The economics of nuclear power

The Divecha Centre for Climate Change, Indian Institute of Science, Bangalore, organized a seminar on 29 August 2011. The speaker was M. V. Ramana, who is currently with the Nuclear Futures Laboratory and Program on Science and Global Security at the Woodrow Wilson School of Public and International Affairs, Princeton University, USA. He studies the future of nuclear energy against the backdrop of climate change and nuclear disarmament, and is presently completing a book on nuclear power in India.

Ramana spoke about why nuclear power is important in the climate-change scenario – nuclear reactors involve little or no burning of fossil fuels. But there exists a debate on the amount of carbon emissions from the complete nuclear fuel chain. The estimates range from 1.4 to 200 g/kWh[1] (see Figure 1). Small estimates are not comprehensive and/or assume country-specific conditions (e.g. Vattenfall, the Swedish power company). Large estimates assume poor uranium ore grades (with current technology; extrapolated) and enrichment by gaseous diffusion (not centrifuges).

Nuclear power is seen by some as a partial solution to climate change. The obvious supporters include nuclear establishments, but the 'surprising' supporters comprise some environmentalists like James Lovelock. One of the 15 strategies proposed by Stephen Pacala and Robert Socolow as part of their wedge model is to substitute nuclear power for coal power. The addition of 700 GW of nuclear power, i.e. roughly twice the current global capacity, would constitute one wedge and could reduce one billion tonnes of carbon by mid-century. (The other 14 strategies include: efficient vehicles; reduced use of vehicles; efficient buildings; efficient baseload coal plants; gas baseload power for coal baseload power; capture CO_2 at baseload power plant; capture CO_2 at H_2 plant; capture CO_2 at coal-to-synfuels plant and geological storage; wind power for coal power; PV power for coal power; wind H_2 in fuel-cell car for gasoline in hybrid car; biomass fuel for fossil fuel; reduced deforestation, plus reforestation, afforestation, and new plantations, and conservation tillage; see also http://www.princeton.edu/mae/people/faculty/socolow/Science-2004-SW-1100103-PAPER-AND-SOM.pdf.)

Ramana said that many integrated assessment models also project large requirements of nuclear power: 3000–4000 GW by the end of the century. These estimates are based on assumptions about the relative costs of nuclear power versus renewables versus coal with carbon capture and sequestration. He compared these requirements to the current levels of nuclear power deployed around the world. In May 2011, there were 439 reactors in ~44 countries. The United States had the highest number (>100) supplying ~20% of its energy, whereas France had ~60 reactors (second highest) providing ~75% of its energy. Next came Japan, the Russian Federation, Republic of Korea and India. Some countries have many reactors, some none.

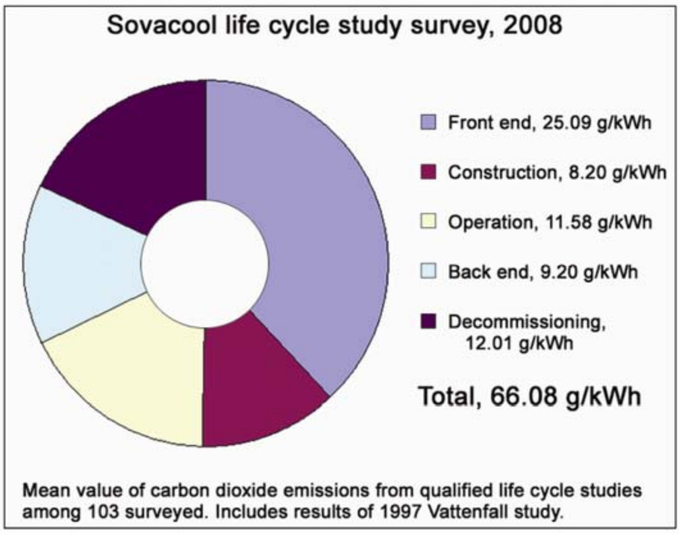
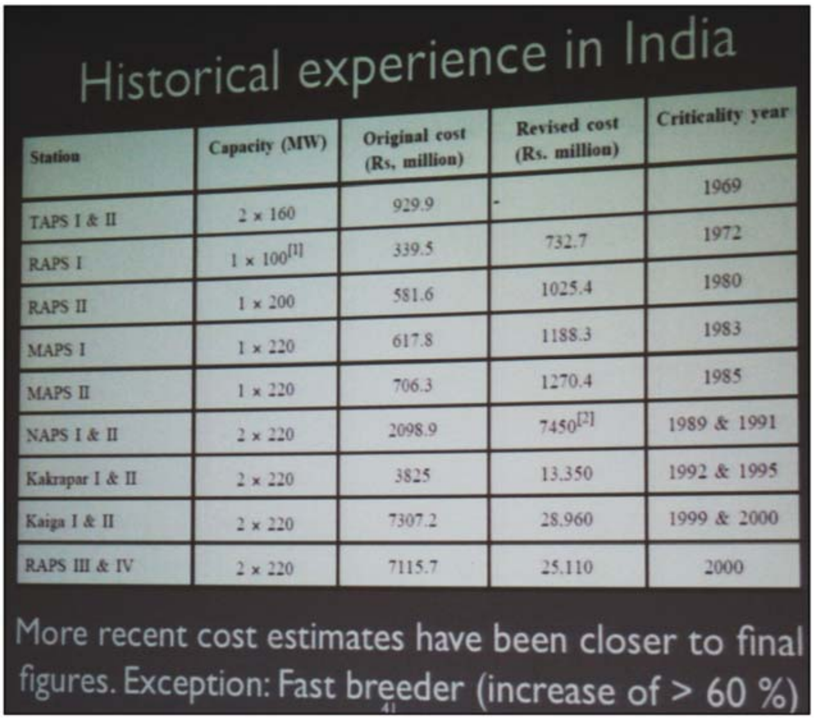


