Heavy Subsidies in Heavy Water: Economics of Nuclear Power in India

Little is publicly known about the efficiency and economics of heavy water production at the Department of Atomic Energy's facilities. We estimate the cost of producing heavy water at the Manuguru plant by analysing the available budget figures and assuming reasonable values for other factors that affect the cost and whose values are not publicly available. Our results suggest that the production costs significantly exceed the price charged under even extremely favourable and unrealistic assumptions. Nuclear power, therefore, is being subsidised through the provision of cheap heavy water.

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One major cost component of producing electricity at most of the nuclear reactors run by the Nuclear Power Corporation (NPC) is heavy water (HW). In its studies of the economics of generating electricity, the NPC assumes that the HW for its reactors is leased from the Department of Atomic Energy (DAE) at a rate of 9.29 per cent [Thakur and Chaurasia 2005: 12].[1] The lease rate is based on a HW price (2003 prices) of Rs 12,525/kg [Thakur 2005]. There is, however, reason to think that the price charged for HW does not actually reflect the full cost of production.

It is not possible to definitively estimate the cost of heavy water production for the simple reason that there are no public figures available for the amounts of HW produced at heavy water plants (HWP) on a consistent year by year basis. The annual reports and performance budgets of the DAE list, for example, the annual electricity production at various reactors. However, they conspicuously avoid giving any numbers for HW production. The same is true of the many internet web sites of the DAE and its associated organisations. At best what is seen in DAE documents are statements like "target met" without any indication of what the target is. One cannot turn to government agencies like the Comptroller and Auditor General (CAG) either because of the DAE's history of poor accounting procedures, deliberate stone walling, and refusal to provide records of performance to various official or parliamentary committees, many of whom have made derisive comments about the quality of the DAE's accounting when it comes to HW [Chandrasekharan 1990; CAG 1994; Public Accounts Committee (1992-93) 1993].

Yet, one can make some rough estimates about the cost of producing HW by analysing the few budget figures that are available and supplementing them with reasonable assumptions. We have tried to do so in this paper. Wherever possible, we cross check our assumptions with other pieces of information publicly available. For example, even though annual HW production is not known and therefore one cannot calculate capacity factors of HWPs, we can estimate the demand for HW from all nuclear reactors in the country.[2] It stands to reason that production at HWP should be commensurate with this demand, which provides a rough range for capacity factors.

Our results show that if one adopts any of the standard accounting methods described in this paper, then the price charged by the DAE for HW to the NPC is substantially below the cost of production. In effect, the DAE, and indirectly the tax payer, is offering a subsidy to the NPC. Since each reactor uses hundreds of tonnes of the substance, the total subsidy amount is considerable.

Production Technologies

Heavy water is water in which both hydrogen atoms have been replaced with deuterium, the isotope of hydrogen containing one proton and one neutron. HW is used in nuclear reactors as moderator, to slow down the neutrons produced when radioactive nuclei undergo a fission reaction (so that there is a higher probability that the emitted neutron will cause another nucleus to fission, thus keeping the chain reaction going), and as coolant, to carry away the heat produced in the fission reactions.

HW is present naturally in ordinary water, but in only small amounts, roughly one part in 5,000 or less. For use in reactors, the HW must be concentrated to nearly 100 per cent. There are multiple ways to do this, but not all of them are practical on an industrial scale or energy efficient.

In India, HW is produced by the Heavy Water Board (HWB), an industrial unit of the DAE that was set up in 1989. (Its precursor, Heavy Water Projects, was set up in 1969.) The HWB's plants are based on two different processes, both based on technologies imported from other countries.[3] One is the hydrogen sulphide water exchange process. The first plant to be constructed based on this process, and using a Canadian design, is at Kota in Rajasthan. This was followed by a larger sized plant based on the same process at Manuguru in Andhra Pradesh.

The second process is the ammonia hydrogen exchange process that was imported from a French consortium, GELPRA. The first unit to use this process was the plant at Vadodara, which was set up following an agreement signed in September 1969 wherein the French government agreed to provide aid to cover the foreign exchange expenses for the purchase of equipment and know-how [Mirchandani and Namboodiri 1981: 63-64]. The other plant using this process is the one at Tuticorin, which was constructed with Japanese and French assistance. Recently the Vadodara HWP has started using a new process – ammonia-water exchange – but it has been described as a "technology demonstration unit" [Anonymous 2004].

A variant of the ammonia hydrogen exchange process is used in the Talcher plant. The technology and equipment for this plant came from a German firm: UHDE. The Talcher plant's operations seem to have been suspended since 1994, though it is still regularly mentioned in the list of HWPs in the country. Ironically, in 2001 the DAE reported as part of its claim that the "performance and safety record of all the operating HWPs during the year 2000 was very good" that the plant at Talcher completed more than "6.44 million man-hours of continuous operation respectively without any reportable accident" [DAE 2001]. But just a few sentences later it also mentions that "Operation of the Heavy Water Plant at Talcher remained suspended due to closure of operation of the fertiliser plant of the Fertiliser Corporation of India on which the plant depends for feed stock and other inputs". The DAE seems to have missed the obvious point that accidents are generally not possible when production at a facility has been suspended. This is also an instance of how the DAE uses technical jargon to create a misleading impression of excellent performance.

