ECONOMICS OF FAST BREEDER REACTORS

INDIAN SCENARIO

Anshu Bharadwaj | S. Rajgopal | L. V. Krishnan | K. C. Bellarmine

Center for Study of Science, Technology and Policy

ECONOMICS OF
FAST BREEDER REACTORS
INDIAN SCENARIO

Anshu Bharadwaj | S. Rajgopal | L. V. Krishnan | K. C. Bellarmine

Center for Study of Science, Technology and Policy

CSTEP is a not for profit research organisation incorporated in 2005 u/s 25 of The Companies Act, 1956. Its vision is to enrich the nation with technology-enabled policy options for equitable growth. The mission is to impact policy by assessing and designing science and technology options with informed and systematic analysis for equitable and inclusive human development and economic growth.

Cover page: Seaside view of Prototype Fast Breeder Reactor under construction at Kalpakkam, Tamil Nadu
Back page: PFBR - Safety Vessel Erection, Approach Jetty and Control Room
Photographs courtesy: *Bharatiya Nabhikiya Vidyut Nigam Limited*

Printed in India at S.L.Digital Inc., Bangalore

ISBN 978-81-903613-2-3

CSTEP/E/02/2012

March 2012

Table of Contents

Acknowledgements

Authors are grateful to several experts who provided key insights, inputs and feedback while preparing this report. We thank Prof. V. S. Arunachalam, Chairman, CSTEP, Dr. R. Krishnan, Chief Advisor, CSTEP and Dr. Rahul Tongia, Principal Research Scientist, CSTEP, for their valuable suggestions and critical feedback. We also thank Bhargavi Kerur and Tejas Pande for editing and designing the report.

We gratefully acknowledge the financial support from International Development Research Centre, OAK Foundation and Wipro.

Executive Summary

Fast Breeder Reactors (FBR) are expected to play a major role in India's power program and help utilise the country's large thorium (Th) reserves. Three decades of operation and maintenance of the Fast Breeder Test Reactor (FBTR) with no serious problems has provided confidence to pursue the FBR program. Yet, there are concerns in the public mind regarding safety, proliferation and economic viability of FBRs. This study examines the economic viability of FBRs. A similar study on the safety aspects is also planned.

The total cost of the 500 MW FBR has been assessed at Rs.5,677crore based on the last revised cost of the Prototype Fast Breeder Reactor (PFBR) being built at Kalpakkam, Tamil Nadu. The Fast Reactor Fuel Cycle Facility (FRFCF) comprising fuel fabrication, fuel reprocessing and waste disposal facilities is estimated to cost Rs.2,731crore. Plutonium (Pu) being a strategic material is owned by the Government. In our economic analysis, we have arrived at the cost of Pu as Rs.6,525 per g ($ 145). The cost of Pu required for the project is estimated at Rs.2,610crore. It is treated as Government's contribution to the cost of project on which, it will earn a fuel usage charge. Providing for the cost of Pu is important from the perspective of building FBRs on commercial basis.

Based on assumptions including Plant Load Factor (PLF) of 75%, O&M expenses at 2.5%, plant life of the FBR and FRFCF at 40 and 15 years respectively, decommissioning and waste disposal costs at 10% of the overnight capital cost and a discounting rate of 12%, the Levelised Cost of Electricity (LCOE) works out to Rs. 5.49 per kWh. Capex at 45% is the major component of LCOE, followed by reprocessing costs of 24% and fuel usage charges of 19%. A sensitivity analysis comparing varying capital costs, load factors, discounting rates and O&M expenses indicates the LCOE to be in range of Rs.5 to Rs.7 per kWh. While this may be higher compared to other sources such as coal, gas and thermal nuclear reactors, considering that the PFBR is a first of its kind built in the country, the LCOE is not significantly higher than the conventional power generating sources. Further, there may be scope for cost reductions with learning and standardisation of technology. It is therefore worthwhile to pursue this option to meet India's growing energy requirements and energy security subject to addressing the safety and security issues.

Introduction

An article published in 1998 in the Current Science, titled "India's nuclear breeders: Technology, viability and options", Tongia and Arunachalam projected the growth of FBRs to be slow and identified various reasons for drawing such a conclusion[1]. They suggested constructing large number of thermal reactors, both indigenous and imported, to achieve rapid growth in nuclear power. They also suggested focused R&D on fast reactors with metallic fuel, which have shorter doubling time so as to hasten transition to reactors that operate on thorium (Th) and plutonium (Pu) fuels.

We seem to be following this very path now with the Department of Atomic Energy's (DAE) plan to import 40 GWe of Light Water Reactors (LWR) for meeting our immediate power needs. This would also accelerate the FBR program, which is expected to be the backbone of the nuclear power program[2]. The success of FBRs would determine how soon we can move on to Th, a large resource this country is endowed with and has the potential to provide the much needed energy security.

