{N} \left[\frac{(O_k + F_k)}{(1+i)^k} \right] + \sum_{j=P+1}^{N+P+1} \frac{W_j}{(1+i)^j} + \sum_{q=N}^{N+T} \frac{D_q}{(1+i)^q}$$

where C_l = capital cost in year l; M = total number of years of construction before reactors becomes commercial; i = real discount rate; N = number of years of operation; O_k = operations and maintenance (O&M) cost in year k of operation; F_k = fuel cost in year k of operation; W_j = waste disposal cost in year j; P = cooling time for spent fuel; D_q = decommissioning cost in year q; T = number of years after completion of operations before decommissioning is expected to take place. Note that in the first term on the right-hand side of the equation, all of the exponents in the denominator are non-positive since the index runs from –M to 0.

The present value of the revenue generated by selling electricity is given by

$$PV\,(revenues) = C_e \sum_{k=1}^{N} \frac{E_k}{(1+i)^k}$$

where C_e = levelised cost per kilowatt hour (kWh), and E_k = energy in kWh generated in year k.

When calculating the price of electricity from a power plant that is yet to be constructed, it is normal to assume that annual energy production is constant. It is also assumed that the O&M, fuel, and waste management costs will increase because of inflation, but are constant in real terms. Since we will be working in fixed year rupees, they will be constant in our calculations.

We will find that the results of our analysis depend sensitively on the discount rate used. There is no consensus on what this rate should be since it is an expression of how planners wish to allocate resources and how they value future benefits in comparison with current sacrifices. Indian official bodies such as the Central Electricity Authority (CEA) and the Planning Commission (PC) have been using a 12 % discount rate in their calculations for planning and evaluation of projects [Bose, 2000]. However, this is a nominal discount rate and translates to a real discount rate of about 7-6 % at the prevalent 5-6 % inflation rates. Our calculations will use a real discount rate, which we vary in order to test the results.

3. Capital costs

The largest component of the cost of producing electricity in the case of nuclear reactors is the capital cost of the reactor. Operating costs typically constitute only a small part of the cost of generating electricity in nuclear reactors. The capital cost consists of the construction cost and the costs of the initial loading of fuel and heavy water. Within the DCF methodology, one does not include the interest during construction (IDC) that is often mentioned as part of the cost of reactors, since interest results from the need to borrow money and is not relevant when comparing alternative investments[8]. Inclusion of the interest component would make nuclear power projects more unattractive since they are capital-intensive and take longer to construct; hence, this assumption is favourable to nuclear power.

Capital costs can vary considerably. We consider two specific cases, one set of two reactors already commissioned, and another set being constructed[9]. In the first case, we use the actual costs of the two 220 MW reactors at Kaiga Nuclear Power Station (Kaiga I & II) that were commissioned in 1999. Along with the RAPS III & IV reactors, these are the newest reactors; thus, one expects that these would have incorporated the lessons of the DAE's experiences with earlier reactors and also be indicative of the future as far as similar reactors are concerned. In the second, we use the projected costs of the two 220 MW reactors at the same site (Kaiga III & IV) that are scheduled to be commissioned in December 2006 and 2007.

3.1. Construction costs

The initial cost estimate of Kaiga I & II, which were originally scheduled to be completed in 1994 [Srinivasan, 1985a, reprinted in Srinivasan, 1990, pp. 127-137], was Rs. 7.3072 billion [DAE, 1996, p. 67]. However, these plants became critical only in 1999[10]. At the time of criticality, the cost of the project was estimated at Rs 28.96 billion [DAE, 1996, pg. 67][11]. The year-wise expenditure on the project is given in Table 3. In our calculations, we convert the expenditure for each year to 2002 rupees using the ratio of GDP deflators in Table 2.

One reason for the long delay and cost overrun in the case of the Kaiga I and II reactors was that the containment dome – the structure that is supposed to prevent the escape of radioactivity into the environment, should an accident occur – of one of the units collapsed in May 1994[12]. But all the reactors built by the DAE have had cost overruns (see Table 4).

Cost increases, though not of such a large magnitude, have occurred with nuclear reactors in other countries as well[13]. There is, therefore, the strong likelihood that capital costs are likely to increase. Despite this, in order to be favourable to nuclear power in our calculations, we will use the stated estimated costs for the reactors under construction.

The financial sanction for Kaiga III and IV, the reactors being constructed at the same site as Kaiga I and II, is Rs. 42.13 billion, including an IDC component of Rs. 5.34 billion, or about 12.7 % of the total [DAE, 2002b, p. 94]. Later reports suggest that the NPC expects a shorter gestation time and has lowered the estimated cost to Rs. 32.82 billion [Lal, 2002]. The reduction of the estimated costs is due not only to lower gestation times but also to a reduction in the prevailing rates of inflation and interest, and government concessions given to mega-projects [DAE, 2002a]. It is not clear how much of the estimated cost is IDC. In line with the earlier DAE [2002b] estimate, we will assume that IDC constitutes 12.7 % of the total cost, or Rs. 4.16 billion.

Plant excavation work for these reactors started in March 2001 and they are scheduled to become critical in 2006 and 2007 respectively [NPC, 2004a]. However, advance procurement for these reactors began as early as 1990-91 [DAE, 1991, p. 1.4]. Up to March 2000, Rs. 3.9405 billion had been spent on the project [DAE, 2002b, p. 94]. Once again, we assume that 12.7 % of this constitutes IDC. We also assume that the expenditure was uniform over these years. For the remaining period and amount we assume a different pattern of annual expenditure, shown in Table 5, expecting shorter construction times. This follows the pattern of expenditure for Canadian PHWRs [NEA, 1998, p. 60].

3.2. Heavy water inventory costs

Heavy water (HW) reactors, as the name suggests, require heavy water – water with the hydrogen replaced by deuterium, a heavier isotope of hydrogen (atomic weight 2). The HW is used both as moderator (to slow down neutrons emitted during fission so that they have a higher probability of being captured by other fissile nuclei) and as coolant (to carry away the heat produced).

The initial coolant and moderator inventory requirements for each 220 MW PHWR are 70 and 140 tonnes (t) of HW respectively [NEI, 1994]. The NPC reportedly treats the initial HW requirements as a non-depreciating asset and calculates lease charges at 8 % per annum to be paid to the DAE [Muralidharan, 1988]. Within the DCF methodology, the correct way to include the cost is to treat the initial HW inventory as an up-front capital cost. However, at the end of the economic lifetime of the reactor when the ("leased") HW is returned to the DAE, there is a cash inflow, which must be discounted to the time of commissioning.

