Cost of electricity from the Jaitapur Nuclear Power Plant

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Abstract: The Indian Government has announced that it plans to purchase six European Pressurized Reactors (EPRs) for Jaitapur from the French company, Areva. No EPR is in commercial operation anywhere else in the world. Estimates of costs from plants under construction in Finland and France suggest that each unit may cost as much as Rs. 60,000 crores; at this price, six units will cost Rs. 3.6 lakh crores. We show that the expected starting tariff for electricity from these reactors, without including transmission and distribution costs, is likely to be around Rs. 15 per unit (kWh) of electricity. We point out that existing revenue model used by the Government already involves a large loss for the taxpayer. The Government may seek to make the tariff from Jaitapur competitive by increasing the scope and nature of these handouts.

Introduction

The Indian Government has promised to purchase six European Pressurized Reactors (EPR) from the French company Areva, and install them at Jaitapur (Maharashtra). In March 2012, the Prime Minister's office informed the Rajya Sabha that it plans to start work on the first two reactors in the XII plan period (Narayanasamy 2012a). These plans have reportedly been delayed by French insistence on the deletion of a relatively unimportant, but marginally progressive, clause in the Indian liability law. Nevertheless, in January 2013, the external affairs minister Salman Khurshid assured his French counterpart that the Indian "government remains committed to the Jaitapur Nuclear Power Project" (PTI 2013).

Local citizens have strongly opposed the proposed construction because of worries about safety and environmental impact (Bidwai 2011). There are good reasons for such worries: the nature of nuclear technology and its susceptibility to catastrophic accidents, albeit infrequently; the untested EPR design; and seismicity of the site (Bilham and Gaur 2011; Gaur and Bilham 2012). There is another reason, though, for why this project may not be in the public interest: the likely economic impact of this decision. To this end, we estimate the cost of electricity that will be produced at Jaitapur when the reactors are commissioned. As the rest of this article shows, this cost could be as high as Rs. 15/unit (kWh). This figure raises serious questions about the commercial viability of the project and raises the concern that the Manmohan Singh government may spend large amounts of public money to compensate for Areva's lack of competitiveness.

There is no international precedent that we could use in this study, since not a single EPR is in commercial operation anywhere in the world. Four EPRs are currently under construction—one each in Finland (Olkiluoto) and France (Flamanville; for more details, see Appendix 1) and two in China (Taishan). The experience with the first two provides us with some estimates of construction costs. (There is little public data about the costs of the reactors at Taishan.) Recent news reports from the construction sites in Olkiluoto (Finland) and Flamanville (France) suggest that the cost of each of those reactors has escalated to about $11 billion; this is about Rs. 60,000 crores at current exchange rates. (Reuters 2012; Yle Uutiset 2013) At this rate, the first two reactors will cost in excess of Rs. 1 lakh crores, and if the Government does go ahead with its plan to purchase six EPRs, the total cost borne by the country will be in excess of Rs. 3.5 lakh crores.

The Manmohan Singh government appears to have decided to award this contract to Areva without any open-bidding or tender process. This is in complete contrast to the usual mode of procuring anything in any branch of the Government including the Department of Atomic Energy (DAE). For example, the Directorate of Purchase and Stores of the DAE explains that while "small purchases of less than Rs. 20,000 … are made to cater to the immediate and urgent requirements of various users" for larger purchases "exceeding Rs. 10 lakh, the mode of tendering adopted is generally by Public Tender" (DPS-DAE 2013).

How were the purchases of the EPRs—even though they are millions of times larger than the standard cutoff for a tender —approved in this capricious manner? Historically, a bidding process was adopted even for the very first set of power reactors constructed in India at Tarapur and resulted in the General Electric Company from the United States putting in the lowest bid and winning the contract (Ramana 2012, 24). But the procedure by which the EPR was selected does not seem to have involved cost minimization in its set of criteria at all.

In fact, cables from the U.S. mission in Mumbai, which were revealed by Wikileaks, indicate that this peremptory decision had been made by early 2007 (Wikileaks 2007). The Government's motivations were explained in a candid article by Anil Kakodkar, who was the secretary of the DAE when this deal was negotiated. Writing for the Marathi newspaper Sakaal, in January 2011, Kakodkar explained: "America, Russia and France were the countries that we made mediators in the efforts to lift sanctions, and hence, for the nurturing of their business interests, we made deals with them for nuclear projects" (Kakodkar 2011).

Lack of Public Information on the Costs

In spite of the enormous public expenditure involved in this project, the Manmohan Singh Government has studiously avoided a public discussion on its financial aspects. A number of cagey and incomplete statements are available in the public domain. These statements are remarkable for the feature that they uniformly insist that the final tariff will be competitive but fail to justify this assertion through details of the costs of purchasing and operating the reactors.

In 2010, the then-CEO of Areva, Anne Lauvergeon, told *The Hindu* that the "[costing] is done" implying that commercial negotiations had concluded. When asked about the unit cost of power, she replied "You have a system in India which is very important: all the sources of electricity have to have a maximum basic cost below four rupees per kilowatt hour... We are below the Rs. 4 figure but I am not going to give you the details … it is not for me to give the price if the customer does not want to give it" (Naravane 2010).

Indeed, in a meeting with the Konkan Bachao Samiti, the NPCIL refused to reveal these details, relying on the excuse that "As such the capital cost of the proposed NPP units at [the] Jaitapur site is under discussion" (KBS 2010). A couple of months later, the NPCIL released a statement which, as usual, provided no substantive cost-information but insisted that "NPCIL has reiterated and assured in general and in particular to KBS that the cost per unit of electricity from the Jaitapur plant … will be competitive to the other power plants in operation in the region. It may be noted that the average tariff of nuclear power during the last four years has been in the range of Rs.2.28 to Rs.2.34" (NPCIL 2010).

The Government refused to be precise even in the parliament. In May 2012, when P. Rajeev asked the Prime Minister's Office in the Rajya Sabha about "the estimated cost of per Mega Watt of electricity produced using Areva reactors vis-a-vis the cost of electricity using Indian Pressurised Heavy Water Reactors?" the Government fell back on its story that "the detailed project proposals including costs and business models envisaging the share of work between the Indian side and French side to arrive at an optimal cost are under finalization … The tariff of electricity from the EPRs planned at Jaitapur is expected to be comparable to those of contemporary Indian Pressurised Heavy Water Reactors" (Narayanasamy 2012b).