There are arguments against fast breeders citing abundance of uranium (U), proven thermal reactor technologies, hazards due to sodium coolant fires and concerns of separation of Pu and its nuclear weapon proliferation aspects. Coupled with this is the general perception that the FBRs are less economical than thermal reactors. These arguments have led to several countries giving up their FBR programs. Presently Russia, China and Japan continue to pursue this technology. India is also following this technology as it is not well endowed in energy resources. The operation and maintenance of FBTR for over three decades without any serious problem has provided confidence to continue with building FBRs.

This study assesses the cost of electricity from FBR and compares it with other sources of electricity. However, the study is constrained to an extent by lack of data in public domain, but the margin of error is believed to be within acceptable limits.

The Program

As stated earlier, India is among the few countries pursuing the FBR program. This is driven by India's limited U reserves (61,000 t), which constrain its nuclear power program. However, India is endowed with large Th deposits (around 2,25,000 t), and Th utilisation is a long-term objective of planners to achieve energy security. With this objective, India embarked on a three-stage nuclear power program:

Stage I:	Pressurised Heavy Water Reactors (PHWR) using natural U fuel: Proven domestic U reserves can sustain 10,000 MW for about 40 years[3].
Stage II:	FBRs using Pu recovered from spent fuel discharged by PHWRs.
Stage III:	Th based reactors utilising excess Pu available from Stage II.

The FBR is a bridge to Th utilisation and to multiply installed nuclear power capacity several fold from the limit of 10,000 MW (PHWR) imposed by domestic U availability [a].

India's present nuclear installed capacity is 4,780 MW, almost entirely based on PHWRs. With two imported LWRs, each of 1000 MW and one 500 MW PFBR to be commissioned shortly, the installed capacity would reach 7,280 MW. DAE is also developing a 300 MW Advanced Heavy Water Reactor (AHWR) using Th as fuel.

DAE's plan is to build up to 40,000 MW of LWRs by importing technology and build another 5,600 MW of PHWRs making use of the access to global markets of U, pursuant to the Indo-US agreement for cooperation in civilian nuclear power. Further, there are ambitious plans to use the spent fuel from these thermal reactors to build a large number of FBRs. A DAE publication projects FBRs at about 1,00,000 MW by 2030 and close to 5,00,000 MW by 2050,[4] which would be almost 50% of India's total generation capacity. However, a CSTEP study estimated this figure to be more likely at 2,00,000 MW[5] assuming vigorous progress in spent fuel reprocessing.

[a]*MW refers to MW (electrical)*

Objective

If FBRs are expected to play a major role in India's future power program mix, it is important to examine in detail all issues including economics, safety, and security. In this study, we have evaluated the economics of electricity from FBRs. We propose to examine safety and security aspects in a future work. This report also compares the cost of electricity from PFBR with other sources including PHWRs.

Brief History of FBR

The concept of using Pu as fuel in civilian reactors originated during World War II. It gained momentum because of concerns that global U resources may not be sufficient to support the rapidly growing nuclear program. Over twenty fast reactors have been built in the world so far. The US was the first to build an Experimental Breeder Reactor (EBR) in 1951; they followed it by commissioning another in 1963. Russia continues to build fast reactors. France has suspended the program now after building PHENIX and SUPER PHENIX[6]. UK also has suspended the program after building and experimenting with two FBRs. Japan has built two experimental reactors (Joyo and Monju). China has recently commissioned its first experimental fast reactor and is building two commercial fast reactors. India has designed and built a 40 MW_{th} FBTR, which is in operation for more than 25 years. Based on this experience, India is now building a 500 MW PFBR at Kalpakkam and there are plans to build two more reactors of similar capacity.

However, the fast breeder reactor technology has remained controversial. Several analysts feel that at the present cost of U, reprocessing spent fuel is not economical compared to direct disposal[7]. Further, recent studies have allayed the concerns about global availability of U[8]. Finally, there are apprehensions about the use of liquid sodium as coolant, in addition to proliferation[9] related issues. On the other hand, nuclear waste reduction and achieving energy security are positive aspects of FBRs.

Fast Reactor Fuel Cycle

The fuel for PFBR is a combination of oxides of Pu (PuO_2) and U (UO_2). Pu doesn't occur naturally and is derived from reprocessing the spent fuel discharged from the thermal reactors. A tonne of spent fuel from PHWR contains about 3.75 kg of Pu. A 500 MW FBR requires roughly 2 t of PuO_2 and 10 t of UO_2 in the core. The fertile U^{238} in UO_2 gets converted to fissile Pu^{239}. Figure 1 shows the fuel cycle for the fast breeder reactor.