There are practically no public figures available for the amount of HW produced in the DAE's heavy water plants (HWPs). The DAE annual performance budgets list, for example, the annual electricity production at various reactors; however, they conspicuously avoid giving any numbers for HW production. In the past, the DAE has claimed that because of its strategic value, it would not disclose the production levels.

What little information is available is suggestive of

Table 3. Expenditure pattern (without IDC) for construction of Kaiga I & II

Year	**1983-84**	**1984-85**	**1985-86**	**1986-87**	**1987-88**	**1988-89**	**1989-90**	**1990-91**	**1991-92**
Base cost (Rs. million)	34.5	79.5	153.3	265.2	144.2	353.1	651.2	1186.2	1495.3
Year	**1992-93**	**1993-94**	**1994-95**	**1995-96**	**1996-97**	**1997-98**	**1998-99**	**1999-2000**	**2000-01**
Base cost (Rs. million)	1377.6	2078.3	1866.0	1850.5	1718.7	1348.3	1139.6	1778.5	640.1

Source: DAE, 2002b

Nlote

1. At the current exchange rate, US$ 1 is about Rs. 44.

Table 4. Capital costs of operating reactors

Station	**Capacity (MW)**	**Original cost (Rs, million)**	**Revised cost (Rs. million)**	**Criticality year**
TAPS I & II	2 × 160	929.9	-	1969
RAPS I	1 × 100[1]	339.5	732.7	1972
RAPS II	1 × 200	581.6	1025.4	1980
MAPS I	1 × 220	617.8	1188.3	1983
MAPS II	1 × 220	706.3	1270.4	1985
NAPS I & II	2 × 220	2098.9	7450[2]	1989 & 1991
Kakrapar I & II	2 × 220	3825	13,350	1992 & 1995
Kaiga I & II	2 × 220	7307.2	28,960	1999 & 2000
RAPS III & IV	2 × 220	7115.7	25,110	2000

Sources: DAE, 1996, p. 67; DAE, 2002b

Notes

1. This was derated from 200 MW.
2. The revised cost estimates for NAPS, Kakrapar & Kaiga include interest during construction.

Table 5. Expenditure pattern assumed for Kaiga III and IV

Year (Y_0 = commissioning year)	Y_0-5	Y_0-4	Y_0-3	Y_0-2	Y_0-1	Y_0
Fraction spent (%)	1.9	9.7	20.2	30.9	27.3	10

Source: [NEA, 1998]

poor performance. In 1992, *The Times of India* reported that only 273 t of HW were produced in all the HWPs put together [Fernandez, 1992], implying an average capacity factor of about 50 %. The Comptroller and Auditor General (CAG) of India's report for 1988 said the "Tuticorin [heavy water] plant produced 20.6 % of the installed capacity in the last eight years" (i.e., between July 1978 and March 1986). The best production was 42.7 % of the design capacity. The plant has "been able to operate on an average for about 150 days ... per annum" and "the consumption of spares and maintenance cost was high and Rs. 190 lakhs [19 million] had been spent per annum on an average" [CAG, 1988].

The performance of HWPs appears to have improved; in 1998, 100 t of HW were exported to South Korea [Anon., 1997][14]. In part, this surplus availability of HW is because the expected growth in nuclear power did not take place. Even in recent years, however, a number of plants have had prolonged outages. The Talcher plant, in particular, has been suspended for many years since the associated fertilizer plant has not been operating satisfactorily [DAE, 2000, pp. 24-25]. Similarly, during 2002-03 the plant at Tuticorin was affected by frequent outages of the connected fertiliser plant [DAE, 2003, p. 5]. The Thal plant had extended outages in 1998-99, whereas the Hazira and Kota plants had prolonged outages in 1997-98 [DAE, 2000, p. 24; DAE, 1999, p. 20]. Consequently in both years, the total production target for HW was not met.

The cost of HW produced in the DAE's plants has been a matter of dispute. For example, in 1983 the AEC quoted a price of Rs. 3,875/kg whereas the CAG calculated that it should be Rs. 13,800/kg [Reddy, 1990]. Since these estimates relied on the earlier plants, and newer plants appear to be performing better, we look at the case of the most recently commissioned HWP at Manuguru.

Sanctioned in 1982, the Manuguru HWP has an annual capacity of 185 t of HW. The estimated cost of the Manuguru HWP when it was sanctioned was Rs. 4.216 billion. In 1989, the plant cost was revised to Rs. 6.6158 billion. The plant finally started production in December 1991 [CAG, 1994]. According to the CAG, the "total capital cost including interest during construction and excluding cost of spares came to Rs. 983.38 crores [9.8338 billion] and the increase, with reference to the original estimated cost ... was ... 133 percent." When questioned about the cost escalation, DAE stated that "the grounds for sanction of this project was strategic and not commercial".

The DAE's initial estimate of the cost of production was Rs. 5,176 per kg of HW (Rs./kgHW). However, because of slippages in the project schedules and consequential delay in commencement of production, the cost of HW worked out to Rs. 7,529/kgHW as of February 1986 [CAG, 1994]. This translates to about Rs. 24,880/kgHW at 2002 prices, in the same ball-park as the 1983 figure of Rs. 6,635/kgHW (Rs. 26,960/kgHW when inflated to 2002 prices) cited by the then head of the DAE [Ramanna, 1985]. However, in its 1994 report on Manuguru, the CAG pointed out "Due to further escalation, the cost would have gone up further – the figures for costing after commencement of production in December 1991 were not produced to Audit (December 1993)." There appear to be no further public estimates of the cost of the project. In line with our attempts to be favourable to nuclear power in our estimates, we will use the figure of Rs. 24,880/kgHW.

One can understand the rather high cost of HW from not only the high capital costs but also the extreme energy intensity of the processes involved in producing it. Therefore, over the last few years, the DAE has been trying to implement energy efficiency measures. According to the DAE, during the period 2001-2002, energy consumption was reduced by about 6 %, thereby effecting savings of around Rs. 850 million [Anon., 2002][15]. Therefore, the total energy consumption bill was Rs. 14.1667 billion. Excluding the Talcher plant where operations have been suspended, the total production capacity of all HW plants at that time was about 490 t/annum. Even assuming an optimistic 80 % capacity factor, the energy cost of producing one unit of heavy water is Rs. 18,070/kgHW. Therefore, a total cost of Rs. 24,880/kgHW is quite plausible.