Production Delays

Heavy water production has been historically a problem area for the DAE. Despite deciding on HW moderated and cooled reactors as the predominant reactor type for the first phase of its nuclear programme in the 1950s, the DAE did not manage to produce sufficient quantities of HW for several decades. There were substantial delays in commissioning HWPs; once commissioned, they suffered frequent failures. Further, the quality of the HW produced was also reportedly poor in quality (low grade) and not useable in reactors [Manchanda 1989].

The Parliament's Estimates Committee has repeatedly criticised the DAE's failure to produce adequate quantities of heavy water. In its 1969-70 report, for example, the committee said "nothing substantial has been done in the matter" of producing the HW required for the Rajasthan and Madras Atomic Power Stations. The concern was repeated in its 1972-73 report and yet again in its 1977-78 report [Mirchandani and Namboodiri 1981: 58-59].

More than a decade later, the Public Accounts Committee (PAC), in their 162nd report (8th Lok Sabha), presented in April 1989, was caustic in its evaluation:

> The Committee regret to observe that the Department of Atomic Energy could not ensure timely supply of requisite quantity of heavy water to both units of Madras Atomic Power Project. The commissioning of the first unit alone was delayed by more than 16 months due to non-availability of heavy water which according to audit, meant an estimated revenue loss of the order of Rs 56.42 crore. Considering the fact that the Madras Atomic Power Project was already running behind the (sic!) schedule, the non-availability of heavy water at appropriate time shows nothing but *another facet of poor planning* in the Department of Atomic Energy (our emphasis).

All these delays resulted in the DAE having to import HW from the US and the Soviet Union. During the 1980s there were also several allegations, persuasively argued but because of the nature of the transactions never fully substantiated, that India had imported HW through clandestine means [Milhollin 1986]. In particular, there was some evidence that some HW from Norway had been diverted to India through Romania [Gordon 1990; Hazarika 1989]. Since the DAE has never been transparent about the functioning of its HWPs, it is not easy to evaluate these allegations.

These teething troubles may all now be a thing of the past. With the commissioning of five HWPs in the late 1980s and the early 1990s, there is evidently enough HW for all of the nuclear reactors in the country. The question is at what cost this HW is produced.

Long Outages, Low Outputs

Commissioning a production plant and getting it to produce some heavy water is not the end of the story. The plant has to work continuously without shut downs and produce high purity HW at the design rate. But the few publicly available pieces of information suggest that many HWPs have been shut down for relatively extended periods of time. These records are almost necessarily incomplete and only give us an "upper bound" on the performance of the HWP; i e, it is quite possible that performance has been poorer and they have had more shut downs than we know. Further, the periods reported for the outages underestimate the actual losses of time because there is typically a substantial period after each outage when the HW produced is not of adequate quality.

For the purposes of trying to estimate the cost of production of heavy water, the reasons for these outages are irrelevant. Each outage means poorer performance and a higher cost of production. The price charged by the DAE for HW is what is called a pool price, i e, all the HW produced in the country is put into a common pool and an average price calculated accordingly. Therefore, higher production costs in one plant imply a higher pool price.

Three plants that seem to have been particularly poor performers are Talcher, Vadodara and Tuticorin. As mentioned earlier, Talcher appears to have been shut down since 1994. We now discuss the other two plants.

The HWP in Vadodara was to be commissioned in January 1973. But it became operational only in July 1977 and actual production started only in November 1977 [CAG 1988]. Within

Table 1: Heavy Water Production Facilities

Facility	Process	Start Date	Capacity (tonnes/year)
Vadodara	Monothermal NH_3-H_2 Exchange	1977	45
Tuticorin	Monothermal NH_3-H_2 Exchange	1978	49
Talcher	Bithermal NH_3-H_2 Exchange	1985	62.5
Kota	H_2S-H_2O Exchange	1985	85
Thal	Monothermal NH_3-H_2 Exchange	1987	110
Hazira	Monothermal NH_3-H_2 Exchange	1991	110
Manuguru	H_2S-H_2O Exchange	1992	185

10 days, it was shut down because of mechanical failures and a major explosion and hydrogen fire causing extensive damage to the plant. It took nearly three years for the plant to restart production. Since then production has been frequently interrupted by disruptions in power or problems with the associated fertiliser plant [Srinivasan 2002: 222].

Reported outputs for the first three years of production after restarting were far below the design capacity of 45 tonnes/year – 12 tonnes in 1981, 5 tonnes in fiscal year 1982-83, and 13.6 tonnes in fiscal year 1983-84 [Milhollin 1986]. According to the CAG, the average annual production for the "seven years three months upto 1987 was less than 30 per cent of the installed capacity" [CAG 1988]. There is little public information available since then about production.