Breeding Ratio (BR) is defined as the amount of fissile material produced per unit of fissile material consumed. Ideally, an FBR should have a BR of more than 1 so that it generates excess fissile material that could be used in new reactors. For the PFBR, BR is predicted to range between 1.05 – 1.08[10]. The future FBRs proposed to be built in 2020 and beyond are expected to use metallic fuels, which would result in higher BR.

One-third of the fuel in the PFBR core is removed at the end of the 240 days[11] and is placed within the reactor in specific locations for in-core cooling. Thereafter, the discharged fuel is taken out and transferred to the spent fuel pool for further cooling. It is then reprocessed to obtain Pu, which is mixed with depleted U and used to refabricate the fuel to be fed back to the reactor. Any surplus Pu generated can be accumulated and used to start a new FBR. The waste arising out of all these operations is processed for disposal ensuring safety of the environment and the public.

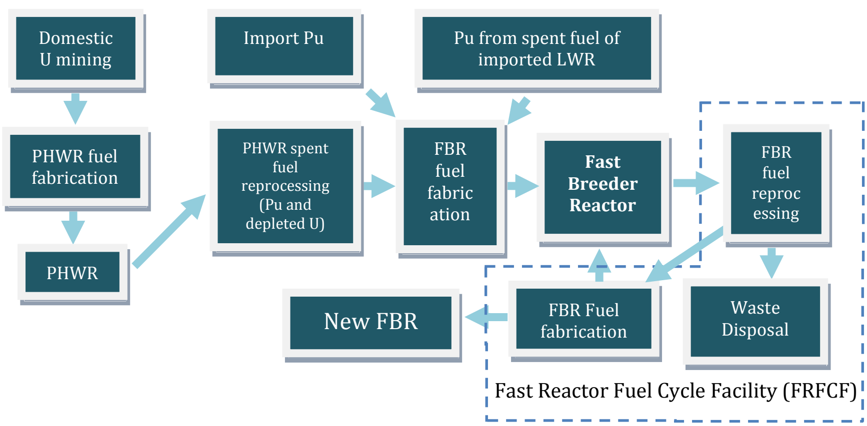

Figure 1 Fuel cycle for Fast Breeder Reactor using reprocessed spent fuel from PHWRs including possibility of reprocessing LWR spent fuel and importing Pu.

Reprocessing

India has two reprocessing plants at Tarapur and Kalpakkam, each with a capacity to reprocess 100 t of PHWR spent fuel. These have been operating for a considerable time and it is understood that the Pu required for the PFBR is already available. However, as mentioned in our earlier study,[12] the present reprocessing capacity is totally inadequate to meet the requirements of large number of FBRs being planned. India needs to add 2,800 t of reprocessing capacity in a phased manner to meet the requirement of the fast breeder program. This requires considerable effort and large investments.

We therefore feel that India should also explore the possibility of importing Pu or getting the Indian spent fuel reprocessed in countries such as UK, France and Russia. The reprocessing plants in UK and France produce Pu for use as Mixed Oxide (MOX) fuel in LWRs. In addition, there is a global stockpile of Pu released from dismantled nuclear weapons, which could be used for FBRs under international safeguards.

The signing of Indo-US nuclear agreement makes these options technically possible. However, these depend on economics and geo-political considerations. We do realise that geo-politics are complicated, but it is still an option worth considering.

Methodology

Capital Cost

The aggregate capital cost of FBR complex includes cost of the nuclear reactor and fuel cycle facility including waste immobilisation plant. Pu, being a strategic material, is owned by the Government of India (GOI). Therefore, the cost of the initial load of Pu is assumed to be part of GOI's contribution to the total capital cost of FBR. In turn, the FBR will pay fuel usage charges. This has been included in the levelised cost of electricity (LCOE) calculations.

We have estimated the capital costs of these components based on the data made available for the PFBR, which is under construction. In addition, we have relied on other published data, in-house research and private communication with relevant sources.

Cost of PFBR

The capital cost of PFBR includes the cost of nuclear island, conventional island, balance of plant, township, etc. The original capital cost of the PFBR was estimated to be Rs.3,500crore[13]. This was recently revised to Rs.5,677crore[14]. This works out to Rs.11crore per MW ($2,523 per kW)[b]. The increase in cost was attributed to increase in input cost and township. To put this in perspective, the two 700 MW PHWRs being built at Kakrapar (Gujarat) are expected to cost Rs.15,000crore ($2,380 per kW)[15]. The two 1,000 MW LWRs in Kudankulam(Tamil Nadu) are expected to cost Rs.16,000crore ($1,778 per kW).