When calculating the cost of the initial loading of HW, one small but pertinent detail is that there is usually a period of about 6 months or more between the reactor becoming critical and starting commercial operations. For example, Kaiga II became critical on September 24, 1999 but started operating commercially only on March 16, 2000 [Anon., 1999b; NPC, 2004b]. The reactor is loaded with fuel and HW well before criticality. We shall assume that the total time between loading with HW and uranium and the reactor producing electricity commercially is 6 months. Therefore, just as there is a credit for the HW returned at the end of the reactor life, there will be an additional component in the initial capital cost.

3.3. Uranium fuel inventory

Another component of expenditure in setting up a nuclear reactor is the initial uranium loading. A 220 MW reactor uses 3,672 fuel assemblies, each containing 15.2 kg of uranium oxide. The cost of each assembly is reported to be Rs. 250,000 [Subramanian, 2002b][16]. This translates to Rs. 16,450/kg of uranium fuel. This is comparable to, but less than, the 1983 price of Rs. 4,545 per kg of uranium fuel cited by the then head of the DAE, when translated to 2002 rupees [Ramanna, 1985].

The NPC obtains its fuel from the Nuclear Fuel Complex. Rather than pay the production costs plus a reasonable rate of return, the fuel is reportedly "hired" at an administrative price set by the DAE [Wood, 1991]. However, the true cost of nuclear electricity must include this cost. A 1985 paper by the DAE suggests that 50 % of the cost of initial uranium fuel-loading is already included in the capital cost estimates [Srinivasan, 1985a, reprinted in Srinivasan, 1990, pp. 127-137]. Even assuming this to be true, within the DCF methodology we have used, the remaining 50 % of the cost has to be included as part of the initial capital costs. Again, because of the assumed six-month period between fuel-loading and the commercial delivery of electricity, there is an additional component to the fuel cost.

We shall also assume that the nuclear plant stores about 1.5 months worth of uranium (at the assumed capacity factor) and HW (to account for expected losses) and incorporate this as a capital cost[17].

3.4. Decommissioning costs

Within the DCF methodology, the cost of decommissioning a reactor, which is done at the end of its economic life and a long period of cooling, which we assume to be 40 years, should be incorporated as a capital expense. While there is little experience with actually decommissioning nuclear reactors and how much it costs, agencies that promote nuclear energy typically assume that decommissioning would cost between 9-15 % of the initial capital cost of a nuclear power plant [UIC, 2001]. There are other estimates. The US Nuclear Regulatory Commission estimates the cost of decommissioning nuclear reactors to be about $ 300-450 million [NRC, 2004]. Since the typical US nuclear reactor costs about $ 1,500/kW and has a capacity of 1,000 MW, this is equivalent to 20-30 % of capital costs or $ 300-450 per kW. On the higher side, decommissioning the 1,240 MW Superphenix is estimated to cost $ 4,000 per kW.

Though based on some limited experience, the numbers cited above are only estimates. Actual experiences have often been significantly more expensive. Decommissioning the 100 MW Niederaibach HW reactor cost $ 1,910 per kW while the 45 MW Japan Power Demonstration boiling water reactor cost $ 3,180 per kW [WISE, 1998].

Nevertheless, in order to be favourable to nuclear power in our estimates, we will assume that decommissioning expenses are 10 % of the initial capital cost. Decommissioning is usually divided into three stages

Table 6. RAPS-I heavy water escape and losses

Year	Escape (kg/day)	Loss (kg/day)	Annual loss (t)
1972	135	31	11.3
1973	197	69	25.2
1974	249	57	20.8
1975	386	77	28.1

Source: [Srinivasan, 1990, p. 24].

[Saddington, 1983]. In rough correspondence with these stages, we assume that 40 % of the decommissioning expenses occur when the reactor is shut down at the end of its economic life, another 20 % at 20 years following shutdown, and the remaining 40 %, 40 years after shutdown.

As mentioned earlier, there is no consensus on what discount rate should be chosen for calculations of economics of electricity generation. This debate is most intense when it comes to costs that are borne by future generations[18]. Choosing a high discount rate would mean that future expenditures are given very little weight in economic calculations. Some economists have proposed that in the interests of inter-generational equity, such activities should be valued at a zero or a very low discount rate [Howarth and Norgaard, 1993]. One suggested approach is to use two discount rates, one for the near-term expenditures and one for long-term expenditures. For example, the Charpin report on the future of nuclear energy in France chooses a 6 % discount rate for expenses in the first 30 years and a 3 % discount rate for expenditures thereafter [Charpin et al., 2000]. Decommissioning expenses would fall in the latter category. For simplicity and in order to be favourable to nuclear power, we choose the same discount rate for all expenditures, which, as mentioned earlier, is varied in our calculations.

4. Recurring costs

4.1. Fuel-loading costs

The amount of fuel needed to produce a unit of electric power is given by the formula:

$$\text{Fuel used} = \text{Electrical power generated} / ((\text{thermal efficiency}) \times (\text{burnup}))$$

The thermal efficiency is the electricity generated per unit thermal power output. The burn-up is the heat liberated per unit mass of fuel irradiated; it depends on the reactor type, the fuel used (level of uranium enrichment), and fuelling practices. In the case of the PHWRs we are considering, the average burn-up is 7,000 MWD/tU (megawatt-day per tonne of Uranium) [Hibbs, 1997a; Changrani et al., 1998]. The thermal efficiency for PHWRs is taken to be the design efficiency of 0.29 [Balakrishnan, 1999]. In terms of gross generation, the uranium utilisation is 20.5 mg/kWh (milligram per kilowatt-hour).

4.2. Heavy water make-up costs

There are also routine losses of heavy water in PHWRs. This is due to many reasons. For example, during the initial years at the Rajasthan Atomic Power Station, there were several failures involving heat-exchangers [Ghosh, 1996]. These have HW on one side and cooling water on the other. Thus, when they fail, the HW could get mixed with cooling water and escape. There have also been a number of HW leaks and spills – just in 1997, such leaks occurred at the Kakrapar I, MAPS II and Narora II reactors [IAEA, 1998, pp. 301-320]. Such leaks could occur because of various causes. For example, on 15 April 2000, vibration caused the failure of a gasket in the moderator system piping of the Narora II reactor and 7 tonnes of HW leaked out [AERB, 2001, p. 13].