Figure 1. Carbon emissions from nuclear power. Source: http://en.wikipedia.org/wiki/File:Sovacool_2008_life-cycle_study.png.

Most reactors were constructed in the 1970s (in USA) and 1980s (in Western Europe). In the mid-1980s, reactor start-ups declined and in recent years, the number of shutdowns has sometimes exceeded the number of start-ups. Most construction has been concentrated in Asia. According to Ramana, projections have been made for nuclear energy by the International Energy Agency and the International Atomic Energy Agency, but these need to be taken 'with a pinch of salt' in view of the vast discrepancies between past projections and what actually materialized.

The key issues regarding nuclear power comprise economics, resources (sustainability), nuclear proliferation, safety (accidents and sabotage), nuclear waste and public acceptance/acceptability. In his talk, Ramana focused on the economics. He started with some past assumptions about the economics of nuclear power: (i) 'Too cheap to meter' (Lewis Strauss, 1954); (ii) 'During the next 10 to 15 years…the costs of (nuclear) power (would) compare very favourably with the cost of power from conventional sources in many areas' (Homi Bhabha, 1958); (iii) Nuclear power compared 'quite favourably with coal fired stations located 800 km away from the pithead… in the 1990s would be even cheaper than coal fired stations at pithead' (M. R. Srinivasan, 1985); and also compared them with a conflicting statement by C. G. Suits, Vice President and Director of Research of General Electric (1950): 'At present, atomic power presents an exceptionally costly and inconvenient means of obtaining energy which can be extracted more economically from conventional fuels…The economics of atomic power are not attractive at present, nor are they likely to be for a long time in the future.' A debate exists as to whether in future nuclear power would become cheap.