In 1998-99, the operation of the Vadodara plant was suspended "owing to change of operating technology at the fertiliser plant to which the HWP is linked" [Standing Committee on Energy 2000: 10]. The DAE began implementing a Vadodara revival project, which was expected to be completed by the end of 2002 [DAE 2002: 36]. In July 2004, the newly constructed ammonia-water exchange technology unit was "dedicated to the nation" [Anonymous 2004]. The new plant evidently developed snags since the 2005-06 annual report of the DAE describes the "restart of the plant in September 2005, after addressing comprehensively and rectification of the corrosion problem of Front End columns of 70 C1/C2". It was only on December 30, 2005 that the plant managed 100 days of continuous operation [DAE 2006: 28]. Elsewhere the new plant was described as just a "technology demonstrator", suggesting that it is not intended for industrial level production [Anonymous 2004].

The Tuticorin HWP has a history of poor performance as well. In 1988, the CAG reported that the "Tuticorin [heavy water] plant produced 20.6 per cent of the installed capacity in the last eight years" (i e, between July 1978 and March 1986). The best production was 42.7 per cent of the design capacity. The plant apparently could operate only for about 150 days per annum on average [CAG 1988]. The CAG also found that "running costs were high due to price variance, quantity variance of direct materials and labour" and that the "manpower employed was about 13 times more than that envisaged in the project report" [Chandrasekharan 1990: 1028-29]. More recent reports suggest that throughout its operating history, production of HW at Tuticorin has suffered from frequent interruptions of power and the low load operation of the fertiliser plant [Srinivasan 2002: 223; DAE 2003: 5]. It was also shut down for over four months in 1995-96 due to the failure of a heater coil [DAE 1996: 16]. In 1997-98, it was shut down for one and a half months when the ammonia plant was shut down [DAE 1998: 3-8]. The plant was shut down for 94 days during 2001-02 [Standing Committee on Energy 2003].

Other plants have also had extended outages. Again because the available information is so sparse, these should only be considered an upper bound on performance; i e, the plants were shut down at least during these reported periods rather than the only times that the plant operations have been suspended. The Kota plant was shut down from September 1986 to February 1987 [DAE 1988: 10]. It suffered from prolonged outages in 1997-98 [DAE 1999: 20], including for five months from June 1997 [DAE 1998: 3-8]. In 2003-04, its performance suffered due to frequent outages of the RAPS-II reactor [Parliamentary Standing Committee on Science and Technology 2004].

In 1989-90, the Thal plant had an extended shutdown of one production stream, total plant shut down due to heavy monsoon, and reduced supply of feed synthesis gas from the fertiliser plant [DAE 1991: 11]. It suffered extended outages again in 1998-99 [DAE 2000: 24]. In 2001-02, the Thal plant was shut down at least 22 times resulting in reduced on-stream hours [Standing Committee on Energy 2003].

Though it began operations in 1991-92, the Manuguru plant achieved "design capacity" only in 1995-96 [DAE 1996: 16]. Since then it has had outages due to poor supply of coal and hydrochloric acid [DAE 1997: 3:8]. It was shut down from February 12 to March 5, 2002 on account of a strike by workers [Standing Committee on Energy 2003].

For many years, the Hazira plant has been described as producing heavy water "under reduced load" due to retrofitting of one of the two ammonia units of the fertiliser plant to which it is linked or restricted natural gas supply from Gas Authority of India [DAE 1994, 1995, 1996: 16, 1997: 3-8]. It also had prolonged outages in 1997-98 [DAE 1999: 20], and was down for 85 days during 2000-01 [Standing Committee on Energy 2003]. Most recently, the Hazira plant was shut down on account of heavy rain and floods in August 2006 [*Business Line* 2006].

There are a couple of scattered reports of combined HW production at the DAE's plants. The total annual yield of all the six operating HW plants as of 1987 was reported to be "no more than 190 tonnes" [Bhargava 1992]. The corresponding figure from 1992 was 273 tonnes [Fernandez 1992]. Both figures imply an average capacity factor of about 50 per cent.

Going by the DAE's and HWB's publicity documents, the performance of HWPs seems to have improved [Anonymous 2002]. But since the earlier performance was dismal, improved performance by itself does not mean a lot. The HWB also seems to have lowered energy consumption and water consumption significantly [Hiremath 2004]. While commendable, one implication is that the initial designs of HWPs and their operations were wasteful in their use of energy and water.

Projections and Demands

As mentioned earlier, after decades of critical shortage, the DAE seems now to have adequate HW for all its reactors. It has even exported 116 tonnes to South Korea [Anonymous 1997; DAE 2001]. Though in part a reflection of better performance, it is also a result of another failure of the DAE – to construct as many reactors as had initially been envisioned.