Typically some of the HW that is spilt or has otherwise escaped is collected, purified and reused but the rest is discharged into the atmosphere. This creates a radiation hazard to workers and potentially the general public because of the build-up of tritium (the isotope of hydrogen with atomic weight 3) in the HW [Ramana, 1999][19].

In the early years of RAPS-I operations, routine escape and losses were fairly high (Table 6). These have since reduced. In the eighties, the DAE estimated that the annual HW make-up requirement for two 235 MW reactors (subsequently de-rated to 220 MW) was 16 t/year [Ramanna, 1985]. More recently, the first Managing Director of the Nuclear Power Corporation stated that the annual make-up of HW in a 220 MW reactor is 7 t/year [Kati, 2003, p. 39]. Another report mentions that average HW losses for the Kakrapar reactors were "between 500 and 600 kg/month", or about 6 to 7.2 t/year [Hibbs, 1997b]. We shall assume that each 220 MW reactor loses 7 t/year.

4.3. Operations and maintenance (O&M) cost

Operating and maintaining a nuclear power plant involves a number of expenses including paying the many trained professionals needed to run the plant, materials for maintenance, site monitoring, operating waste management facilities, collecting and purifying heavy water that escapes, and so on. Once again there is little data available publicly. We shall assume that this is 2 % of the capital cost.

4.4. Waste management

The problem of dealing with radioactive nuclear wastes has been one of the most contentious aspects of nuclear power programmes around the world [NEA, 1996; Berkhout, 1991]. Since some of these wastes are extremely long-lived, their generation represents a burden to future generations who will not utilize the electricity produced in these nuclear reactors but may have to undertake measures to ensure that these radioactive materials do not enter their food chain, water resources, and so on. Any attempt at quantifying the costs involved is bound to have enormous uncertainties. Nevertheless, the approach used by nuclear power advocates has been to use the cost of setting up a structure that is expected to contain the radioactive materials within it for a long period of time as the cost of waste management. Despite the controversies involved, we shall follow this approach.

Most of the radioactivity generated is contained in the spent fuel, i.e., fuel after irradiation in nuclear reactors. Besides this, large quantities of low-level solid and liquid wastes are also produced during reactor operation and maintenance[20]. These are largely treated on-site and we shall assume that the expenses incurred therein are included in the O&M costs.

Countries around the world have adopted one of two approaches to deal with the highly radioactive spent fuel. In the first, the spent fuel is "directly disposed of" by first keeping it in intermediate storage and eventually storing it in geological repositories. The other approach is to "reprocess" the spent fuel to extract plutonium and the unused uranium, and concentrate the most highly radioactive components in the spent fuel into liquid "high-level waste". Though controversies remain, it is generally accepted that direct disposal is the cheaper method of dealing with nuclear wastes at current uranium prices on the international market [Berkhout, 1997; NEA, 1994; Bunn et al., 2003]. At current uranium prices, Bunn et al. [2003] estimate that reprocessing adds "more than an 80 % increase in the costs attributable to spent fuel management (after taking account of appropriate credits or charges for recovered plutonium and uranium from reprocessing)" and the difference in costs "is likely to persist for many decades."

The DAE has adopted the more expensive route of reprocessing to deal with spent fuel. The rationale offered for this choice has been the three-stage programme envisioned by the DAE. The first stage involves the use of uranium fuel in PHWRs, the second stage involves fast breeder reactors that use plutonium from reprocessed spent fuel from PHWRs and thorium to produce uranium-233, and the third stage involves reactors using uranium-233 and thorium [Kakodkar, 2000]. Since the second stage of the programme requires plutonium, reprocessing is needed to proceed with this programme. This requirement is used by the NPC to neglect the cost of waste disposal from PHWRs. In the NPC's analysis of the economics of PHWRs, "the cost of waste disposal has been assumed to have trade off with the amount of reprocessed fuel generated for next stage of nuclear power programme" [Nema, 1999].

Even if one were to follow the NPC's logic and assume that the hugely expensive infrastructure needed for reprocessing is a part of the second stage of the nuclear power programme, there is still the cost involved in dealing with the spent fuel before reprocessing. Because the spent fuel as it comes out of the reactor is highly radioactive and produces a lot of heat, it is initially kept under water for cooling. In India, this is done for a minimum of 430 days [Changrani et al., 1998]. In practice it may be more, even up to 5 to 10 years, which would increase the waste management costs at the nuclear power plant [Srinivasan, 1995]. Then it has to be shipped to the reprocessing plant[21]. Once again because of the high radiation levels (even after cooling), spent fuel shipping containers must be heavily shielded, and must be designed to stringent safety standards. For these reasons the cost of spent fuel shipping is not an insignificant component of the fuel cycle cost [Graves, 1979, p. 261]. The OECD's Nuclear Energy Agency quotes a price of $ 13/kg (1991 US dollars) for transporting spent fuel from PHWRs [NEA, 1994, p. 78]. Converting this to 2002 rupees, this is equivalent to Rs. 878/kg of spent fuel.

To estimate the cost of waste management, we shall assume that the spent fuel is simply handed over to the reprocessing plant and the only cost incurred as part of the fuel cycle of the PHWR is the cost of transportation. This assumption is favourable to nuclear power when calculating the electricity price from PHWRs. A fairer evaluation would attribute at least part of the reprocessing expenditures to the electricity generation costs at PHWRs. Preliminary estimates of the cost involved in reprocessing indicate that it is in the range of Rs. 10,000-20,000/kg of spent fuel depending on the efficiency of the plant [Ramana and Suchitra, forthcoming].

5. Performance

The cost of electricity depends on the efficiency, measured in terms of load factor or capacity factor, with which the generation facility operates. For long, the DAE's reactors were among the poorest performers in the world. In December 1994 *Nuclear Engineering International*, a standard trade journal, found that the average lifetime load factor for Indian reactors was 36.08 %, the lowest among the 18 countries with four or more nuclear reactors; only Brazil, with just one reactor, fared worse [Howles, 1995]. Four years later, this position was unchanged, with the lifetime average load factor still the lowest [Anon., 1999c]. However, the performance of the NPC's reactors has been improving over the last few years. This suggests that the NPC is over its teething problems. But it also reflects the recent dramatic increases in funding for the DAE (Table 1). Further, at the level of individual reactors, performance has remained erratic. For example, in 2002-2003, the Kakrapar-I reactor had a record 98 % capacity factor, but it decreased to 78 % in 2003-2004, and has deteriorated further in 2004-2005 [NPC, 2004c].