The subsidies that are involved in existing nuclear tariffs have been discussed elsewhere by one of us (Ramana 2007; Ramana 2012, 165–66), but if the cost of electricity from Jaitapur is indeed to be similar, it would be a rather simple matter for the Government to substantiate its claims: it merely has to perform the calculation that we present below and provide a figure (or a range of figures if the exact price is under negotiation) for the tariff. Why has it refused to do so?

In an attempt to get more information, one of us (SR) wrote to the executive director of the Nuclear Power Corporation, who has previously taken the initiative in contacting us to rebut our arguments on other issues. However, this email had not been answered by the time this article was submitted for publication (See note 1).

The Government's reticence is explained in another cable from the U.S. consulate in Mumbai. This cable, again revealed by Wikileaks, recorded that "N. Rao, General Manager (Finance) of NPCIL, confided to Congenoff [Consul General's Office] that NPCIL paid a 'high' price for French reactors from Areva" (Wikileaks 2009).

Our calculations below buttress this hypothesis. By using the NPCIL's own methodology, we find that the expected tariff from the Jaitapur reactors will be about three or four times as high as that from other sources. So, it is hardly surprising that the Government is unwilling to have an open public discussion on the matter.

The NPCIL's Tariff Calculation Methodology

In 2007–08, when the Manmohan Singh Government was trying to push the Indo-US nuclear deal, the DAE performed a "study" entitled "Economics of light water reactors in India" stating that expected tariff from the imported reactors would be around Rs. 2.50/unit. This is the study that the UPA quoted from in its debate with the Left parties on the nuclear deal (UPA 2007, 44).

The following year, an executive director of the NPCIL, Sudhinder Thakur, published an analysis with an identical conclusion (Thakur 2008). This figure for generic imported reactors—although as we mentioned the Government has refused to commit to anything specific for Jaitapur—seems to have persisted at least until 2009, when the managing director of the NPCIL referred to it (Jain 2009).

We will refer to the paper authored by Thakur in 2008 as the NPCIL's paper in our analysis below. Though not all details of the calculation are provided in this paper, we have been able to precisely reproduce all the figures there, and so infer its methodology. This methodology is rather similar to others used for setting tariffs—albeit with a few quirks. We have tried to adapt the NPCIL's method, as faithfully as possible, to the case of Jaitapur.

However, as we describe below, we were forced to correct several numerical assumptions that were made by the NPCIL. Some of these were wildly optimistic, while others were simply internally inconsistent.

The central reason that the NPCIL's analysis cannot be directly applied to the EPRs at Jaitapur is that it assumes that the reactor can be built at a capital cost of $1,500 per kilowatt (kW) of installed capacity. The international experience suggests a much higher figure ranging from $5000 to $7300 per kilowatt [see appendix]. Since the capital cost is the central variable in the cost calculation, in this paper we present results that can be used to calculate the tariff for any value of this variable. However, as our base case, we use the figure of $4000 per kilowatt, which we believe is about the best that the NPCIL can hope for.

The NPCIL also assumes that it will only take a period of five and a half years from "first pour of concrete", one of the standard markers for commencement of construction, for the reactor to be commissioned. This figure was repeated in parliament by the Prime Minister's Office (Narayanasamy 2011).

However, according to the IAEA's figures for reactor construction periods (IAEA 2011), the global weighted average reactor construction time is 91.7 months; the corresponding figure for India is 114.5 months. In France, the last four reactors commissioned in the late 1990s had an average construction time of 124 months, or more than ten years.

Given that the EPR seems to be a particularly complicated design to construct—as the experiences in Olkiluoto and Finland demonstrate—the NPCIL's schedule is hopelessly ambitious. In this paper, we will use the actual experience from the VVER reactors installed at Kudankulam, which have taken, as of the time of this writing, at least eleven years to commission. We emphasize that this is another charitable assumption: the VVERs at Kudankulam, unlike the EPR, belong to a group of reactors that are in commercial operation elsewhere and similar—although not identical—plants have been constructed previously; it is unlikely that the EPRs will be constructed in the same time frame.

The NPCIL's calculation also assumes that the company will be able to access debt (denominated in Indian rupees) at a nominal interest rate of 6%. In 2007, when the NPCIL's calculation was performed, the yield on 10-year Indian Government bonds consistently hovered around 8% (Trading Economics 2013). The trend has continued and in the last two years, the yield has varied between 7.5% and 9%. There is little basis for the NPCIL's assumption that it would be able to borrow money for a longer period, at a rate that is 200 basis points smaller.

The Government may try and arm-twist public sector banks into giving the NPCIL easy credit but this is clearly irrelevant to an objective comparison of the Jaitapur tariff with that of other sources, which may have to follow the norms laid by regulatory authorities in this matter. Therefore, in this paper, we will follow the 2012 notification of the Central Electricity Regulatory Commission, and assume that the Jaitapur project will have to access debt at the standard market rate of 13.21%, which is used for other power projects (CERC 2012).

Another serious problem has to do with the revenue-model that NPCIL assumes to obtain a return on its equity. This return is fixed at a nominal percentage of the total equity spent during the project—the NPCIL uses 14%. However, as we describe below, this is problematic for this return starts flowing only after the reactor starts functioning. In particular, this implies that the equity is sitting idle for the entire gestation period. When this idle time is taken into account, even with the very short gestation period assumed by the NPCIL, the effective return on equity turns out to be just 9.5%. With the longer and more realistic gestation period assumed by us, this effective rate drops to just 7.7%

In our calculation below we have set the return on equity to a higher level of 16.83% used by the CERC (CERC 2012), but as we describe below, this still leads to an effective return on equity of only 8.6%. Clearly, there is a significant opportunity cost associated with this, since the NPCIL could have invested its equity at a higher rate of return. What this implies is that the Indian public, which is where the NPCIL's equity ultimately draws from, will receive a lower effective interest rate than the debtors for the project despite having to assume the majority of the risk! To correct this requires a broader debate on the revenue-model used for fixing tariffs, but we have not attempted that here.

We should point out that in its 2009 – 2014 regulations, the CERC states that the rate of return on equity may be "grossed up" with the tax rate, which will substantially increase this figure and also the final tariff (CERC 2009a). We have neglected these tax implications in this calculation.

Calculation of Tariff

In this section, we explain the parameters and procedure for the calculation of the tariff from the EPR reactors in more detail. The reader who wants to follow all the steps of the calculation should look at the computer programs available at the authors' websites.[1] On the other hand, the reader who is not interested in the details of this computation can jump directly to the next section, where we discuss our results.

There are three major elements in the calculation of tariff. The first is an estimate the total construction cost; the second is an estimate the cost of fuel; the third is the calculation of the tariff using these two costs. This is done sequentially below.