International estimates of FBR costs vary and are invariably higher than that of the thermal reactors. For instance, Nuclear Energy Agency (NEA) estimated the cost of fast reactors at $2,000-2,800 (2004$)[16]. The cost of French Phenix reactor (250 MW) was FRF 800 million (1974), or $3,200 per kW[17]. Given the international experience, the capital cost of PFBR does appear low. However, in the absence of any other data, we have assumed DAE's cost estimate and carried out a sensitivity analysis for a range of $2,250-$3,250 per kW.

Fuel Cycle Facility

The Indira Gandhi Centre for Atomic Research (IGCAR) has done extensive R&D in the domain of reprocessing of FBTR fuel from its early days of inception. The first facility called Compact Reprocessing of Advanced Fuel in Lead Shielded Cells (CORAL) established the feasibility of reprocessing carbide fuel as well as design parameters for the future plant called Demonstration Fast Breeder Reprocessing Plant (DFRP) and a commercial scale Fast Reactor Fuel Cycle Facility (FRFCF). The integrated FRFCF is assumed to have a balanced capacity to reprocess the discharged fuel from 500 MW PFBR and are expected to cost Rs.5,000crore[18]. The two proposed 500 MW FBRs planned at this site are estimated to add an expenditure of Rs.1,000crore towards the FRFCF. The life of a reprocessing plant is typically 15 years. The lower plant life is attributed to the highly corrosive and aggressive fluids used in the processes. However, it is assumed that the plant can be refurbished at 15 year intervals to match the life of the PFBR. Hence, the total apportioned cost of the FRFCF for the 500 MW FBR (including two refurbishings) is estimated to be Rs.2,731crore.

---

[b] *1USD = Rs.45*

Plutonium

The FBR requires an initial load of about four tonnes of Pu, of which about two tonnes is loaded into the reactor core while the remaining forms the out-of-pile inventory. At the end of the first year, one-third of the core is removed for reprocessing after allowing sufficient time (240 days) for in-core cooling. It is assumed that it would take about two years for the reprocessed and refabricated fuel to be available for loading into the reactor core. Therefore, the initial few loads of Pu would have to come from out-of-pile inventory.

The DAE has not assumed any cost for the initial load of Pu in the PFBR. This is probably because Pu is a strategic material, and its ownership rests with the GOI. However, we believe that a true costing of FBR on commercial basis requires the cost of Pu to be taken into consideration. This would also be the case if India were to get the spent fuel reprocessed abroad or import Pu.

We have estimated the cost of Pu reprocessed from PHWR spent fuel at $145 per gram based on assumptions given in Table 1. This is observed to be similar to the results obtained in another study[19]. The cost of 4 t of Pu for the FBR is estimated to be Rs.2,610crore. The cost of PHWR spent fuel is assumed to be nil, which is the globally followed practice.

Pu content in spent fuel	3 kg per t
Efficiency of reprocessing plant	70%
Capital Cost of reprocessing plant	Rs.5crore per t of spent fuel [20] (adjusted for cost escalation at 5% p.a.)
Weighted average cost of capital	12%
O & M Cost	5%
Life of plant	15 years
Cost of spent fuel	Nil

Table 1 Cost assumptions for PHWR spent fuel reprocessing

Working Capital

The aggregate requirement of long term working capital has been assumed at Rs.382crore which is provided in the cost of PFBR. This is based on receivables of one month of Rs.185crore and cost of certain critical spares and consumables assumed at Rs.197crore.

Assumptions

Table 2 summarises the cost estimates.

Particulars	Nominal Value	Range assumed for sensitivity analysis
Capital cost of FBR	Rs.5,677crore ($2,523 per kW)	$2,250 – $3,250 per kW
Cost of Pu	Rs.6,525 per g ($145)	
Capital cost of FRFCF	Rs.2,731crore ($1,214 per kW)	
Plant Load Factor	75%	55% to 95%
Financing	Debt Equity Ratio: 1	
Weighted average cost of capital	12%	6% to 16%
Plant life	40 years (FBR); 15 years (FRFCF)	
Captive consumption	6% for FBR and 3% for FRFCF	
O & M	2.5% of capital cost	2% to 4%

Table 2 Key assumptions for FBR costing, profitability and sensitivity analysis

a. Means of financing: The PFBR is being built by the government with 100% equity contribution. However, we have assumed that for a realistic cost assessment of future FBRs, we need to consider commercial borrowings, as is the case with fossil fuel based power projects. For nuclear projects, market borrowings may be possible only with some level of government guarantees, as is the practice in the US. In this study, we have assumed a debt - equity ratio of 1:1. Further, the cost of government guaranteed debt and return on equity are both assumed to be 12%. Therefore, the Weighted Average Cost of Capital (WACC) for the project is 12%.