When the DAE was set up in 1954, the Atomic Energy Commission predicted that there would be 8,000 MWe (megawatt electric) of installed nuclear power by 1980 [Hart 1983: 61]. By 1962, Homi Bhabha, the founder of the atomic energy programme, even predicted 20,000 to 25,000 MWe of installed capacity by 1987. Reality has been quite different. Installed capacity in 1979-80 was about 600 MWe and about 950 MWe in 1987. This slowdown has often been attributed to the impact of international sanctions following the 1974 nuclear test. However, even as late as 1984, a decade after the test, the "Nuclear Power Profile" drawn up by the DAE suggested a goal of 10,000 MWe by 2000 [CAG 1999]. Given past history, it should not be a surprise that once again this was not to be. Current capacity is only 3,900 MWe.

Nevertheless, the DAE's planning for HW in the country was based on this projection and it is the mismatch between projections and achievements that is the primary cause for the increased availability of heavy water, allowing the DAE to export the substance. Given this mismatch, one can evaluate the performance of HWPs by estimating the demand for heavy water by the NPC's reactors. We do so for the last decade and a half, since 1992 when the most recent HWP at Manuguru was commissioned.

Heavy water reactors need HW initially to attain criticality; once they start operating, they need HW periodically to make up for losses. The initial coolant inventory requirements for each 220 MWe and 540 MWe HW reactors are 70 and 177 tonnes of HW respectively; the corresponding initial moderator inventory requirements are 140 and 285 tonnes respectively [NEI 1994]. We assume that these initial inventories are required in the calendar year prior to the reactor being commissioned.

The annual make-up requirement for a 220 MWe reactor is about seven tonnes of HW per year [Kati 2003: 39; Hibbs 1997]. Since there is no experiential information available for the recently commissioned TAPS-3 and four reactors, we scale the loss for a 220 MWe reactor by the ratio of the power ratings and assume that each 540 MWe reactor loses 17 tonnes per year. The above information is summarised in Table 2.

These requirements for power reactors are laid out on an annual basis in Table 3 where column 2 lists the make-up requirements of already operating reactors and column 3 is the demand from new reactors. The total demand from the power reactors over the last 15 years has been 3,414 tonnes. In addition, the reactors at the Bhabha Atomic Research Centre that produce plutonium for nuclear weapons, CIRUS and Dhruva, would also have some annual losses. But these should be much smaller than the losses at power reactors because they have much smaller power ratings and because they do not have the turbines and other components which go into producing electricity and which are the source of considerable HW loss. Further, CIRUS was down for refurbishment between 1997 and 2003. Nevertheless, we can assume that between them, the two reactors required about a tonne a year on average, adding another 15 tonnes during the period we are considering. To this we can add 19 tonnes that CIRUS would have required for starting up after refurbishment [Milhollin 1986]. Finally, the HWB has exported 126 tonnes of HW to South Korea in three consignments [HWB 2006].

The total demand over the 15 operating years has been 3,668 tonnes. On average, therefore, the annual demand is about 245 tonnes. The combined capacity of all HWPs except Talcher (from Table 1) is 584 tonnes/year. Clearly production capacity exceeds demand and the necessary minimum capacity factor is a mere 42 per cent. Including the Talcher plant would bring this down to less than 38 per cent. Such inclusion is justified because the capital cost of Talcher has been spent and has to be recovered. There are unconfirmed reports of other exports, but these are of small amounts and make no difference to our conclusion that the average capacity factors needed to meet demand are quite low.

The cost of production at a facility has two components: fixed and variable costs. Fixed costs remain the same irrespective of the volume of production. Examples are the capital cost or interest payments on it, and a significant fraction of labour costs. Variable costs are roughly proportional to the rate of production. An example is the fuel cost. When translated to the cost per unit of production, the variable cost component remains independent of the rate of production, whereas the fixed cost component increases as the volume of production declines.

Excess capacity is a peculiar problem. If the DAE were to run its HWPs at high capacity factors, assuming that the DAE's claims about improved performance are true and there are no technical problems, then production would exceed demand. There is at best a limited export market for HW since very few countries operate heavy water reactors. Thus, production at high capacity factors would only lead to surplus accumulation with increased total variable cost, but no corresponding revenue. The alternative to this scenario is to run the HWPs at lower capacity factors – around 40 per cent going by the estimates above. This would mean a larger fixed cost component. In either case, if the DAE were to meet the expenses involved in repaying capital and production by charging a fair price for the HW, it would have to increase the price it charges the NPC.

Dubious Accounting

Even for government agencies trying to estimate the cost of heavy water production at the DAE's plants has largely been impossible, and the resultant estimates necessarily inaccurate. The DAE has tried to stonewall even Parliament on this question and mostly succeeded in the task. The government agency that has tried hardest to examine the DAE's HW accounts is the CAG, whose function is to enhance accountability of various public sector organisations and departments to Parliament and state legislatures.

