# Whither Nuclear Power?

*India is targeting an ambitious GDP growth rate of 8 per cent and for that the power sector needs to grow in tandem. At this rate, India's present installed generation capacity of 123 GW would need to increase by 90-120 GW in the coming decade. This paper makes an assessment of the potential for capacity addition from various energy sources such as coal, natural gas, hydro, wind and biomass and concludes that these sources will be found wanting in closing the gap between desired growth and business as usual growth. In this background, the recent India-US declaration on cooperation in nuclear power provides an opportunity for accelerated growth. India stands to benefit from imported nuclear fuels and reactors to augment its indigenous capabilities. We critically examine the oft-stated criticisms regarding the economics of nuclear power and its role in $CO_2$ mitigation, and find these to be issues worthy of further analysis but not "deal-breakers". The recent US-India declaration should be viewed not with suspicion or alarm but rather as an opportunity for India to increase its power generation from nuclear sources and also as recognition for its outstanding nuclear non-proliferation practices. This agreement will also provide the much-needed breathing space the Indian atomic energy establishment needs for enabling the plutonium fast breeder and thorium reactors to come on stream.*

**ANSHU BHARADWAJ, RAHUL TONGIA, V S ARUNACHALAM**

The Indo-US declaration on civilian nuclear power co-operation has sparked off intense debates, both for and against, in India and the US. The proposal envisages the separation of civilian and military areas from the present unified structure of the Indian Atomic Energy Establishment, and building cooperation between India and the rest of the world in areas of civilian nuclear power. Such cooperation does not presently exist because India has not signed the nuclear non-proliferation treaty (NPT) and it is not a member of Nuclear Suppliers Group (NSG). India's nuclear energy programme has therefore become self-sufficient in all areas, from extracting nuclear materials to building power reactors. Unfortunately, the present trajectory is not sustainable. Domestic uranium reserves are modest and can provide the fuel for only about 10,000 MW and that too, for only a few decades. The fast breeder reactors and thorium reactors that India is presently working on are still a few decades away in moving from prototypes to wide-scale commercial reactors. Thorium, about which much is written, is not a fissionable fuel and it must first be transformed to uranium by irradiation in reactors, and later chemically separated to provide fuel. All these take time: nuclear transmutations and the half-life of isotopes are invariant and cannot be hurried.

What then are the options for India in the coming decades to build its electricity generation, and what should be the contribution of nuclear power to this growth? Critics of the Indo-US deal argue that nuclear power is not required at all since it contributes a mere 3 per cent to installed capacity [Mian and Ramana 2005; Reddy 2005], and that in India the nuclear industry has a history of perennial delay, falling well short of the goals [Ramana et al 2005]. They also quote economics, safety, and nuclear waste disposal problems as main concerns and disagree with the oft-stated assumption that nuclear power can mitigate greenhouse gas emissions [Reddy 2005]. In this paper, we attempt to make an objective assessment of the role of nuclear power in India's future electric power needs. Specifically, we address three issues:

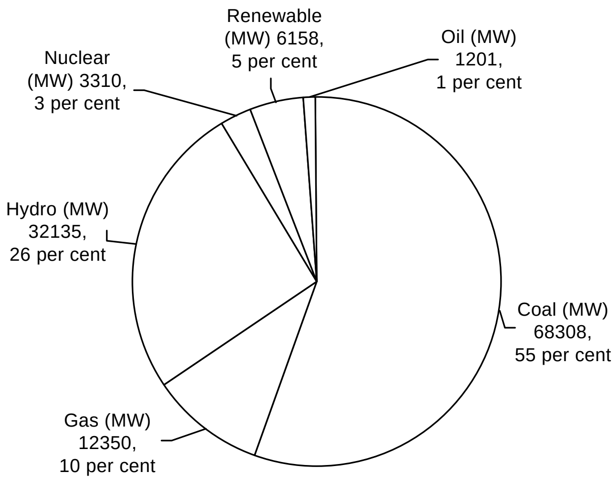
(i) India's future electric power requirements and the role of nuclear power.
(ii) Nuclear power and carbon emissions.
(iii) Economics of nuclear power and on sustaining indigenous capability.

We purposefully limit the scope of this paper to the potential of nuclear power to meet demand; even economics is studied from a supply-side perspective. We acknowledge the immense importance of political economy and utility viability in India's power sector,[1] and emphasise that new sources of power are not sufficient solutions alone – however, they are required [Tongia forthcoming].