Cost of Construction

For reasons of convention, the construction-cost is calculated by starting with an estimate of an "overnight cost of construction." While this term is used in different ways in the literature, the NPCIL defines it to be the cost of construction, without including any interest payments or cost escalation due to inflation, i.e., as though one could construct the reactor overnight.

As mentioned above, the NPCIL takes the overnight cost of construction to be $1500 per unit of installed capacity. While this may be applicable to the VVER reactors installed in Kudankulam, the international experience at Flamanville and Olkiluoto suggests that this cost should be much higher for Jaitapur. As described in the appendix, estimates of the capital cost of the EPR range from $5,000 to $7,300 per kilowatt in Western Europe and the United States.

The NPCIL claims that "The cost towards construction and commissioning (local activities) form a sizeable portion of about 40% of the total cost"(Thakur 2008). Civil construction costs, in India are estimated to be 60% lower than in Europe (Turner & Townsend 2009). Assuming the NPCIL's estimate of the extent of local activities, this would lead to only about a 24% cost reduction. This is consistent with the "25-30% cost advantage" claimed by the former managing director of the NPCIL (Sharma 2010).

Given that the international estimates of costs for the EPR range from $5,000 to $7,300 per kilowatt, we believe that it is unlikely that the overnight cost of the EPR in Jaitapur will drop below $4,000 per kilowatt.[2] Nevertheless, although we discuss this figure in detail, since it represents our judgment rather than a rigorous number, we eventually present results that can be used to simply obtain the tariff for any value of the overnight cost.

At the current exchange rate of Rs. 55/$, the overnight cost of $4000 is translates into Rs. 2.2 lakhs per kilowatt of installed capacity. So, if the EPRs could be constructed overnight, they would each cost $\text{Rs.}\,2.2\times 10^5\times 1650\times 10^3=\text{Rs.}\,36{,}300\text{ crores}$

Of course, the reactors cannot be constructed overnight and the expenditure must be spread out over various years. In its analysis, the NPCIL provides a distribution of expenditures assuming that the gestation period will be only 65 months. This is a purely arbitrary expenditure curve and does not comport with the historical experience.

We will instead adopt the same pattern of expenditures as the Kudankulam reactors, which have so far taken 11 years to construct from the first pour of concrete—on 31 March 2002—to the commissioning which is expected later this year.[3] By mining data from the Ministry of Statistics and Programme Implementation (MOSPI 2004), and adjusting these for inflation, we have put together a distribution of annual expenditures on the Kudankulam plants (see Table 1). When listed in terms of cumulative expenditure, this distribution is termed an S curve because of its shape.

Year 0 refers to the first pour of concrete. The NPCIL also includes some costs that are incurred before this—for example, money spent on ordering components that take a long time to manufacture. However, we have simply dropped these expenditures since we have no way of estimating them for Jaitapur. This omission will lower our estimates of the cost of electricity from Jaitapur.

Table 1: Pattern of expenditure on construction of reactor

Year	0	1	2	3	4	5	6	7	8	9	10
Cumulative expenditure (%)	19	31	40	54	67	73	80	86	90	95	100
Annual expenditure (%)	19	12	9	14	13	6	7	6	4	5	5

We should emphasize that while the S-curve is important— it determines how debt is taken and serviced, and also the "effective return on equity" that we introduce below—it is ultimately determined by the actual experience of construction and cannot be predicted ahead of time. We have merely chosen the closest empirical experience at hand. It is quite possible that the EPR reactors will actually take longer to build and so the S-curve will have to be modified.

Starting with these initial estimates, one now arrives at a final cost estimate by inflating them and computing the cost of servicing the debt. Throughout this paper, we will use a constant inflation rate of 5%. This rate is well below what has been the rate of inflation in the last seven years in India; again, this assumed inflation rate will lower the estimate of the electricity generation cost. The total expenditure must be divided between debt and equity. We follow NPCIL in assuming that the final proportions of equity and debt are 30% and 70% respectively. We also follow the convention of the NPCIL, where the first year is purely equity and then initial expenditure is divided equally between debt and equity, which stops when equity reaches 30% of the total cost.

One important element that enters here is the rate of interest on debt. As we mentioned above, based on the recent CERC guidelines, we will assume that NPCIL can access debt at an interest rate of 13.21%. We assume that this debt is taken in equal monthly installments, and that interest is also paid monthly. What this means in effect when calculating yearly figures is that interest is paid on the debt accumulated over the previous years, and half of the current year's debt. Using this, we can work out the following cash-flow table for a single EPR.

Table 2: Cash Flow Table for a single EPR (in crore rupees)

Year	0	1	2	3	4	5	6	7	8	9	10
Initial expenditure estimate	6797	4521	3286	5163	4414	2216	2801	2077	1517	1785	1723
Inflated expenditure estimate	6797	4748	3623	5977	5365	2828	3753	2922	2241	2770	2806
Debt	0	2455	2041	3398	3313	2273	5925	5874	5975	7386	8470
Interest on debt	0	162	459	818	1262	1631	2172	2951	3734	4616	5664
Equity	6797	2455	2041	3398	3313	2186	0	0	0	0	0
Total	6797	4910	4082	6796	6627	4459	5925	5874	5975	7386	8470

This cash flow table results in a total expenditure of Rs. 67,300 crores for each EPR, of which Rs. 20,190 crores is equity (exactly 30%), and Rs. 47,110 crores is taken as debt. Note that the interest on debt, and inflation during the gestation period means that initial overnight construction cost has increased by about 85% and the unit cost becomes $7416/kW.

The Effective Return on Equity

We pause here to point out an important technique that the Government may use to subsidize the project. Notice that in the cash flow table, while interest on debt is paid regularly, the Government spends a lot of equity for which it obtains *no return* during the gestation period.

The later tariff calculation will adopt a model assumed by NPCIL where this equity earns a constant return, once the reactor starts functioning. We will call this rate, "r_n" since it is only naïvely the return on equity. The effective return on equity, which we call "r_e", takes into account the idle-time, in which no return was earned. If the equity spent in each year above is called e_i, then we define r_e by the equation

$$r_e \sum_{i=0}^{l-1} e_i (1 + r_e)^{l-i} = r_n \sum_{i=0}^{l-1} e_i$$

where l is the total gestation period—in this case, 11 years.

The left hand side of this equation is the amount the Government would receive as dividend were it to simply invest its equity at the rate r_e, allow it to compound for the gestation period, and then start withdrawing the annual interest payments. The right hand side is the current revenue model: the equity sits idle for the gestation period and then obtains annual dividends at the rate r_n from year l.