b. Debt Service Coverage Ratio (DSCR): The proposed debt is assumed to have a moratorium of 24 months from the date of full scale commercial operations and would be amortised over the next 12 years. Based on the above means of financing and the profitability assumptions detailed below, the average DSCR for the debt works out to a comfortable level of 2.14 times.
c. Plant life: We have assumed the useful life of FBR to be 40 years. It could be extended by refurbishing and relicensing as has been the experience with LWRs.
d. Plant load factor (PLF): DAE assumes a normative PLF of 68.5%. The actual experience could vary significantly; the PLF could be much lower in the initial years and stabilise at a higher value subsequently. We have therefore assumed a normative PLF of 75%.
e. Captive (auxiliary) consumption: It has been assumed at 9% of gross generation comprising 6% for the nuclear reactor and 3% for the FRFCF (1% each for the Fuel Reprocessing Plant (FRP), Fuel Fabrication Plant (FFP) and Waste Immobilisation Plant (WIP).
f. Operating and Maintenance Costs: 2.5% of the total capital cost excluding cost of initial load of Pu.
g. De-commissioning and waste disposal costs: 10% of the overnight aggregate capital cost spread over the life of the project.
h. Reprocessing efficiency: One-third of the core is discharged every year for reprocessing at the FRFCF. The FBR is reported to have a BR of 1.05[21]. We have assumed the combined losses in reprocessing and fuel fabrication to be 5%, which would obviate the need for any further addition of Pu.
i. Since significant quantity of depleted U is already available, we have not assigned any cost to the same.
j. Insurance premium costs have been assumed at 0.5% per annum of the capital cost.

Levelised Cost of Energy (LCOE)

LCOE has been worked out on the discounted cash flow method[22&23] with the life of the project taken at 40 years and discounting rate at 12%. The LCOE consists of the following components:

- Cost of capital for FBR
- O&M costs for FBR
- Fuel charge for initial load of Pu (4 t)
- Fuel reprocessing, fabrication and waste immobilisation costs
- De-commissioning and waste disposal cost
- Insurance cost

$$LCOE = \frac{C_0\left[\frac{r}{1-(1+r)^{-t}}\right]}{Q} + F + O$$

where: Co = Capital cost
r = rate of interest (discounting rate)
t = life of plant in years
Q = annual output (kWh)
F = Fuel costs
O = O&M and other costs

Results and Discussion

The FBR is expected to generate about 3 billion kWh (Net) per annum at a PLF of 75%. The LCOE for the base assumptions listed in Table 3 works out to Rs.5.49 per kWh. FBR is highly capital intensive and therefore, the capital cost accounts for the major part of LCOE (45%). The fuel usage charge on the initial load of Pu contributes to 19%. The cost of reprocessing, fuel fabrication and waste immobilisation accounts for 24%. The O&M expenses contribute to 9% of the LCOE (Table 3 and Figure 2).

The DAE had initially estimated an LCOE of Rs.3.25 per kWh, which was later revised to Rs.4.44 per kWh[24]. Our estimates of the LCOE are higher by 24% mainly on account of the fuel charge on initial load of Pu, which has not been considered by DAE.

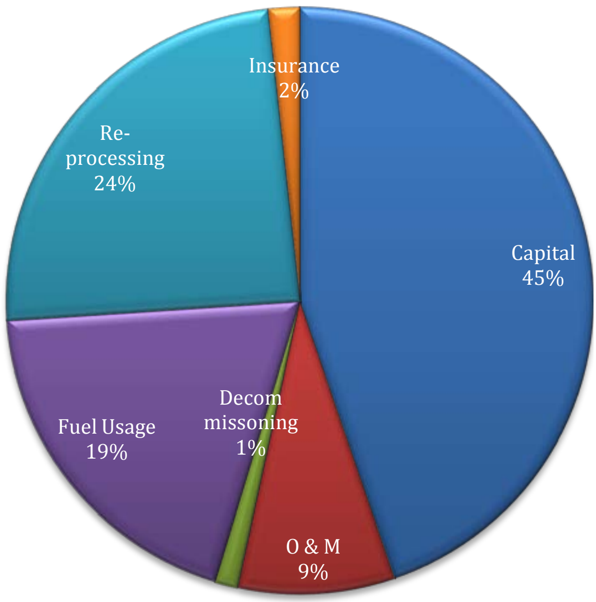

Figure 2 Components of LCOE

Installed capacity (MW)	500
Load Factor (%)	75
Gross generation (million kWh)	3,285
Net generation (million kWh)	2,989
LCOE (Rs.per kWh)	
Cost of capital	2.46
O&M Cost	0.47
Fuel usage charges (Initial load of Pu)	1.06
Fuel reprocessing and fabrication	1.34
Decommissioning and waste disposal	0.07
Insurance	0.09
Total LCOE	**5.49**

Table 3 Components of LCOE

For comparison, Figure 3 shows the LCOE for other sources of electricity. Clearly, FBR is more expensive than coal, gas and thermal nuclear reactors, while being lower than that of solar. However, it should be reiterated that this is the first FBR being built in the country and therefore there is scope for cost reduction with standardisation of technology and serial building. Given that FBR is an important component in India's quest for energy security and a link to the eventual utilisation of Th, there is merit in pursuing this technology.