This improved performance of nuclear reactors must be balanced with two factors. The first is the fact that similar improvements in performance have also been noted in many other sources of power. The second is that with the commissioning of several reactors over the past few years – more than half of the currently installed capacity was commissioned during the 1990s – the average age of the reactor units is low. As these age, one would expect to see a deterioration of performance as well as increased costs to keep them running.

It is instructive, therefore, to look at the average lifetime load factors of the DAE's PHWRs (listed in Table 7). The average of these is 65.1 %. To accommodate the possibility of improved performance and to be favourable to nuclear power, we shall assume a capacity factor of 80 % as the base figure in our calculations. Such a high capacity factor partially offsets the capital-intensive nature of nuclear power.

Another aspect of plant performance is the amount of

Table 7. PHWR load factors till 2003

Station	Cumulative load factor (%)
RAPS I	23.31
RAPS II	52.65
MAPS I	52.82
MAPS II	52.92
NAPS I	60.62
NAPS II	67.82
Kakrapar I	70.91
Kakrapar II	84.14
Kaiga I	80.70
Kaiga II	80.91
RAPS III	77.98
RAPS IV	79.20

Source: PRIS (Power Reactor Information System) Database, International Atomic Energy Agency, available on the Internet at http://www.iaea.org

electricity consumed by the power plant itself. The official in-plant consumption for all electricity-generating plants is 7-8 % [NTPC, 2004; CSO, 1999]. However, looking at actual figures for gross generation and net exports at the DAE's nuclear reactors, the in-plant consumption figures are 13.4 %, 12.4 %, 11.5 %, 11.3 %, 12 %, 11.7 %, and 11.9 % for the years 1994-95, 1995-96, 1996-97, 1997-98, 1998-99, 1999-2000, and 2000-01 respectively [DAE, 1997, p. 10; DAE, 1998, p. 14; DAE, 1999, p. 12; DAE, 2000, p. 13; DAE, 2002b, p. 27]. We shall, therefore, assume 12 % for the in-plant consumption in the case of the Kaiga reactors.

6. Costs of coal power

For calculating the cost of producing electricity from coal, we chose the case of the Raichur VII Thermal Power Station (RTPS VII). Like the Kaiga I and II reactors, RTPS VII is also a relatively recent plant. It has a capacity of 210 MW, roughly the same as each of the Kaiga reactors, and is an example of multiple projects at the same location (just as Kaiga III and IV are co-located with Kaiga I and II). Being in the same geographical region, it feeds into the same grid and therefore faces roughly similar problems from grid instabilities.

The RTPS VII project was sanctioned on March 4, 1999 and the plant was synchronised to the grid on December 10, 2002; till March 2003, the total expenditure (not including IDC) came to Rs. 4.9133 billion [CEA, 2004a][22]. The annual expenditures during the four years 1999, 2000, 2001, and 2002 are assumed to be 10 %, 40 %, 40 %, and 10 % of the total. As with nuclear plants, we shall assume that the plant stores about 1.5 months' supply of coal and furnace oil and incorporate this into the capital cost.

O&M expenses at thermal plants are usually set at 2.5 % of the capital cost and we shall follow that practice [Mahalingam, 2001]. On the basis of actual generation data at the Raichur units [CEA, 2002], we use an auxiliary consumption rate of 8.5 %. We shall assume that the RTPS VII station has an economic lifetime of 30 years (as opposed to 40 years for the Kaiga reactors).

The main expense in producing electricity from thermal power stations is the fuel. The fuel cost depends on the amount of coal used to generate one unit of power. At the other Raichur stations (RTPS I to VI), the coal consumption for 2001-02 was 0.63 kg/kWh [CEA, 2002]. We assume the same consumption rate for RTPS VII.

The two primary qualities of coal that are of interest to thermal power plants are the calorific (energy) content and the proportion of ash. Inferior grade varieties of coal have lower calorific content and higher ash content. Since the quality of coal used varies from plant to plant and over time, we follow the Expert Committee on Fuels for Power Generation (ECFPG) and assume a standardized coal grade with calorific content of 3,750 kCal/kg [CEA, 2004b] (or about 15.7 MJ/kg). The basic cost of this grade of coal at the pithead including taxes, duties and royalty is estimated by the ECFPG to be Rs. 517/t; the distance from Raichur to the coal-producing regions of Eastern India is about 1200 km and the cost of freight for distances above 1,200 but below 1,500 km is Rs. 894.9/t [CEA, 2004b][23]. Thus, the effective cost of domestic coal at the Raichur plant works out to be about Rs. 1,412/t.

The corresponding cost for imported coal with calorific content of 22.6 MJ/kg at the port is about Rs. 1,925/t; the distance from Raichur to Mangalore port is about 450 km and the cost of freight for distances between 300 and 500 km is Rs. 251/t. Thus the effective cost of imported coal at the Raichur plant works out to about Rs. 2,175/t. With these figures, the levelised cost of electricity using imported coal is about Rs. 0.03/kWh higher than when using domestic coal.

Thermal plants also use furnace oil, whose consumption at the Raichur plant is about 2 ml/kWh. Its price is about Rs. 18 per litre (l) [NTPC, 2005].

All these prices are, of course, subject to market fluctuations and standard inflationary increases. In principle, the price of uranium would also be subject to similar changes[24]. We shall ignore the fluctuations since these should get averaged over the long lifetime of the plant. The inflationary increases are implicitly taken into consideration by working in fixed-year rupees.