With a long gestation period, the difference between r_n and r_e can be quite significant. For example, with the expenditure curve above, we find that a naïve return on equity of 16.83% (which is what we will use below) corresponds to an effective return of equity of just 8.6%. So, if the NPCIL were to simply park its money from day one in a fixed deposit with this interest rate, it would earn the same income as it would earn from the "return on equity" component of the EPR tariff!

The relation between this naïve and effective rate for the expenditure pattern assumed here is plotted below in Figure 1. As the reader can see, with this revenue model it is only with a naïve return on equity of about 37% that the effective rate of return on equity becomes equal to the rate of interest on debt of 13.21%.

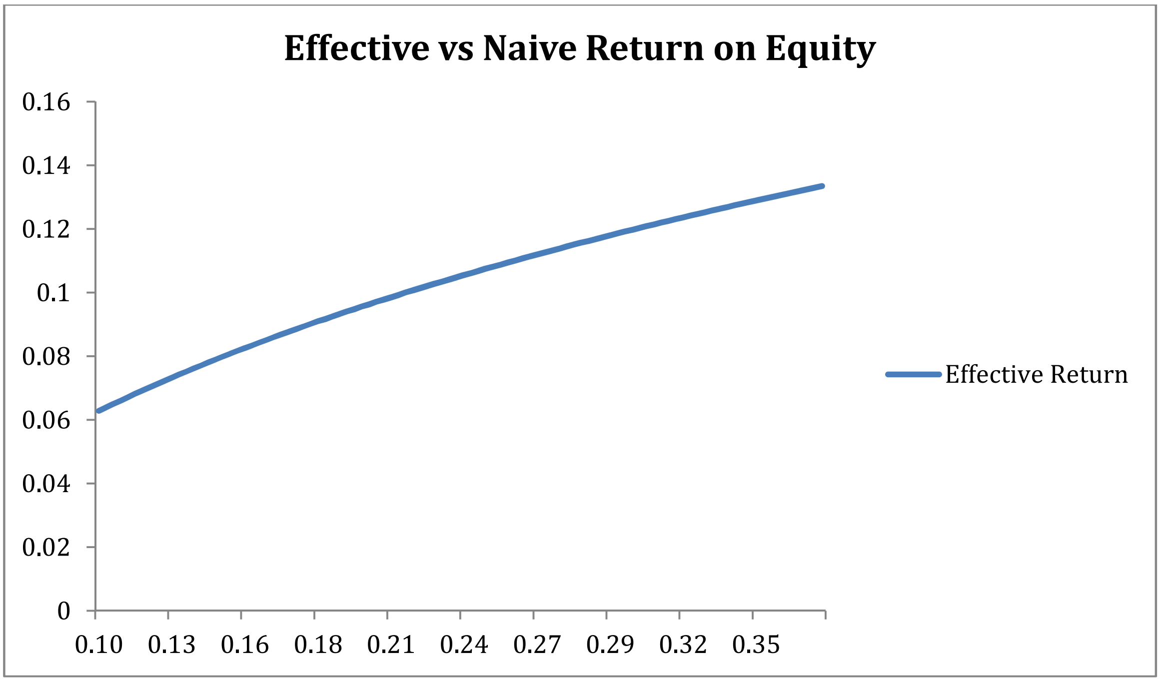

Figure 1: Effective Return as a Function of Nominal Return

This revenue model requires a serious public debate. The standard market logic for a "high" return on equity is that the risk involved in the project is taken by the party which provides the equity. It makes no sense for a public sector corporation to earn a lower rate of return on than the external debtors. One way to correct this may be to budget for the return on equity during the gestation period as well, even though the actual returns may only be paid later. This would increase the final cost and make the EPR even more economically unattractive.

Fueling Cost

The cost of fueling the EPR can be estimated from the fuel requirements and the market cost of enriched uranium. The annual fuel requirement of a nuclear power plant depends upon the thermal power generated, the fuel "burn-up," i.e., the thermal energy generated per unit mass of fuel, measured in thermal gigawatt-days per metric ton of uranium (or plutonium) in the fuel, and the capacity factor with which the reactor operates. Only a fraction of this heat—the efficiency—can be converted into electricity.

The different EPRs under construction appear to have slightly different thermal and electrical outputs. Even within India, various Governmental agencies and Areva have provided varying figures for the Jaitapur plant. For the sake of consistency—and since these small variations are unimportant for the point that we wish to make—we will choose figures presented in the Environmental Impact Assessment carried out by the National Environmental Engineering Research Institute (NEERI 2010). According to this document, the EPR's thermal power output is 4500 MWt and the electrical output is 1650 MWe. This is the gross output and the net output to the grid will be slightly smaller, since part of the power is consumed within the plant itself.

These figures for thermal and electrical outputs correspond to an efficiency of conversion (of heat into electricity) of about 37%, and it is unclear whether Areva—which has advertised similar figures elsewhere—will be able to attain this, given the warmer waters of the Arabian sea.[4]

The next question has to do with the amount of thermal energy generated by a given amount of fuel —this is called the "burnup." Areva has often advertised burnups as high as 62 MWth-days/kg-U to sell its claim that the EPR uses less fuel. However, in its submission to the United Kingdom's Nuclear Decommissioning Authority, where it was beneficial to advertise a low burnup to minimize the amount and radioactivity of the spent fuel, Electricité de France and Areva estimated that the average burn-up for the EPR will be 48.3 MWth-days/kgU (Areva and Electricité de France 2009, 30). Here we will assume that this burnup is 50 MWth-days/kgU—our use of only one significant figure emphasizes the uncertainties in this physical parameter.

For these values of the burnup and efficiency, generating each kWh (gross) of electrical energy will require $\frac{1000}{0.37\times50\times24} = 2.25$ mg of low enriched uranium (LEU). Each EPR, operating at a load factor of 0.8 will require about 26 tons of LEU fuel per year. The EPR reactor core has 241 fuel assemblies and each assembly contains 527.5 kg of uranium, resulting in an initial core loading of 127 tons of uranium (Areva and Electricité de France 2009).

The cost of uranium fuel depends on various cost factors—the cost of raw (purified) uranium, the cost of converting the uranium from uranium oxide to uranium hexafluoride, the cost of enriching the uranium, and the cost of fabricating the LEU into fuel. The work involved in enriching the uranium is measured in "separative work units" and depends on the levels of U-235 concentration in the final enriched product (termed x_p), the natural uranium feed (x_f), and the discarded tail (x_t). The value of x_f is simply the proportion of U-235 in naturally occurring uranium, which is 0.007; x_p is set by the design of the reactor to be 0.05, and the value of x_t is chosen by optimization to be 0.002.