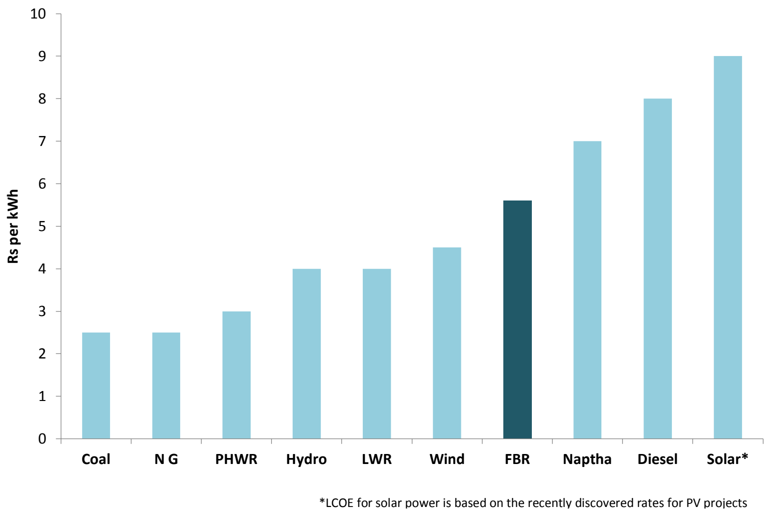

Figure 3 Indicative LCOE from various sources

Sensitivity Analysis

The capital cost of FBR has significant impact on LCOE. We have assumed a base capital cost as reported by DAE (Rs.5,677crore). The reactor is still under construction and the final cost may be higher. At the same time, the cost of future FBRs may become lower on account of learning acquired from this project. We have therefore, varied the capital cost from $2,250 per kW to $3,250 per kW in our sensitivity analysis. Accordingly, the LCOE varies from Rs.5.18 per kWh to Rs. 6.34 per kWh.

LCOE is also very sensitive to PLF. We have assumed a base PLF of 75%, at which LCOE is Rs.5.49 per kWh and it varies from Rs.4.34-Rs.7.49 per kWh as the PLF varies from 95% to 55%.

We have assumed a project discount rate of 12%, which is a reasonable assumption in the Indian context. However, given that LCOE is highly sensitive to discounting rates, we have varied it from 6-16%. Accordingly, the LCOE varies from Rs.3.4 to Rs.7 per kWh.