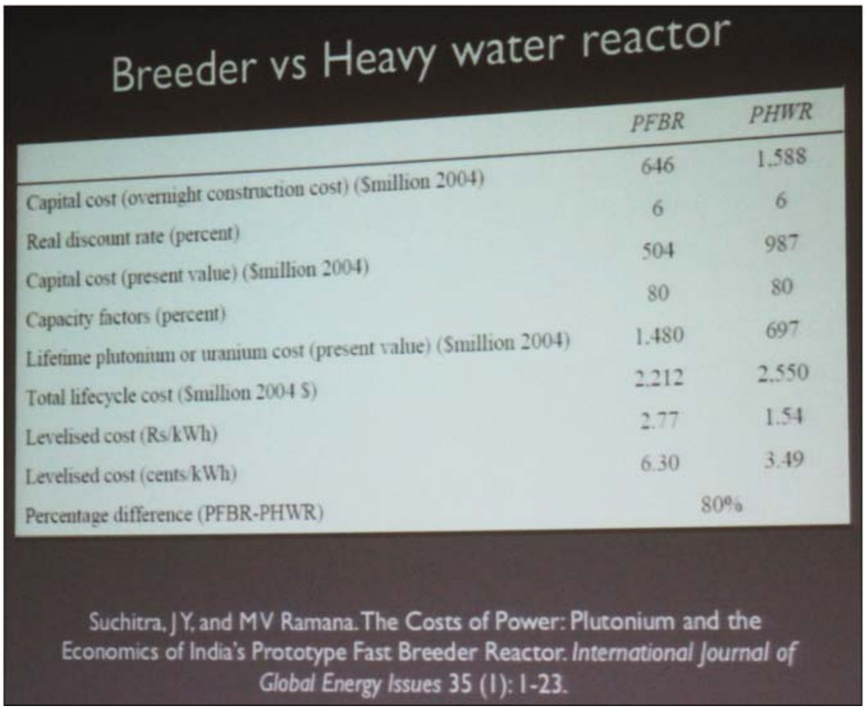


Historical experience in India

Station	Capacity (MW)	Original cost (Rs. million)	Revised cost (Rs. million)	Criticality year
TAPS I & II	2 × 160	929.9	-	1969
RAPS I	1 × 100[1]	339.5	732.7	1972
RAPS II	1 × 200	581.6	1025.4	1980
MAPS I	1 × 220	617.8	1188.3	1983
MAPS II	1 × 220	706.3	1270.4	1985
NAPS I & II	2 × 220	2098.9	7450[2]	1989 & 1991
Kakrapar I & II	2 × 220	3825	13.350	1992 & 1995
Kaiga I & II	2 × 220	7307.2	28.960	1999 & 2000
RAPS III & IV	2 × 220	7115.7	25.110	2000

More recent cost estimates have been closer to final figures. Exception: Fast breeder (increase of > 60 %)

Figure 2. India: differences between projected and actual costs of nuclear reactors.



Breeder vs Heavy water reactor

	PFBR	PHWR
Capital cost (overnight construction cost) ($million 2004)	646	1.588
Real discount rate (percent)	6	6
Capital cost (present value) ($million 2004)	504	987
Capacity factors (percent)	80	80
Lifetime plutonium or uranium cost (present value) ($million 2004)	1.480	697
Total lifecycle cost ($million 2004 $)	2.212	2.550
Levelised cost (Rs/kWh)	2.77	1.54
Levelised cost (cents/kWh)	6.30	3.49
Percentage difference (PFBR-PHWR)	80%	

Suchitra, J Y, and M V Ramana. The Costs of Power: Plutonium and the Economics of India's Prototype Fast Breeder Reactor. *International Journal of Global Energy Issues* 35 (1): 1-23.

Figure 3. Cost comparison between fast breeder reactor and heavy water reactor in India.

The determinants of the cost of electricity from a nuclear plant comprise: (i) capital cost of constructing the facility, including initial loading of fuel and other materials; (ii) operations and maintenance; (iii) fuel, including uranium enrichment and heavy water, and (iv) waste disposal, including decommissioning the reactor. The obvious simple formula would be: cost of electricity = total cost/total number of units of electricity generated.

But it gets complicated, as the costs are not evenly spread out over different years. This creates a necessity for a levelized cost, which involves discounting all cash flows, both expenditure and revenue, to some arbitrary but fixed reference year. The levelized cost is determined by setting the sum of discounted costs equal to the sum of discounted revenues.

Ramana indicated that discounting is mathematically simple, but philosophically and economically debated extensively. A positive discount rate would mean that future consumption is less valued than the same amount of consumption today. A high discount rate would make a fuel-intensive process look good. At high discount rates, nuclear power becomes expensive. The costs for disposal of long-lived radioactive wastes are discounted heavily for non-zero discount rate.

There is therefore necessarily some arbitrariness in deciding the discount rate. In market-based financing, the discount rate is the weighted average of the interest rate and the equity return rate. The rates depend, in part, on the financial risk perception of nuclear technology on the part of investors.

Capital cost is the most important determinant of the economics of nuclear power. Here, there are huge differences between the projected and actual costs. For example, in the US, for five plants whose construction started during 1976–1977, the estimated overnight cost was US$ 1630/kW and the actual overnight cost was US$ 4377/kW – a difference of 269%. The experience in India is shown in Figure 2.

Ramana estimates (based on the scanty details available in the public domain) that one EPR, to be supplied by Areva in Jaitapur, would cost ~Rs 13.5 crores/MW. This can be compared with the recent thermal power plant contracts (through competitive bidding) at Rs 3.5–4.5 crores/MW.

Financial risk is a major factor affecting nuclear prospects. There exist three kinds of risks. The first one is related to the higher fixed costs due to capital intensity, leading to higher systematic risk. This necessitates the use of higher discount rates for capital (risk premium). The second is related to accidents and the third to construction periods. The actual construction times are much larger than those assumed in projections. In Olkiluoto, Finland, an ~3 year delay resulted in ~50% increase in costs; there were problems due to poor-quality concrete and welds, delays in design completion and problems with contractors.