Conservation of mass, for the U-235, and the other elements, now implies that the total amount of natural uranium feed required to produce a unit mass of enriched uranium is given by

$$F = \frac{x_p - x_t}{x_f - x_t}.$$

The amount of separative work needed to actually produce one unit of light enriched uranium from this feed is given by

$$N_s = V(x_p) + (F-1)V(x_t) - F\,V(x_f),$$

where the "value function" is given by

$$V(x) = (2\,x - 1)\ln(\tfrac{x}{1-x}).$$

The cost of producing the fuel is now given by

$$C_{leu} = F(C_u + C_c) + N_s C_s + C_f,$$

where $C_u, C_c, C_s, C_f, C_{leu}$ are respectively the cost of natural uranium, the cost of conversion, the cost per separative work unit, the cost of fabrication, and the final cost of the fuel respectively. There are actually small losses at each step: conversion, enrichment and fabrication. We have not included them above, to avoid cluttering up the equations. Since they are quantitatively small compared to the other uncertainties in the calculation, they are irrelevant for our final analysis.

Assuming values of $150/kg for the uranium (Corp 2011),[5] $10/kg for conversion, $160/SWU for enrichment and $250/kgHM for fabrication (Kazimi, Moniz, and Forsberg 2011, 102), and a 10 percent increase due to the cost of packing, transport, and insurance (Thakur 2005), the total cost of LEU fuel works out to $3542 per kilogram.

Setting the Tariff

We finally turn to the computation of the tariff from the EPR reactors. This is conceptually a very simple calculation, except that it involves keeping track of various tedious accounting details.

The major components of the first year tariff are the interest on debt at $r_d = 13.21\%$, which is now passed on to consumers, and the return on the equity. In the NPCIL paper, this return on equity is simply a nominal return on the (nominal) sum of equity spent. As we discussed in detail above, we set this rate to $r_n = 16.84\%$ here but with the assumed expenditure pattern where much of this equity is spent during the initial years of construction, this is equivalent to a very low effective rate of about 8.54%. These costs are just calculated by multiplying these interest rates with the total equity, and outstanding debt

$$P_{eq} = r_n E; \quad P_{debt} = r_d D_o,$$

where E is the total equity spent during construction and D_o is the outstanding debt. The interest on debt reduces progressively as the debt is repaid, but in the conventions adopted by the NPCIL, the return on equity is fixed at a nominal amount for the entire lifetime of the reactor.

Next, the cost of the fuel (calculated as above) is also passed onto consumers. Then, there is depreciation which is assumed to be a constant fraction of the total construction cost each year. Although the NPCIL takes the rate of depreciation to be 3.6%, we will take it to be 5.28% as notified by the CERC in its latest notifications (CERC 2009b).

The reactor needs to be loaded with an initial inventory of fuel, which we calculated above. It is also periodically stopped and refueled and the cost of fuel we described above goes towards this refilling. The initial inventory should properly be counted as part of the capital cost, but following the NPCIL's somewhat arbitrary convention, we count this cost separately and assume that it will be recovered from consumers in constant yearly installments over 15 years at the same rate of interest as the debt. The value of each installment is given by

$$P_{fr} = L_i C_{leu} \frac{r_d(1+r_d)^n}{(1+r_d)^n - 1},$$

where L_i, n are the size of the initial load (127 tons) , and the period over which this cost is recovered (15 years). We remind the reader that r_d and C_{leu}, which appeared above, are the rate of interest on debt and the cost of fuel.

Then there are operations and maintenance costs, which we have taken to be 2% of the total construction costs in line with the NPCIL assumption. A rather intricate, but quantitatively small, component of the tariff is taken up by the "interest on working capital." The working capital comprises what the NPCIL calls a "stores inventory", at 2% of the total completion cost, six months of fuel, tariff collections for two months, and O&M costs for a month. These time periods and parameters are a little arbitrary but we have taken them to be the same as what NPCIL assumes. The NPCIL assumes an interest rate of 12% on the working capital; this is again arbitrary, but we have retained this assumption.

Finally, there is a small constant levy of 2 paise per unit for decommissioning. This is an arbitrary fixed nominal cost and the NPCIL does not provide any details on how this decommissioning fund will be managed over the years, or what the eventual costs are likely to be. We emphasize that spent-fuel management is completely excluded from these cost-calculations because the NPCIL claims that this is not part of its job but must be handled by the DAE.

Results

For an overnight cost of $4000/kW, we find the following components of the first year tariff by dividing the gross amounts above by the net number of fuel units produced in a year. We assume that 7% of the reactor's output will be consumed within the reactor (i.e., auxiliary consumption), and that it will function at a load-factor of 80%. More precise details of the calculation are available in the computer programs mentioned above for the interested reader (See note 1).

Table 3: Components of the first year tariff for the EPR with an overnight cost of $4000/kW

Return on Equity	3.16
Interest on market borrowings	5.43
Interest on working capital	0.49
Depreciation	3.30
Fuel consumption	0.78
O&M cost	1.25
Annual fuel recovery charge	0.59
Provision for decommissioning	0.02
Total	15.03

Figure 2 shows the variation of the tariff as a function of time. The NPCIL can use the collection of tariffs to progressively repay the debt that it has accumulated. Here, we follow the NPCIL in assuming that the debt is repaid in 8 years, in constant monthly installments. As a consequence, the "interest on market borrowings" component of the tariff starts to decrease. After 15 years, the "annual fuel recovery charge" also vanishes. Furthermore after 17 years, the tariff dips again because depreciation is assumed to end (since more than 90% of the value of the original construction is assumed to have been lost).