Just as we included the cost of waste disposal in the case of nuclear power, here we include the cost of disposal of ash. Typical ash content in Indian coal is about 40 %, of which about 80 % is fly ash and the remaining 20 % is bottom ash [CPCB, 2000]. In 1999, the Ministry of Environment and Forests stipulated that all coal thermal power plants should utilize the fly ash generated for manufacturing bricks, road-laying, making embankments, in land-fills, and so on. The same notification also ordered brick manufacturers, public works departments, the National Highway Authority, and other agencies to use ash generated in coal plants. The ash is, at least initially, to

Table 8. Cost of making fly ash bricks

	Percentage I	Percentage II
Fly ash bricks cost differential (Rs. per 1000 bricks)	100	100
Volume per brick (cm^3)	1795.4	1795.4
Density of brick (kg/m^3)	1770	1770
Mass of 1000 bricks (kg)	3177.8	3177.8
Fly ash utilization in fly ash clay brick	0.25	0.25
Fly ash utilization in fly ash sand lime brick	0.6	0.6
Percentage of fly ash clay bricks as fraction of total fly ash-based bricks (assumed)	50	30
Percentage of fly ash sand lime brick (assumed)	50	70
Fly ash used in 1000 fly ash-based bricks (t)	1.35	1.57
Cost of fly ash utilization (Rs/t-flyash)	74.0	63.6
Transportation cost (Rs/km-t)	2	2
Assumed distance of transport to brick kiln (km)	50	50
Cost of fly ash utilization including transport costs (Rs/t)	174	163.6

be provided free of cost. However, there are definite savings for the end-users in terms of reduced requirements for various inputs[25].

In the case of the Raichur thermal plant, the fly ash generated is used for the manufacture of portland pozzolona cement (PPC) by the Associated Cement Companies Ltd., which has exclusive rights to collect fly ash free from three of the seven plants at that site [Giriprakash, 2001]. The use of fly ash for PPC manufacture lowers the costs of cement production because of reduced requirements for thermal and electrical energy, and lower consumption of clinker. Therefore in general PPC manufacturers have been willing to pay the costs of transporting the fly ash from thermal plants [Shah, 1999]. In some cases, they have even been willing to purchase the fly ash.

Rather than assuming the above, we chose to assume that the thermal plant internalizes the cost of disposing of the ash. To do this, we followed [Bhattacharjee and Kandpal, 2002a] and estimated the cost of using fly ash for brick manufacture. Using these numbers, and assuming the same figures for bottom ash as well, we estimate an ash disposal cost of not more than Rs. 174/t (Table 8).

At Rs. 174/t of ash, the disposal cost for coal with 40 % ash content is Rs. 0.05/kWh. It should be emphasized that this is costlier than current practice because it assumes that the power plant bears the cost for a more environmentally benign way of disposing of waste. This is also more expensive than using the ash for cement manufacture. However, in order to be favourable to nuclear power, we use this figure.

7. Results and comparison

We now compare the costs of nuclear power from the Kaiga I/II and Kaiga III/IV reactors and the cost of thermal electricity from RTPS VII using domestic coal. Table 9 summarizes the figures used in our calculations.

As mentioned earlier, the cost of electricity is calculated as a function of discount rate. We begin with the comparison for a (real) discount rate of 1 %. As seen in Table 10, the levelised cost of electricity from nuclear reactors is lower than the case of RTPS VII (using domestic coal). The cost of nuclear power is dominated by the capicity cost whereas that of thermal power is dominated by the fuel cost.

Since only the capacity cost varies with discount rate, for other values of the discount rate we only list the total levelised cost. These are listed in Table 11 and shown graphically in Figure 1. The last row in Table 11 lists levelised costs for a real discount rate of 6 %, which, as mentioned earlier, roughly corresponds to the discount rate assumed by the Planning Commission (PC) and the Central Electricity Authority (CEA).

The exact value of the discount rate (i.e., the crossover point) at which the cost of thermal power becomes cheaper than nuclear power from Kaiga I and II stations is about 2.33 % (levelised cost of Rs. 1.366). While there is debate on the appropriate discount rate for public investments, few would argue that 2.33 % is a high rate for long-term investments, especially in a country with multiple demands for capital. The crossover point determined by Reddy [1990] varied from 5 to 7.5 % (nominal discount rate).

As mentioned earlier, the utilisation of a power plant (expressed through the capacity factor) is a determinant of the price of electricity generated. Since nuclear power is capital-intensive, lower capacity factors would reduce its competitiveness. This is demonstrated in Table 12 which lists the crossover point in discount rates for three different capacity factors. If the capacity factor is only

Table 9. Figures used in calculations

	Kaiga I & II	Kaiga III & IV	RTPS VII
Sum of annual construction costs[1] (Rs billion)	18.16	28.6688	4.913
Power plant capacity (MW)	440	440	210
In-plant consumption (%)	12	12	8.5
Economic lifetime (years)	40	40	30
Uranium fuel price (Rs/kg)	16,450	16,450	
Initial uranium loading (t)	111.6	111.6	
Fraction of initial fuel cost included in capital cost	0.5	0.5	
Assumed burn-up (MWD/tU)	7,000	7,000	
Uranium utilization (kg/kWh (gross))	2.05×10^{-05}	2.05×10^{-05}	
Heavy water price (Rs/kg)	24,880	24,880	
Initial heavy water loading (t)	420	420	
Heavy water losses (kg/year)	14,000	14,000	
Transport of spent fuel (Rs/kg)	878	878	
Decommissioning cost (as percentage of capital cost)	10	10	
Coal cost (Rs/t)			1,412
Coal calorific content (MJ/kg)			14.7
Coal consumption (kg/kWh)			0.63
Coal ash fraction			40 %
Ash disposal cost (Rs/t)			174
Furnace oil consumption (ml/kWh)			2
Furnace oil cost (Rs/l)			18
O&M cost (percentage of capital cost)	2	2	2.5

Note

1. This is the sum of the actual expenditures incurred (or projected, in the case of Kaiga III & IV) and does not include interest during construction (IDC).

75 %, then nuclear power is cheaper than coal power only for discount rates lower than 1.7 %.

The crossover point also varies with the assumed lifetimes of the power plants. If one were to assume that the economic lifetime of the coal plant is the same as that of the nuclear plant, i.e., 40 years, the crossover point (at 80 % capacity factor) between Kaiga III and IV and RTPS VII becomes 2.01 %, and that between Kaiga I and II and RTPS VII becomes 2.06 %. As mentioned earlier, all of these crossover points are unrealistically low values. Therefore, for realistic values of discount rates, nuclear power from the Kaiga reactors is more expensive than electricity generated in RTPS VII.

8. Conclusions

Our primary goal in this paper was to calculate in detail, dealing exhaustively with many of the sub-processes involved and using updated data, the cost of producing electricity from the DAE's pressurized heavy water reactors. We have done so in a transparent manner laying out the methodology and assumptions explicitly. This allows for the possibility that it can be corrected, should better data become available; given the limited amount of data publicly available, this is quite likely.