Even with the CAG, the DAE has tried very hard to deny it the information needed to calculate costs of production. For example, while examining the case of the Baroda HWP, the DAE "did not produce to Audit either the actual production of heavy water or the cost of production" and that in the "case of maintenance and spares, actual expenditure is not being booked and only a notional expenditure of 4 per cent of capital cost is booked" [CAG 1988]. Thus, it was not possible for them to calculate exactly the cost of production at the Baroda HWP.

A few years later, the CAG noted that the DAE had not prepared the "proforma accounts for the years after 1982-83

Table 2: Initial and Annual Requirements of HW

	220 MWe Reactor	540 MWe Reactor
Initial coolant inventory (tonnes)	70	177
Initial moderator inventory (tonnes)	140	285
Annual make-up (tonnes/year)	7	17

Table 3: Heavy Water Demand for Reactors

	Operating (Tonnes)	New (Tonnes)
1992	43	
1993	43	210 (Kakrapar 1)
1994	50	210 (Kakrapar 2)
1995	57	
1996	57	
1997	57	
1998	57	100 (Export to South Korea)
1999	85	840 (Kaiga 1 and 2, Rajasthan 3 and 4)
2000	85	16 (Export to South Korea)
2001	85	10 (Export to South Korea)
2002	85	19 (CIRUS refurbishment)
2003	85	
2004	102	462 (Tarapur 4)
2005	119	462 (Tarapur 3)
2006	119	210 (Kaiga 3)

though they were prepared till that year" [CAG 1992].The parliamentary PAC considered this refusal of the DAE to provide accounts and production details as yet "another instance of lack of proper accounting procedure which in turn is due to their disregard of accountability on their part. The committee strongly deprecate such attitude" [PAC (1992-93) 1993]. In their response, the DAE stated "Heavy Water being strategic material, it is not advisable to divulge information relating to its production and cost to functionaries at all levels". The committee did not agree with this and maintained that "as already recommended proforma accounts will have to be compiled… the Committee do not understand how preparation thereof will result in release of any sensitive data. The Committee consider such claim as a way of evading accountability by escaping scrutiny of audit and this Committee under the guise of sensitivity, public interest etc." More than a year after the PAC tabled its report in Parliament, the CAG complained "The proforma accounts of Heavy Water Pool Management for the years 1982-83 onwards have not been sent for audit so far despite this fact being mentioned in successive Reports of the Comptroller and Auditor General of India: Union Government (Scientific Departments) since 1987" [CAG 1994].

In August 1998, finally, the Heavy Water Board "made available the pro-forma accounts for the period 1993-94 to 1996-97… for audit certification." But then what the CAG found, perhaps not surprisingly, was "that the cost of production of heavy water had been reckoned at a rate lower than the actual cost… As a result, the pool prices of heavy water notified by DAE during 1993-98 on provisional basis were less by Rs 409 to Rs 2,168 per kg than the actual pool charges derived from the certified pro-forma accounts, except for the year 1993-94, where it was slightly higher" [CAG 2005: 21]. This resulted in DAE recovering Rs 130.87 crore less from NPC during 1993-98 when compared to what it may have recovered at the "correct" prices.

Unfortunately the CAG does not explicitly mention what the correct pool prices should have been. Therefore we come up with our own independent estimates and compare it with the stated cost of HW.

Estimate of Production Cost

Since we do not have all the necessary data for all HWPs, as a proxy we look at the total cost of producing HW at the most recently commissioned HWP at Manuguru with an annual capacity of 185 tonnes of HW. Being the most recent HWP, it has presumably benefited from earlier experiences and hence would have lower costs of construction and operations and maintenance. Calculating the HW cost from one HWP also enables us to reduce the number of necessary assumptions.

We consider two ways of estimating the cost of HW production at Manuguru. The first method amortises the capital costs into an average annual capital cost and this amount is added to the average annual operations and maintenance (O&M) and fuel costs. These costs are divided by the average annual production to get an estimate of the per kg cost of HW. The second method calculates a levelised cost, which is the ratio of the present values of the lifecycle cost of producing HW and the annual amounts of HW produced over the lifetime of the plant.

First (annualised) method: In this method, we amortise the capital cost over the lifetime of the plant to come up with an average annual capital cost that is given by: ACC = K × CRF where K is the total capital cost of the plant including interest during construction (IDC) and CRF is the capital recovery factor.[4] The capital recovery factor, in turn, is given by

$$CRF = r \Big/ \left(1-(1+r)^{(-N)}\right)$$

where r is the discount rate, and N is the period over which the capital cost is amortised, which we have chosen to be the lifetime of the plant. The cost, C(Y), of production of heavy water in year Y is given by C(Y) = ACC + OMF(Y) and the annual production P is given by P = R × CF where R is the rated capacity of the plant and CF is the assumed average capacity factor (independent of year). The unit cost of heavy water is given by

$$U(Y) = C(Y) \big/ P = \left(ACC+OMF(Y)\right) \big/ (R \times CF).$$

We use a 12 per cent nominal discount rate as is used by the Central Electric Authority for planning and evaluation of projects [Bose 2000]. The Planning Commission uses the same rate. Finally, 12 per cent is also the rate of return that is expected of capital expenditures in the area of atomic energy [PAC (1991-92) 1992: 3].