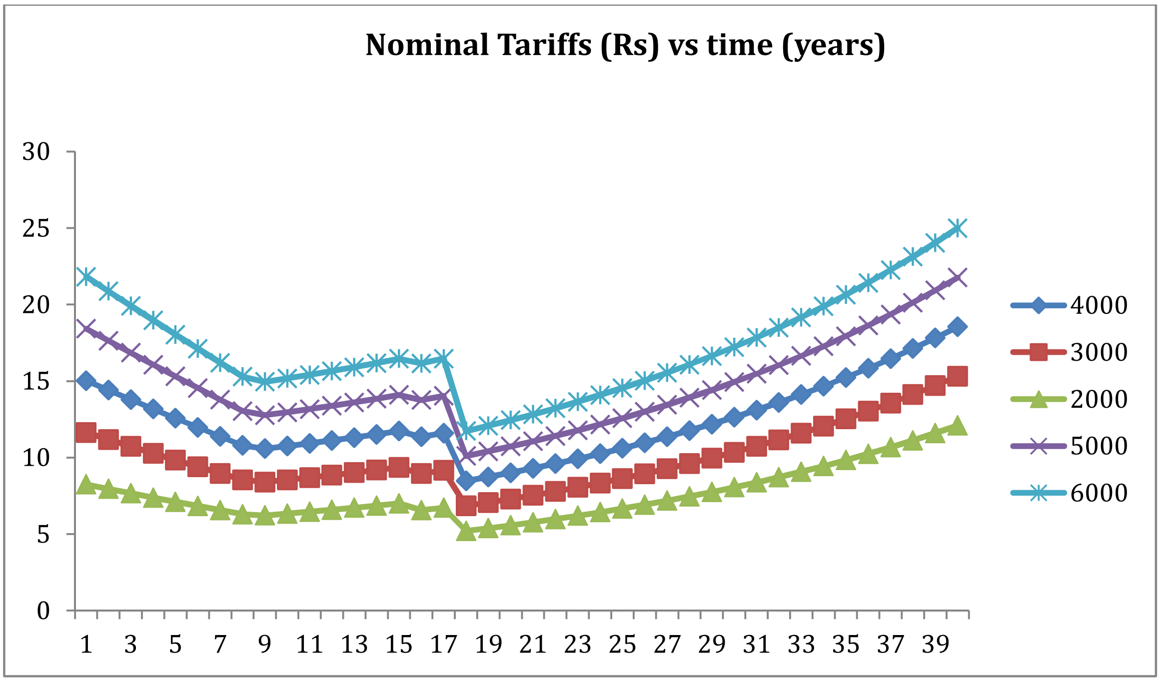

Figure 2: Tariff as a function of time for various overnight costs of construction

On the other hand, various costs start to escalate. While the NPCIL assumes differential inflation rates for various costs,[6] these are rather tricky to project into the future. For simplicity, we simply assume that all costs, such as the O&M costs and fuel costs, will escalate at a rate of 5%. Changing these parameters slightly does not change the conclusions, and the reader is welcome to adapt our computer programs, using different parameters. A graph of the (nominal) tariffs with time is presented in Figure 2 for a range of overnight costs.

As we mentioned, the overnight cost of $4000/kW is our most charitable estimate for what can be achieved at Jaitapur. Nevertheless, we have plotted the costs for other values, ranging from $2000/kW to $6000/ kW. Even at the unrealistically low overnight cost of $2000/ kW, we see that the first year tariff is rather high at Rs. 8.24/unit.

Although we have plotted the tariffs over a period of 40 years, obviously the long term projections suffer from large uncertainties, which come from uncertainties in the price of fuel, inflation, and the performance of the reactor.

It is also possible to compute, what is called, the "levelised tariff", which is the weighted mean of all tariffs, with the weights taken to be the discounting factors for each year. More precisely, for the levelised tariff l, we have

$$l = \frac{\sum t_n (1+d)^n}{\sum (1+d)^n},$$

where the sum is over the lifetime of the reactor, t_n is the tariff for year n, and d is the discount rate. In our case, for an overnight cost of construction of $4000, we find a levelised tariff of Rs. 12.32 over a 40 year period. The reason, we have not emphasized this figure is that while the levelised tariff is useful for comparing different methods of generating electricity, it does not have any direct relevance for the consumer—who must pay the nominal tariff each year—or for the producer, which recovers its investment using the detailed model presented in the text. We note that the Government is also moving towards a consideration of the first year tariff rather than levelised tariffs, to evaluate bids for "ultra mega power projects"(Saikia 2012).

Variation of Tariff with the Cost of Construction

Figure 3 plots the first year tariff as a function of the overnight cost of construction.

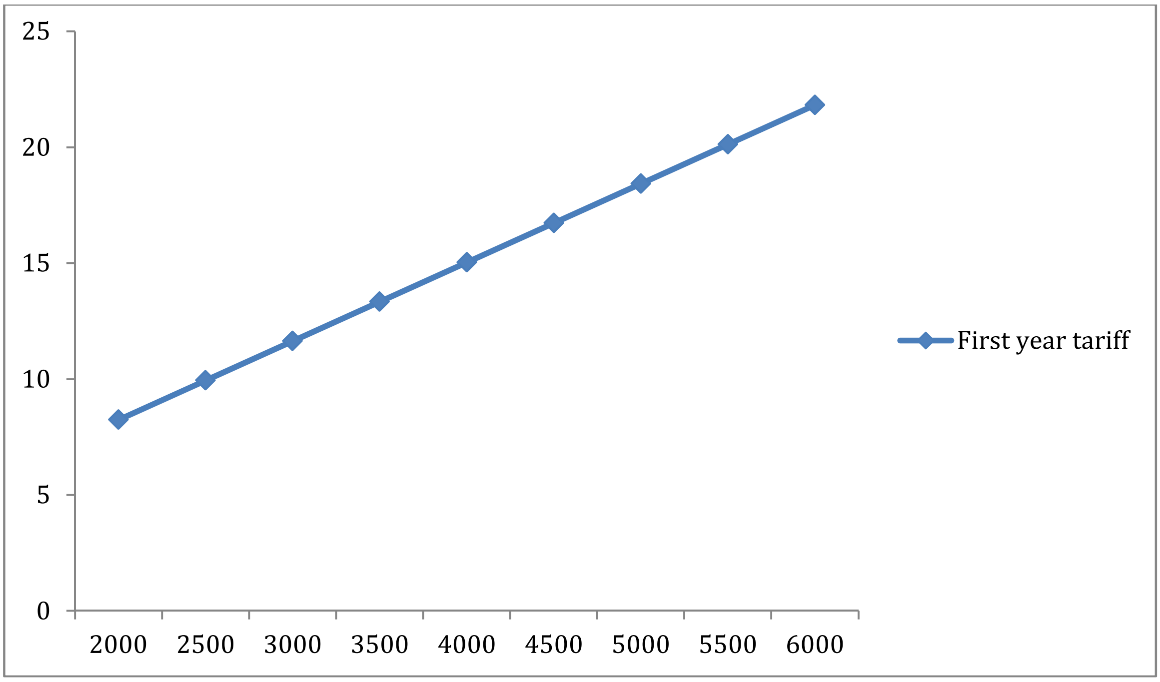

Figure 3 First year tariff against overnight cost of construction

In fact, the tariff for *each year* is a linear function of the overnight cost of construction, albeit with a non-zero intercept since some of the costs are unrelated and come from fuel. More precisely, if t_n is the tariff for year n, then we can write

$$t_n = f_n + v_n \frac{O}{4000},$$

where O is the overnight cost of construction in dollars. We present the coefficients f_n and v_n in Table 4. This table can be easily used to compute the tariff for any year, for any value of the overnight cost. For example, we can see from this table that for an overnight cost of \$6000/Kw, the tariff for the first year is given by Rs. $1.46 + 13.58 \times \frac{6000}{4000}$ = Rs. 21.8! Table 4 can be considered to be our final result.