Our analysis demonstrates that electricity from PHWRs is more expensive for real discount rates above about 2-3 %, under most reasonable assumptions. Such rates may not be realistic over the decades that these plants are to operate.

One criticism of this study has been that we have considered nuclear plants of smaller capacities, namely 220 MW, even though it is expected that electricity from larger capacity nuclear plants would be cheaper. And therefore, the argument goes, if one were to compare such larger sized plants, then electricity from nuclear reactors would be cheaper than electricity from similar sized coal-based thermal power plants. There are two problems with this argument. First, the experience of the last five decades of nuclear power suggests that early predictions of costs are frequently wrong. This is especially true in the case of the DAE. In all the reactors constructed so far, final cost figures have been higher than originally estimated[26].

Table 10. Levelised costs (in Rs/kWh) of different options for discount rate of 1 %, capacity factor of 80 %, economic lifetime of 40 years for nuclear reactors, 30 years for thermal plant

	Kaiga I & II	Kaiga III & IV	RTPS VII (D)
Capacity cost (including O&M) (Rs/kWh)	0.65	0.67	0.27
Heavy water make-up cost (Rs/net kWh)	0.13	0.13	0
Fuel cost (Rs/net kWh)	0.38	0.38	1.01
Waste disposal cost (Rs/net kWh)	0.02	0.02	0.05
Total levelised cost (Rs/kWh)	1.18	1.20	1.33

Table 11. Total levelised costs (in Rs/kWh) of different options for different discount rates, capacity factor of 80 %, economic lifetime of 40 years for reactors, 30 years for thermal plant

Discount rate (%)	Kaiga I & II	Kaiga III & IV	RTPS VII
2	1.32	1.32	1.36
2.5	1.39	1.39	1.37
3	1.48	1.46	1.39
4	1.66	1.62	1.42
5	1.87	1.79	1.45
6	2.10	1.98	1.49

Thus, without experience with actually constructed reactors at lower prices, any claims about their cost should be viewed with some scepticism.

Second, a fair comparison would also include the effects of cost-cutting measures at coal-based thermal plants, including both capital cost reductions and fuel cost reductions[27]. In this regard, RTPS VII can be counted as an example of a plant that has reduced capital costs and construction times successfully. However, this reduced capital cost does not make the comparison of Kaiga nuclear plants with RTPS VII an unfair one because its distance from coal mines is somewhat large, thereby increasing its fuel costs, which dominate the cost of producing electricity at thermal plants.

A different shortcoming of this study is that it does not take into account the costs imposed by both nuclear power and coal-based thermal power on the environment and public health. In particular, we have not imputed any economic costs to the air pollution resulting from coal-based thermal plants, though such pollution has gained in policy relevance with the heightened concern about global warming. We do realize that both of the sources of power that we have studied, and many others that we haven't considered, do pollute the environment, with the impacts of such pollution often being borne disproportionately by the disempowered sections of society. Currently the "costs" of such impacts are not reflected in the economic costs of these sources of power in India and elsewhere.

The inclusion of pollution costs is problematic, especially in the case of nuclear power. This is because the

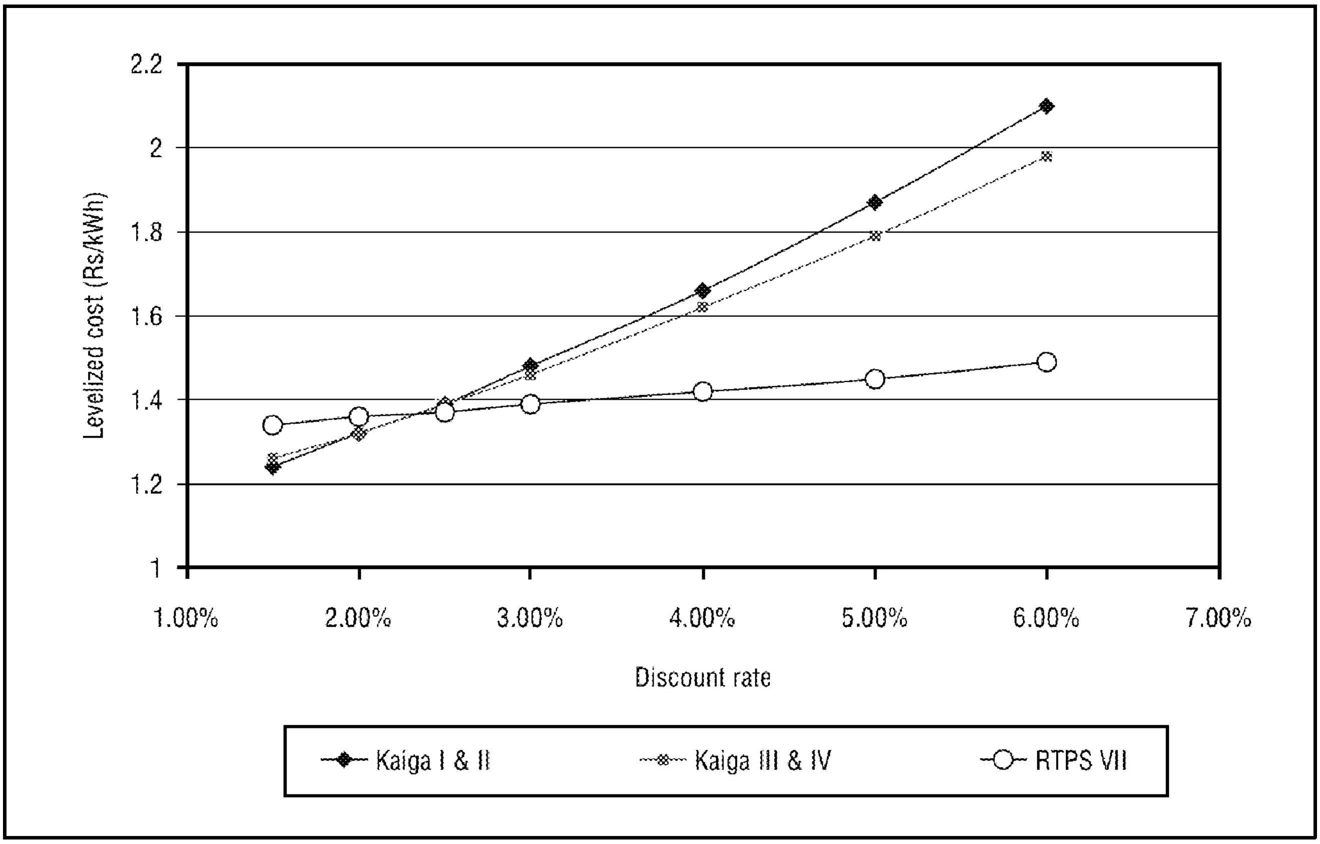

Figure 1. Levelized cost (Rs/kWh) vs. discount rate for Kaiga nuclear power plants and Raichur thermal plant VIIth stage