The estimated cost of the Manuguru HWP when it was sanctioned was Rs 421.60 crore. In 1989, the plant cost was revised to Rs 661.58 crore. 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 crore and the increase, with reference to the original estimated cost… was…133 per cent".[5] When questioned about the cost escalation, DAE stated that "the grounds for sanction of this project was strategic and not commercial" [CAG 1994].

We assume that there were no capital expenditures after the plant was commissioned and use Rs 983.38 crore as the total capital cost. We assume no refurbishment costs or working capital costs. Neither do we include any decommissioning costs. All of these would only increase the cost of producing HW.

Apart from the capital cost of the HWP, the other major components in the cost of producing HW are the O&M cost and the cost of fuel inputs into the process. Again, the actual figures for these are not given in any of the DAE documents. Fortunately the annual union budget allotments to the Manuguru

Table 4: Union Budget Allocations for Production at Manuguru HWP

Year	Budget (Rs Crore)
1992-93	71
1993-94	93.39
1994-95	99.09
1995-96	107.73
1996-97	105.4
1997-98	110.12
1998-99	126.63
1999-2000	135.5
2000-01	129.24
2001-02	115.07
2002-03	111.85
2003-04	124.48
2004-05	131.68
2005-06	139.56
2006-07	147.1

Source: Government of India, Expenditure Budget, Volume 2, various years.

HWP help us estimate the sum of these.[6] We list these figures in Table 4 for the first 15 years of Manuguru's operating history, i e, till the most recent revised estimates.[7] We average these figures (after converting each to 1992 rupees to correct for inflation) and use Rs 78 crore/year (1992 rupees) as the sum of the O&M and fuel costs at the Manuguru plant. This is assumed to remain constant in real terms. To convert between expenses incurred in different years, we assume a 6 per cent inflation rate, roughly the average inflation rate between 1992 when Manuguru began operations and the present. Thus, the assumed sum of the O&M and fuel expenditures in year Y (Y>1992) is OMF (Y) = 78 × $(1+i)^{(Y-1992)}$ Rs crore, where i is the inflation rate.[8]

Unfortunately, because there is no public information about how much HW was produced each year, we cannot break down the production costs into fixed and variable components. Therefore we cannot estimate the cost of HW as a function of the capacity factor.

Though the exact amounts of HW produced at Manuguru is not known, we assume that it will operate at an effective capacity factor of 60 per cent over its lifetime and calculate the cost of production at this facility. This is much higher than the approximately 40 per cent needed to meet the estimated demand. The effective capacity factor might be lower than the actual capacity factor since it includes losses at the plant or during transportation to the reactor. We emphasise that what is relevant to such a costing exercise is the lifetime capacity factor not production levels during one or a few years, which may be higher than this nominal value. Those would be compensated by poorer performance in other years. For example, the Manuguru plant did not manage to reach "design capacity" till 1995-96 [DAE 1996: 16].

As the last row in Table 5 shows, the cost of production of heavy water is well above the price paid by the NPC for any reasonable assumption. Even for an unrealistically large 100 per cent capacity factor, the 2003 HW cost is Rs 14,600 or above (depending on the assumed lifetime). Both of these are higher than the cost claimed by the NPC. In contrast, the cost of heavy water would be Rs 36,500 if one assumes that the HWP runs at a 40 per cent capacity factor, which is roughly the capacity factor needed to meet the NPC's demand.

As discussed earlier, HWPs like Manuguru are likely to have run at relatively low capacity factors. Strictly speaking, the OMF costs that we have assumed are applicable only for that actual capacity factor. If the plant were to run at a higher capacity factors, such as a 100 per cent capacity factor, then the variable component of OMF costs will be higher. Therefore, the figure we have calculated for high capacity factors is an underestimate, which we use only to highlight the point that all of our estimates are higher than the NPC's claim.

Second (lifecycle costing) method: As mentioned earlier, in the second method, one calculates the present value of the lifecycle cost of producing HW and divides that by the present value of the HW produced to obtain a levelised cost. In mathematical terms:

$$\mathrm{PV(Lifecycle\ Costs)} = \sum_{l=-M}^{0} \frac{C(l)}{(1+r)^l} + \sum_{k=0}^{N} \left[\frac{(\mathrm{OMF}(k))}{(1+r)^k} \right]$$

where C(l) is the capital expenditure (cash outflow) in year l; M = total number of years of construction; r is the discount rate; OMF(k) is the sum of the O&M and fuel expenses in the year k, and N is the number of years of operation.