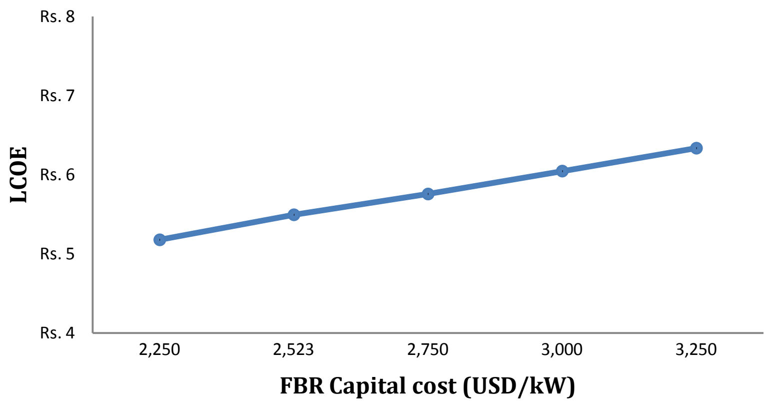

Figure 4a LCOE of FBR as a function of capital cost

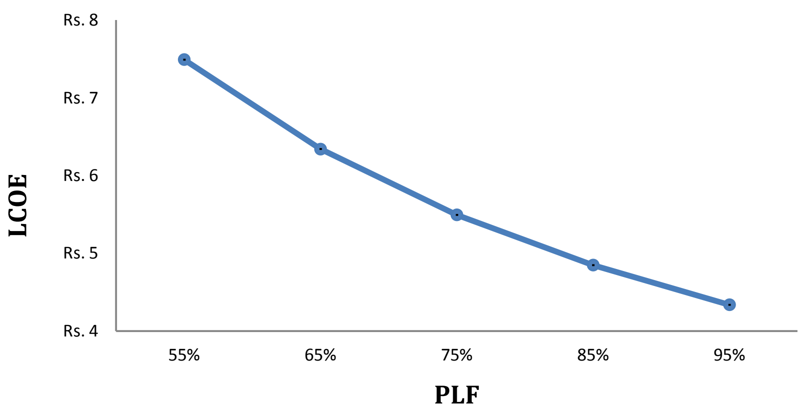

Figure 4b LCOE of FBR as a function of PLF

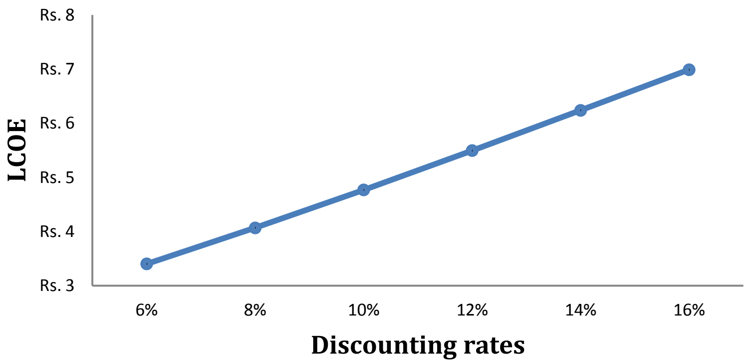

Figure 4c **LCOE of FBR as a function of discounting rates**

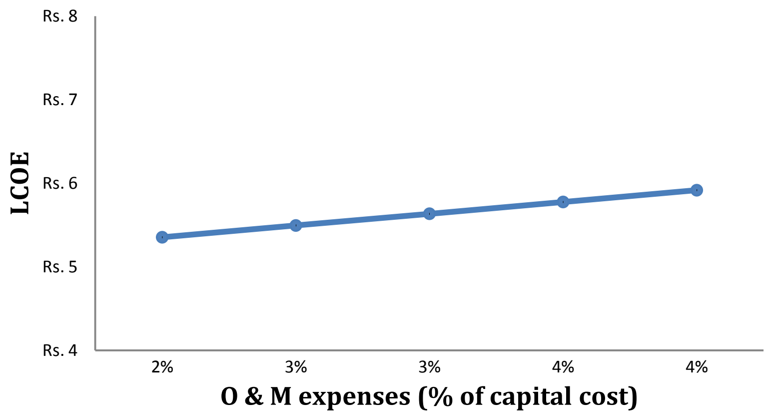

Figure 4d **LCOE of FBR as a function of O&M expenses**

Conclusions

After having built and operated fast reactors, some countries have chosen to develop their nuclear power program around LWRs, citing abundance of U and unfavourable economics of reprocessing. Russia and China however continue to build fast reactors. India's decision to pursue FBRs is based on shortage of domestic U and also the desire to utilise large Th reserves to ensure energy security.

This study focuses on the economics of FBR. It is hard to obtain credible cost data and therefore, this study is based on inputs from several sources. We have accounted for the economic value of the initial load of Pu. This is important, especially if FBRs have to be built on a large scale on commercial basis. The calculations suggest that LCOE for FBR is expected to be in the range Rs.5.5 to Rs.7 per kWh depending on the key assumptions of PLF, capital cost and discount rate.

The LCOE is higher than that of other sources such as coal, gas and thermal nuclear reactors, while being lower than that of solar power. Considering that PFBR is a first of its kind being built in the country, the LCOE is not significantly higher than that of conventional power generation sources. There is scope for cost reductions with learning and standardisation of technology. It is therefore worthwhile to pursue this option to meet India's growing energy requirements subject to safety and security issues fully addressed.

Future expansion of FBR program depends on the availability of Pu, which calls for building several reprocessing plants. As an alternative, India could consider reprocessing spent fuel in facilities abroad or importing Pu to speed up the FBR program subject to economics and geo-political considerations.

We have not considered the safety, security and proliferation concerns often raised about FBRs, but plan to examine them in a future work.