Year (n)	v	f	Year (n)	v	f	Year (n)	v	f
1	13.58	1.46	15	9.45	2.28	29	8.88	3.31
2	12.91	1.50	16	9.60	1.76	30	9.16	3.47
3	12.25	1.54	17	9.75	1.85	31	9.46	3.65
4	11.59	1.59	18	6.53	1.94	32	9.77	3.83
5	10.93	1.64	19	6.70	2.04	33	10.10	4.02
6	10.28	1.69	20	6.87	2.14	34	10.44	4.22
7	9.64	1.74	21	7.05	2.25	35	10.81	4.43
8	9.00	1.80	22	7.25	2.36	36	11.19	4.65
9	8.73	1.86	23	7.45	2.47	37	11.58	4.88
10	8.83	1.92	24	7.66	2.60	38	12.00	5.12
11	8.95	1.99	25	7.88	2.73	39	12.44	5.38
12	9.06	2.05	26	8.11	2.86	40	12.90	5.64
13	9.19	2.13	27	8.36	3.00			
14	9.32	2.20	28	8.61	3.15			

Table 4 Coefficients for the variation of yearly tariff with cost of construction

Conclusion

International experience suggests that the Jaitapur EPR reactors are likely to cost huge sums of money. The Government seems to have decided on this expenditure without any due process and has refused to enter into a public discussion on the details of the expected tariff. It is worrying that the Manmohan Singh regime has staked immense political capital on an import-fuelled nuclear expansion. Its past actions suggest that it is willing to go to great lengths to fulfill, what it believes are its “international obligations”(Raju 2008; Raju 2010).

The economic costs of acting in such a fashion are evident through the calculations performed in this paper. We estimated the tariff from the Jaitapur reactors by adopting the methodology that the NPCIL had used to justify the import of reactors during the Indo-US nuclear deal. The first year tariff on the electricity from the Jaitapur reactors, assuming a likely figure for the capital cost, turns out to be as high as Rs. 15 per unit.

Since it is impossible for the Government to pass on tariffs of this magnitude to consumers, without public outrage, it may seek to reduce consumer tariffs by bearing a loss through the exchequer. In fact a large subsidy of this sort is already built into the existing revenue model, where the Government plans to put down money for the project up front, but obtain returns from it only after a long gestation period. There are good reasons to worry that, as has been the case in Finland and France (see Appendix), the project could take much longer to construct than envisioned. This will only increase the economic burden on the public.

In addition, the Government may also try and influence public sector banks to provide cheap credit for the project, and provide other subsidies to reduce costs. The costs of such actions are likely to be immense. Each EPR will generate about 1075 crore units (kWhs) every year at a capacity factor of 80 %. Thus, each Rs. 1/kWh reduction in the tariff that the Government absorbs will translate to a loss of Rs. 1075 crores per year per reactor to the exchequer; to bring the tariff from the first two reactors down to, say, Rs 6/kWh will require an annual expenditure of about Rs. 19,350 crores!

A common refrain from the establishment is that it will succeed in dramatically reducing costs by using indigenous manufacturers — in other words, by intensely exploiting local labour. However, these claims are untenable. We first note that we have already incorporated a significant saving by using a cost estimate of $4000/kW for the EPR. It is unlikely that savings obtained in this manner alone will make the EPR competitive. Second, in trying to reproduce the NPCIL's calculation, it has become obvious to us that the Government's methodology includes several disingenuous assumptions about capital costs, time of construction, uranium price, escalation with time, overall escalation rates, debt and equity rates, and distribution of cash flows between equity and debt. When these manipulations are set aside, it becomes absolutely clear that even with favourable assumptions, it is impossible to make Jaitapur economical.

The Manmohan Singh Government has repeatedly demonstrated its willingness to protect corporate profits, even if this involves losses for the country. However, the amounts of money involved in the import of the Jaitapur reactors are so large that they will put even the telecom and coal scams into the shade. It is only powerful popular mobilization and a sustained demand for transparency that can stop these plans to effect a massive transfer of resources from the Indian public to "nurture the business interests" of a French corporation.

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Disclaimer

The views expressed in this paper are solely those of the authors and do not represent the official positions of any of the academic institutions that the authors are affiliated with.

Appendix 1: The EPR

The history of the selection of the site at Jaitapur is rather interesting and has been reviewed by one of us (Ramana 2012, 94). In this Appendix, however, we would like to discuss the history of the EPR reactor itself and explain why we believe that it is unlikely to be substantially cheaper in India, than elsewhere.

In 1989, the German company Siemens and the French nuclear vendor Framatome (now integrated into AREVA) formed a consortium called Nuclear Power International (NPI) (which later turned into Framatome ANP and then AREVA NP) for the development and marketing of the European Pressurized Water Reactor (EPR) (Thomas 2010). Siemens and Framatome had both been licensees of Westinghouse for their PWR technology and the EPR design was based on Siemens' and Framatome's most recent PWR designs at that time, the Konvoi design and the N4 respectively.

The expectation was that EDF would order the first unit before 2000 and have it in service by 2006. EDF's initial cost estimate was €3.3bn. However, only the site preparation for the first EPR in France, at Flamaville, began in 2006; at that time, the reactor was expected to begin operating in March 2012 (MacLachlan 2006).

Because of this delay, Areva switched its focus to Finland after the country's parliament approved the construction of a fifth nuclear unit in 2002 (Thomas 2010). After a tendering process involving seven designs, in December 2003, the Finnish utility Teollisuuden Voima Oy (TVO) signed a turnkey deal with Areva NP for a 1600MW EPR at a cost, including interest during construction and two fuel charges of €3bn. The reactor was to commence electricity generation in 2009.

Of course, as we reviewed above, none of these projections have materialized, and neither of the two European reactors is close to being commissioned. In the meantime, costs have ballooned(Chaffee 2011b).