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

$$\mathrm{PV(revenues)} = \sum_{k=1}^{N} \frac{L(k)P(k)}{(1+r)^k} = L_0 \times R \times CF \times Q(N)$$

$$Q(N) = \sum_{k=1}^{N} \frac{(1+i)^k}{(1+r)^k}$$

where L_0 = levelised cost per unit of HW in the year of commissioning plant, which is inflated to the year k to obtain the levelised cost L(k) in that year, P(k) is the amount of heavy water produced in year k, R is the rated capacity of the plant, and CF is the assumed average capacity factor (independent of year). The levelised cost is calculated by setting PV(revenues) = PV(Lifecycle costs) and solving for L_0.

As in the earlier method, we use a 12 per cent nominal discount rate and a 6 per cent inflation rate. All cash flows are discounted to the commissioning date of the HWP. As shown

Table 5: Annualised Cost of Producing Heavy Water at Manuguru HWP

Symbol	Quantity	Alternative Scenarios			
K	Total capital cost including IDC (Rs crore)	983.38	983.38	983.38	983.38
N	Economic life (years)	30	40	30	30
r	Discount rate (per cent)	12	12	12	12
CRF	Capital recovery factor	0.124	0.121	0.124	0.124
ACC	Annualised capital cost (Rs crore)	122	119	122	122
OMF (1992)	Average O&M and fuel cost in 1992 (Rs crore)	78	78	78	78
OMF (2003)	Average O&M and fuel cost in 2003 (Rs crore)	148	148	148	148
C(2003)	Cost of output of plant (Rs crore)	280	277	280	280
CF	Capacity factor (per cent)	60	60	70	50
P	Heavy water production (tonnes)	111	111	130	92.5
U(2003)	Unit cost in 2003 (Rs/kg HW)	24,300	24,100	20,900	29,200

Note: Final cost figures have been rounded off.

Table 6: Annual Construction Expenditures on Manuguru HWP

Year	Budget (Rs Crore)
1981-82	0.016
1982-83	6.67
1983-84	32.59
1984-85	95.45
1985-86	155.8
1986-87	163
1987-88	54.94
1988-89	39.89
1989-90	48.21
1990-91	42.17
1991-92	11.4
1992-93	5.16

Source: Performance Budget of the Department of Atomic Energy, various years.

Table 7: Levelised Cost for 40 and 30-Year Lifetimes at 60 Per Cent Capacity Factor

	40 Years	30 Years
Future valued capital cost (Rs crore)	1312	1312
Lifecycle discounted OMF cost (Rs crore)	1156	1051
Total lifecycle cost (Rs crore)	2468	2363
Q(N)	16.60	15.09
R×CF×Q(N)	1843	1675
Levelised cost (1992 Rs/kg)	13400	14100
Levelised cost (2003 Rs/kg)	25400	26800

in the equation above, the total lifecycle cost consists of two components. The first is the future valued capital cost, which is the sum of all the annual capital expenditures on the plant, future valued to the date of commissioning. For the Manuguru HWP annual construction expenditures are listed in Table 6. These figures do not include the IDC component because that is evaluated at some lending rate, which is not in general the same as the discount rate.[9] Thus, the sum of the figures is only Rs 655 crore, smaller than the Rs 983 crore figure used in the earlier method, but the total future valued cost is Rs 1,312 crore. This difference in figures is the main, though not only, reason for the difference in the estimated costs of HW using these two methods.

The second component of the lifecycle cost is the sum of the present values of the O&M and fuel expenses for each year. As in the earlier method, the sum of the O&M and fuel in year Y (Y>1992) is assumed to be OMF(Y) = $78 \times (1+i)^{(Y-1992)}$ Rs crore. This series of cash flows is discounted to the commissioning date and summed up to calculate the lifecycle discounted OMF cost. The figures for the two cost components and the product of all the factors other than the levelised cost for a capacity factor of 60 per cent are provided in Table 7. At that capacity factor, the annual production at Manuguru would be 111 tonnes. The resultant levelised costs are slightly larger than the figures obtained in the annualised method.

Net Present Value

In addition to the above two costing methods, we also calculate the realised Net Present Value (NPV) of the Manuguru HW plant, which is the discounted sum of all expenditures and revenues and is given by:

$$NPV = O_0 \times R \times CF \times Q(N) - PV \text{ (Lifecycle Costs)}$$

where the first term is the same as the expression for PV(Revenues) with the levelised cost of HW replaced by O_0, the HW price of Rs 12,525/kg (2003 prices) set by the government (DAE) and PV(Lifecycle Costs) is the same as given earlier. As before, we assume an inflation rate of 6 per cent to calculate the HW price for other years; i e, O(Y) = $12525 \times (1+i)^{(Y-2003)}$. The net present values are listed in Table 8 for capacity factors of 60 per cent and 100 per cent. It is clear that even at the unrealistically high capacity factor of 100 per cent, these plants are a losing proposition at the price set by the DAE. As discussed earlier, the lifecycle cost figures for the 100 per cent capacity case end up underestimating what would be the actual figure.

The large and negative figures for the net present values should not be surprising at all. We have already demonstrated that a realistic estimate of the unit cost of producing HW at the Manuguru plant using two different methods is about Rs 12,000/kg or more, higher than the figure the NPC is charged. Thus, when the DAE sells the HW at a lower price, the NPV becomes negative.