References

1 *Rahul Tongia and V S Arunachalam, "India's nuclear breeders: Technology, viability and options" Current Science, Vol.25, No.6, 25 September 1998*

2 *Kakodkar A., "Evolving Indian Nuclear Programme : Rationale and Perspectives", 4 July, 2008*

3 *Department of Atomic Energy, "A Strategy for Growth of Electrical Energy in India", August 2004*

4 *Ibid, (3) above*

5 *Anshu Bharadwaj, et.al. CSTEP, "Nuclear Power in India: The Road Ahead", October 2008*

6 *Thomas B Cochran, et.al. International Panel on Fissile Materials, "Fast Breeder Reactor Programs: History and Status", February 2010*

7 *Matthew Bunn, et.al., The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel, July 2003; and Peter R. Orszag, Cost of Reprocessing vs. Directly Disposing of Spent Nuclear Fuel, CBO Testimony, November 2007*

8 *International Atomic Energy Agency, Vienna (IAEA), "Analysis of Uranium Supply to 2050" May 2001; and IAEA, "Latest Data Shows Long term Security of Uranium Supply", Press Release, July 2010*

9 *Alexander Glaser, et.al., Weapons Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor, May 2007*

10 *Ibid, (9) above*

11 *Indira Gandhi Center for Atomic Research, (IGCAR), Annual Report 2020, Chapter 4, Fuel Cycle*

12 *Ibid, (5) above*

13 *The Hindu Business Line, India's first fast Breeder reactor to cost Rs.2,177 crore more, April 30, 2011*

14 *Ibid, (13) above*

15 *Personal Communication, October 2011*

16 *Ramana M.V., India and fast Breeder Reactors, Science and Global Security, April 2009*

17 *Ibid, (16) above*

18 *Baldev Raj, Director of IGCAR as told to IANS, September 06, 2011*

19 *Ramana M.V, et.al., Costing Plutonium : economics of reprocessing in India, Int. J. Global Energy Issues, Vol.27, No.4, 2007*

20 *Ibid, (5) above*

21 *Ibid, (9) above*

22 *Denise Grubert, et.al. "Nuclear Processing in the US : A Levelized Cost Analysis" Duke University, 2009*

23 *OECD/IEA (2005), p.173 f, quoted by Stefan Thomas, Wuppertal Institute*

24 *Prabhat Kumar, Director, Bharatiya Nabhikiya Vidyut Nigam Limited, as told to IANS, April 30, 2011*

Bibliography:

i *Schneider E.A. et.al, "Cost Analysis of the US spent nuclear fuel reprocessing facility", Energy Economics 31 (2009) 627-634*

ii *Byung Heung Park, et.al., "Comparative Study of different nuclear fuel cycle options: Quantitative analysis on material flow", Energy Policy 39 (2011) 6916-6924*

iii *M. Jonathan Haire, "Nuclear Fuel Reprocessing Costs", Oak Ridge National Laboratory, October 2003*

Authors

Anshu Bharadwaj

Dr. Bharadwaj is a B.Tech in Mechanical Engineering from the Indian Institute of Technology, Kanpur and PGDM from the Indian Institute of Management, Kolkota. He joined the Indian Administrative Services (IAS) (Karnataka 1992) and worked for the Government of Karnataka till 2007. He got his twin PhD from Department of Engineering and Public Policy and Mechanical Engineering, Carnegie Mellon University. His interests are in emerging technology and fuel options in India's energy sector. He specialises in computational modeling of energy systems. He is presently the Executive Director of CSTEP.

S. Rajgopal

Mr. Rajgopal is a graduate of the College of Engineering, Guindy and Post Graduate Diploma in Systems Management from Jamnalal Institute of Management, Mumbai. He started his career with the Neyveli Lignite Corporation and subsequently moved to the Department of Atomic Energy. He was the Secretary, Atomic Energy Commission and Controller, Bhabha Atomic Research Centre. He headed the technical liaison mission in Paris after being a fellow of IAEA at South West Research Institute, US. He was a visiting professor and Dean at the National Institute of Advanced Studies (NIAS), Bangalore.

L. V. Krishnan

Mr. Krishnan graduated in Physics with an Honors Degree from Presidency College, Chennai. He joined the Training School of the then Atomic Energy Establishment, Trombay and served in the Health Physics Division of Bhabha Atomic Research Centre. He specialized in Safety Analysis of Nuclear Facilities at the Oak Ridge School of Reactor Technology. He established a Safety Research Laboratory at IGCAR, Kalpakkam and retired as Director of the Safety Research and Health Physics Program.

K. C. Bellarmine

Dr. Bellarmine has a Ph.D. in industrial fisheries from Cochin University of Science and Technology. He has been with financial services sector for over two decades and has expertise in investment and corporate banking, structured financing and distressed assets. At ICICI Limited/ICICI Bank, he appraised/structured funding arrangements for several large and medium projects/companies in a wide range of industries. He is presently the Chief Financial Officer at CSTEP.

CSTEP

Center for Study of Science, Technology and Policy
Dr.Raja Ramanna Complex, Raj Bhavan Circle, High Grounds, Bangalore – 560 001

Tel : +91 80 4249 0000
Fax : +91 80 2237 2619

www.cstep.in
admin@cstep.in