Areva has publicly claimed that its reactors at Taishan in China are on their way to being more successful. It secured this contract without any international tender competition after lobbying at the highest levels; the Chinese President Hu Jintao and French President Nicholas Sarkozy presided as Areva signing the agreement with the China Guangdong Nuclear Power Group (GNPG) in November 2007 (Xinhua 2007). The GNPG is a 70% partner on the project with the French Électricité de France (EDF) holding the remaining 30%.

Estimated at €8 billion ($12.6 billion) at the time it was signed in November 2007 (Bodgener 2008), the Taishan reactors are scheduled to be commissioned in 2014-15. There have been some reports of price increase even in this case, especially in the case of nuclear components (Chaffee 2011a). However, there is little public data of how exactly the costs have been divided between Areva and the GNPG, or on what direct and indirect subsidies have been provided to the project. This is why we have not used this example in our calculations.

Areva has put in bids for several projects around the world since the Taishan reactors. Most famous among these was the bid to build four reactors in Abu Dhabi where it lost out to

South Korea's Korea Electric Power Company (KEPCO) mainly on account of the cost of the EPR. Other unsuccessful efforts included bids to construct reactors in the United States, in South Africa, and in Ontario, Canada. High cost was one factor in many of these projects not going forward. The latter two were reported to cost on the order of $6000/kW and $21 billion, but there is no official confirmation of any of these figures (Thomas 2010). In the United States, though there were multiple EPRs proposed, the project that got furthest was one at Calvert Cliffs, Maryland, which was forecast at $7.2 billion.

As of February 2012, Areva had made formal bids on three more power stations: Wylfa-3-4 in the United Kingdom, Hanhikivi-1 in Finland, and Temelin-3-4 in the Czech Republic (Chaffee 2012). It has been in negotiations over building two more reactors at Taishan, but as of December 2012 Areva still listed these in the "ongoing negotiations" category. In yet another EDF bid for a two-unit EPR project at Hinkley Point in the United Kingdom, the price of the reactor has been reported at £14 billion (Webb 2012), resulting in a per unit cost of €5400 per kW. EDF estimates that the reactor will take about ten years to construct (Gosden 2013).

In summary, the estimated costs of constructing an EPR in Western Europe or the United States are around €3700 to €5400 per kW, or $5000 to $7300 per kW, or about $6100 on average. There are three sets of reasons to expect that EPRs will continue to be expensive.

The first is material: compared to generic nuclear reactors, EPRs have higher requirements for construction materials such as steel and concrete. It has been estimated that in comparison with a Generation II Pressurized Water Reactor, the EPR uses a little over 40% more steel and 70% more concrete per unit of power capacity (Peterson, Zhao, and Petroski 2005). One might interpret this as the higher cost of safety.

A second problem with the EPR has been its complexity. As described in the 2010 Roussely report:[7] "The complexity of the EPR comes from design choices, notably of the power level, containment, core catcher and redundancy of systems. It is certainly a handicap for its construction, and its cost. These elements can partly explain the difficulties encountered in Finland or Flamanville" (NEI 2010). These design choices, again, are a result of aiming for greater safety.

However, greater complexity does not always mean more safety; indeed, as Charles Perrow famously argued about two decades ago, interactive complexity is one of the contributors to what he termed normal accidents (Perrow 1999). Complexity implies that it is difficult to predict how the reactor would behave under unusual circumstances, such as those that occur during accidents. While reviewing the different designs in 2003, the Finnish Radiation & Nuclear Safety Authority (STUK) observed: "Several details of the design require additional work, especially the core design, the reactor emergency borating system, the containment liner, the capacity of the reactor emergency cooling systems, recirculation of emergency cooling systems, and the severe accident management strategy. The cooling of the core melt in a severe accident is complicated in this plant type, so its successful functioning is difficult to prove" (NW 2003) .

In November 2009, the nuclear safety regulators from Finland, France, and the United Kingdom issued a joint statement that focused on the EPR's Instrumentation and Control (I&C) system, noting that AREVA's design "doesn't comply with the independence principle, as there is a very high degree of complex interconnectivity between the control and safety systems."

Finally, a third problem with EPR costs has been the use of different supply chains. This implies that there is little scope for learning and and economies of scale to help lower costs. In future proposed projects, again, Areva promises "significant subcontracting to local British, American and Indian companies" (Chaffee 2011b, 6).

The EPR is also a good illustration of the inapplicability of the idea that capital costs of nuclear reactors decrease with experience and learning. Historically, the French nuclear industry, arguably the most successful case of "scale up experience in an industrialized country", and one based on a standard Pressurized Water Reactor design, has exhibited a remarkably consistent increase in costs (in real Francs) over the roughly two and half decades over which the current operating fleet was constructed (Grubler 2009). The EPR takes this trend to a new level.

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[1] The supplementary materials referred to in this paper, including (a) a Mathematica script to compute the tariff (b) an Excel spreadsheet to do the same (c) an email to the Executive Director of the NPCIL (d) the minutes of the meeting between KBS and NPCIL are available at http://www.suvratraju.net/eprdocs and http://mvramana.yolasite.com/nuclear-2013.php. These documents are available from the authors on request.

[2] Translating the reported international figures into an "overnight cost" is necessarily somewhat imprecise, since the NPCIL excludes the cost of debt-servicing and inflation during construction from its definition of the "overnight cost." Moreover, the international figures also have to be inflated since construction on the EPR is likely to start only after a few years. This is another reason that we take the overnight cost to be a variable in our final results.

[3] It is worth anticipating and rebutting one response from the establishment: the popular resistance to Kudankulam can be blamed, at most, for about six months of this delay. For most of this time, the state used repressive techniques to continue with reactor-construction, and delays appear to have been caused by technical holdups and due to the inefficiency of the NPCIL and other agencies involved.

[4] According to a very basic principle in physics, one factor that determines the efficiency of engines is the temperature of the "reservoir" into which they can deposit heat at the end of every cycle. Cold reservoirs lead to better efficiency than warmer ones.

[5] This is the reported price value after the slump due to the Fukushima accidents.

[6] NPCIL's argument for why it assumes a lower rate of inflation for uranium fuel costs is that there will be new sources of uranium in the future (Thakur 2008, 65). However, the nuclear establishment on the whole has been using exactly the opposite argument—that uranium will become scarce in the future—to justify its pursuit of expensive and unsafe breeder reactors.

[7] This report was authored by Francois Roussely, European vice-president of Credit Suisse and honorary president of EDF, and was commissioned in the aftermath of France losing a contract to supply nuclear reactors to the UAE.