Table 12. Variation of crossover point with capacity factor

Capacity factor	75 %	80 %	85 %
Crossover point between Kaiga I & II and RTPS VII	2.0 %	2.33 %	2.65 %
Crossover point between Kaiga III & IV and RTPS VII	1.93 %	2.33 %	2.7 %

pollution externalities for nuclear power are difficult to quantify for many reasons. Two proximate ones are the scientific and political controversies surrounding the health impacts of low-level radiation and the lack of reliable data on radioactive emissions from nuclear facilities and the impossibility of independent verification of the scarce data available in the Indian context [Ramana and Gadekar, 2003]. Finally, unlike carbon dioxide, which has substantial sinks in the terrestrial and marine ecosystems, there is no way to render radioactive materials benign. Hence, the environmental and public health impacts of long-lived radioactive wastes could occur well into the future, possibly tens of thousands of years from now. There are inherent problems with quantifying these. Thus, it is all but impossible to impute a fair economic cost to such environmental externalities.

Considering that electricity from the 220 MW Kaiga plants is costlier than thermal power for a large range of parameters, the conclusion that nuclear power is more expensive than thermal power from coal is robust. This contradicts numerous claims by the DAE that nuclear power is cheaper than coal-based thermal power at sites which are 800-1000 km away from coal mines. Nuclear power plants, therefore, have been and remain a costlier way of trying to address India's electricity needs than coal-based thermal plants.

The DAE was set up with the promise of delivering cheap nuclear electricity for development. Over the decades, it acquired a new rationale for its existence and continued funding, building nuclear weapons, and started promising a new good – security [Abraham, 1998; Perkovich, 1999]. This second promise, again, has proven to be a false one [Ramana and Reddy, 2003; Ramana and Mian, 2003]. In the end it seems that atomic energy has neither delivered energy nor security. ■

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Notes

1. This paper is a modified version of [Ramana et al., 2005] incorporating the suggestions offered by the reviewer.
2. Two 540 MW reactors are due to become commercial soon, raising the total nuclear capacity to 3,850 MW.
3. The summary of this study was published as [Nema, 1999]. When asked for a copy of the full study, the NPC's spokesperson told one of the authors (Ramana) that it was not available to the public.
4. For comparison, the final (revised) budget for the Ministry of Non-Conventional Energy Sources, which is in charge of developing solar, wind, small hydro and biomass-based power, in 2002-03 was Rs. 4.7356 billion. These sources between them comprise 4800 MW of generating capacity [MNES, 2004], as compared with the 2,770 MW of nuclear power. Their contribution to actual electricity generation would, of course, be smaller because they are intermittent sources of power.
5. Pressurised heavy water reactors use heavy water (in which the hydrogen atoms are replaced by deuterium, a heavier isotope of hydrogen, with atomic weight 2).
6. This compares the economics of generating electricity from two different sources of power. Transmission and distribution costs are external to the production process itself and their inclusion would make the comparison dependent on the locations of the power plant and the load centres.
7. The data is available on the Internet to subscribers at http://www.worldbank.org/
8. In other words, the comparison is for an investor who already has the required funds.
9. The DAE typically constructs two nuclear reactors at one time at each site. This is why we treat the two reactors as one unit.
10. A nuclear plant is said to become critical when it starts sustaining a chain reaction. There is usually a period reserved for safety checks and other operational matters before the reactor actually starts supplying electricity to the grid.
11. This is in mixed year rupees, and cannot be directly compared with future reactors whose costs are given in present day rupees.
12. The collapse is usually termed "delamination" in official documents [Mohan, 1994]. There was also a less publicized fire on the same dome [Anon., 1999a].
13. For nuclear power cost increases in the case of the USA, see [Komanoff, 1981].
14. From the reported value of $ 20 million for the 100 t of heavy water exported, it would seem that the heavy water was probably sold below cost of production.
15. Elsewhere the savings have been quoted as being Rs. 1 billion [Anon., 2001].
16. The article itself mentions a price of "about Rs. 25 lakhs" (Rs. 2.5 million) for a fuel assembly. However, this appears to be a misprint or an error. When asked for clarification, the author confirmed that the engineers at the Nuclear Fuel Complex had actually mentioned a price of Rs. 250,000 [Subramanian, 2002a].
17. This is sometimes called working capital.
18. See the discussion in [Bunn et al., 2003].
19. In the case of the leak at Narora-II on 15 April 2000, one worker received an internal dose of 47.12 mSv, well in excess of the 30 mSv annual limit on radiation doses to workers.
20. For an estimate of the quantities involved see [Ramana et al., 2001].
21. Like most of the DAE's nuclear power stations, the Kaiga nuclear reactors do not have a reprocessing plant on-site. Therefore, if its spent fuel is to be reprocessed, it must be shipped to either Tarapur (near Mumbai) or Kalpakkam (near Chennai).
22. Expenses after that are considered part of O&M expenses.
23. We are being somewhat unfavourable to the cost of coal power since the kind of inferior-grade coal that we have assumed for RTPS is available from points closer to Raichur.
24. In the case of uranium, however, one would expect to see an increase in the price over and above inflation in the not-too-distant future because of diminishing domestic reserves. We ignore this increase in order to be favourable to nuclear power in our calculations.
25. For an estimate see [Bhattacharjee and Kandpal, 2002b].
26. Even in the case of the 540 MW reactors coming up at Tarapur, the initial cost estimate was only Rs. 24.2751 billion. The final cost estimate is of the order of Rs. 60 billion.
27. One way to lower fuel costs would be through coal-washing, which decreases ash content, which in turn reduces transportation costs and increases plant efficiencies.

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