Ramana explored two possibilities to lower the costs: (i) technological learning, and (ii) new competition or economies of manufacturing scale. The learning rate is related to the percentage reduction of costs for each doubling of the cumulative volume of production. But data from the Organisation for Economic Co-operation and Development show, for example, that the learning rate for wind technology is 17%, whereas for nuclear technology it is 6%. Though there is a lot of competition amongst vendors of certain kinds of nuclear reactors, no manufacturer has full order books. If many orders are not available, there cannot be economies of scale. This makes it difficult for vendors to lower the costs, in turn making nuclear power expensive and unattractive.

Ramana then briefly discussed the economics of dealing with spent fuel. The two ways of managing spent fuel are through direct disposal (for example, long-term storage in geological repositories) and reprocessing. It is more expensive to reprocess. Using plutonium to produce mixed oxide (MOX) fuel and utilizing it in reactors makes the electricity generated more expensive than that from uranium fuel-based reactors, until the uranium prices rise multiple times. At the Kalpakkam plant in India, the cost of reprocessing spent fuel is ~Rs 26,000/kg (http://www.princeton.edu/~ramana/IJGEI_Vol27_No4_Reprocessing.pdf).

A comparison of the electricity generated by the fast breeder reactor (FBR; which uses reprocessed fuel) and that generated by the heavy water reactor (HWR) shows that the former is 80% more expensive (Figure 3; see also http://www.princeton.edu/~ramana/IJGEI-Volume35-Number01-2011.pdf). So, why are FBRs being constructed? The argument is that since India has limited uranium reserves, in order to increase the capacity, spent fuel has to be used. But Ramana says that if people are willing to pay higher prices (to meet the cost of extracting poorer quality uranium, which is available), then the obtainable uranium in future may be 300 times that available today.

In conclusion, Ramana pointed out that today, nuclear power is not an economically competitive choice (http://web.mit.edu/nuclearpower/pdf/nuclearpower_summary.pdf). There is high capital cost and large financial risk, with slow build-up in most countries.

1. Sovacool, B. K., *Energy Policy*, 2008, **36**, 2950–2963.

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Tiger estimate, 2010

Monitoring of tiger populations is done at regular intervals of four years and is a crucial component of evaluating the efficacy of tiger conservation efforts. The Ministry of Environment and Forests (MoEF), Government of India (GoI) published a booklet containing the results of the All-India Tiger Estimation exercise for the year 2010. This estimation was carried out between December 2009 and December 2010. The National Tiger Conservation Authority and independent technical experts and institutions have evaluated the population status of tigers in all the tiger reserve states using robust scientific techniques.

The Project Tiger is a centrally sponsored wildlife conservation movement initiated in India in 1973, launched under the personal leadership of the then Prime Minister of India, late Mrs Indira Gandhi to protect tigers. The project aims at tiger conservation in specially constituted tiger reserves representative of various regions throughout India and strives to maintain viable populations of Bengal tigers in their natural environment. At the same time it is meant to identify limiting factors and to mitigate them by suitable management. The damages done to the habitat were to be rectified so as to facilitate the recovery of the ecosystem to the maximum possible extent.

The potential tiger habitats being covered are Sivalik–Terai Conservation Unit (Uttaranchal, Uttar Pradesh, Bihar, West Bengal) and in Nepal, North East Conservation Unit, Sunderbans Conservation Unit, Central Indian Conservation Unit, Eastern Ghats Conservation Unit and Western Ghats Conservation Unit[1].

At the end of the 19th century, the tiger population in India was approximately 45,000. In 1972, the first tiger estimation was done, which showed the presence of only 1827 tigers. Hence in 1973, the Tiger Conservation Project was launched in Palamau Tiger Reserve, now in Jharkhand, and various tiger reserves were created in the country based on a ‘core-buffer’ strategy.

Today 39 tiger reserves (Table 1) exist in India, which represent around one-third of India’s high-density forest area. More than 350 Indian rivers originate from these reserves. These tiger reserves help in sequestering carbon as well as provide oxygen and slowly release groundwater to regulate floods. Tigers shape the community structure of ecosystem as top predators. They prevent overgrazing of the ecosystem by limiting herbivore numbers and maintain ecological integrity and hence it has become necessary to save the tigers.

The Project Tiger is administered by the National Tiger Conservation Authority, which was established in December 2005 following a recommendation of the Tiger Task Force, constituted by the Prime Minister of India for reorganized management of Project Tiger and the many tiger reserves in India. The National Tiger Conservation Authority was set up under the Chairmanship of MOEF. The Authority has eight experts or professionals having qualifications and experience in wildlife conservation and welfare of people, including tribals, apart from three Members of Parliament, two elected by the House of the People and