Table 8: Net Present Values for 40 and 30-Year Lifetimes

Capacity Factor	60 Per Cent		100 Per Cent	
Annual HW production R×CF (tonnes)	111		185	
Lifetime N	40 Years	30 Years	40 Years	30 Years
Future valued capital cost (Rs crore)	1312	1312	1312	1312
Lifecycle discounted OMF cost (Rs crore)	1156	1051	1156	1051
PV of total lifecycle cost (Rs crore)	2468	2363	2468	2363
PV of total lifecycle revenues (Rs crore)	1086	987	1810	1644
Net present value (Rs crore)	-1383	-1376	-659	-718

Note: Figures may not add up due to round off approximations.

Conclusion

It has long been conjectured that the DAE subsidises the NPC through providing cheap heavy water. For example [Muralidharan 1988] has argued that "in addition to cheap finance, the nuclear power programme enjoys, in all probability, another implicit subsidy in the form of the cost and lease rate borne for its heavy water supplies" (our emphasis). What we have attempted to do in this paper is to try and quantify the extent of the subsidy. Our results show that as per standard and required accounting practices, a subsidy of over Rs 12,000 per kg is being offered.

We have also highlighted the various factors that contribute to the high cost of heavy water: high capital costs, high O&M and fuel expenditures, and low capacity factors. The last factor cannot be changed by running the plants at higher capacity because there is no corresponding demand, itself a result of the DAE's failure to plan appropriately and implement those in time. Finally, we have briefly described the many ways in which the DAE has sought to defeat attempts by other government agencies to assess the performance of HWP, mostly by refusing to be open and by adopting dubious accounting procedures, thereby not allowing a fair price for HW to be estimated.

Given this lack of transparency in the operations and costs at HWPs, the estimates made here is necessarily approximate. For a better and more reliable estimate, the DAE should provide *full and complete* operating records and expenditures at all heavy water related facilities for public scrutiny. Partial releases of information would be unsatisfactory because it opens up the possibility of releasing data that are favourable to the economics of heavy water and suppressing unfavourable figures.

The cost of the initial loading of heavy water, which is subsidised both through a low price and by leasing HW at a low rate, constitutes over 15 per cent of the initial capital cost of the reactor, which in turn is the dominant contribution to the cost of producing electricity. Studies of the relative economics of nuclear power would therefore depend strongly on what is assumed for the heavy water cost. Our estimates here, in combination with earlier work [Ramana 2007; Ramana D'Sa, and Reddy 2005], imply that atomic energy is unlikely to be economically competitive if the true cost of producing heavy water is taken into account. EPW

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Notes

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1 The lease rate used to be 12 per cent per year earlier but was lowered some years ago; according to the DAE, the reduction was one of several measures to make "nuclear power tariff competitive" [DAE 2005: 34].

2 We use the term capacity factor to mean the same as what it does in the case of electricity generation stations: the ratio of the actual production to the maximum possible production.

3 The now dismantled plant at Nangal used a third method called the electrolysis process. This process again came from outside the country. The overall engineering work of the Nangal plant was done by Vitro Engineering Division of New York; the contract for supplying electolysers was awarded to Deonara of Italy, while the electric equipment was supplied by the English Electric Company of the UK. The contract for the hydrogen distillation plant was awarded to a company from Munich in Germany [Mirchandani and Namboodiri 1981: 61].

4 There are other ways of converting capital costs and O&M expenses into annual costs that would give different though comparable results. For example, one could amortise the capital cost over, say, the first 10 years of the plant's lifetime.

5 Manuguru is by no means an exception. This sort of increase has been typical of the DAE's heavy water plants. The Baroda plant, for example, had an initial financial sanction of Rs 15.19 crore. The DAE finally adopted Rs 55.52 crore as the total capital cost, including interest during construction (IDC) [CAG 1988]. But there were capital expenditures even after the plant was commissioned. As in the case of the Tuticorin plant, "running costs were high due to price variance, quantity variance of energy consumed, undetected ammonia leakage, etc" [Chandrasekharan 1990:1032].

6 We use are the revised estimates as an approximation to the actual expenditures. The expenditures are further categorised under plan and non-plan expenditures; once the plant starts operating, essentially all the expenditure is under the non-plan component.

7 These are only a lower bound on the O&M and fuel expenses because there are other line items listed in the union budget as expenditure towards heavy water, for example, pool management, feed stock, and loss of heavy water, that we do not include.

8 There would, of course, be both statistical variations and general trends in the O&M cost over the years. The expected general trend is that the cost (in real terms) would be higher during the initial years, become lower during the middle of the lifetime, and increase again towards the end of the life of the plant.

9 The exact procedure and rates used in calculating the IDC has not been explicitly stated in any public DAE document. In the case of Manuguru, we estimate this rate to be around 7 per cent, lower than the adopted discount rate of 12 per cent.

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