## India's Future Electric Power Requirements and Role of Nuclear Energy

India's present installed capacity is 123 GW and Figure 1 shows the fuel mix [Ministry of Power 2004]. Coal accounts for 55 per cent of installed capacity, followed by hydro (26 per cent) and gas (10 per cent). Nuclear and wind are around 3 per cent each [Ministry of Power 2004]. Of course, the actual generation by fuel is different from the capacity shares given by different plant load factors (PLFs) for different fuels. Coal and nuclear contribute more than their nominal capacity share. The presently installed capacity is clearly not adequate. There are peak and average shortages of power, frequent blackouts and brownouts and high system losses. India's annual per capita power consumption is at best 600 kWh, well below the global average of 2,500 kWh, and much less than one-half of China's reported 1,500 kWh. This Indian figure itself includes captive power consumption as well as treating stolen electricity as "consumed."

**Figure 1: India's Present Fuel Mix (Capacity)**




Unlike China, India's economic growth has not been as power intensive. For instance, India's three major exports, textiles and garments, gems and jewellery, and computer software/services are not as dependent on large amounts of power as iron and steel production and heavy manufacturing. This is likely to change when India embarks on large infrastructure building projects and rural industrialisation. A way to estimate what the future demand will be is to assume that GNP growth and increase in electricity demand is linearly related. In the past, this elasticity varied between 1 and 5 [Planning Commission 2002a]. With increasing efficiency in the use of electricity, this ratio may fall compared to the historical average, but remain greater than one. For this analysis, based on recent data from State Electricity Boards and successor utilities, we have assumed the elasticity to be one [Planning Commission 2002a].

Consequently, if India is to target its economic growth rate to be around 8 per cent, electric power generation must also grow at roughly 8 per cent. This implies that by 2015, India's generation capacity should be over 250 GW, an addition of 130 GW in the next decade. At a relatively modest economic growth rate of 6 per cent, India would still need to add about 90 GW.[2] The question remains: from where will this additional capacity come, and what would be the fuel mix for generating this power? The supply side equation is a function of the plant (fuel) types, each of which has different capital costs, construction lead times, fuel availability, operating/variable costs, and expected (average) kilowatt-hour (kWh) costs. And all these depend on the plant load factor as well (Table 1).

The generated electricity must be absorbed by the system, which includes the physical infrastructure (the grid), utilities (which are regulated), and consumers. Clearly, electricity must be sustainable; otherwise, the State Electricity Board deficits will further increase, discouraging investments in new generation capacity.

In the following section, we shall examine the potential for capacity addition from coal, hydro, gas, wind and biomass.

## Coal

India's coal reserves are estimated to be 247.85 billion tonnes, with proven reserves of about 92.9 billion tonnes [Ministry of Coal 2004]. At the present rate of consumption, coal is expected to last for another 250 years. India's reliance on coal will therefore continue. Coal mines are mainly concentrated in the north-eastern belt of the country; Jharkhand, Orissa and West Bengal have almost 64 per cent of the coal reserves while Madhya Pradesh and Chhattisgarh account for 23 per cent. Thus, coal has to be transported over large distances to thermal power plants located across the country. Indian coal is characterised by high ash content; sometimes as high as 45 per cent and therefore coal transportation is accompanied with a huge amount of inert ash. Coal production for 2003-04 was 355 million tonnes, out of which 265 million tonnes was consumed in the power sector alone [Ministry of Coal 2004]. Coal consumption in the power sector is steadily increasing, while the consumption in other sectors has remained more or less constant (Figure 2).

Present coal production capacity in India is already strained. Over the last few years, coal production has not kept pace with the increasing output from coal generating stations. Coal stocks are reportedly at dangerously low levels in several thermal power generating stations[3] [Anon 2005a]. During 2003-04, India imported 12 million tonnes of coking coal and 9.5 million tonnes of non-coking coal [Ministry of Coal 2004]. In the first quarter of 2005, Coal India failed to reach the production target and it

**Table 1: Fuel Supply Matrix (for New Plants in India)**

| | Typical Largest Optimal Scale (Per Unit) | Construction Time (estimate) (Years) | Capital Costs (estimate (US$/kW), Indian Conditions) | Operating Costs (including Fuel) | Fuel Supply | Engineering Constraints (Constrction Limits on Number of Large Sites/Plants) | Ultimate Potential (GW) Running for Decades | Average KWh Costs |
|---|---|---|---|---|---|---|---|---|
| Coal | 500-1,000 MW | 4 | 900+ | Low/Medium | Regional constraints | dozens | 100s | Low/medium |
| Hydro | 1,000 of MW | 5-10+ | Highest (varies) | Low | Sharp geographic constraints | several | 80-100 | Low |
| Gas/Liquid | 250 MW per unit | 2 | <600 | Highest | Limited LNG today pipeline in few yrs | dozens | 40-50 | Med/High (depends heavily on fuel costs) |
| Nuclear (domestic PHWRs) | 500-700 MW | 4-5 | 1,350+ | Medium/Low | Limits to domestic fuel | 5-8 | ~10* * Excludes thorium and breeder cycles | High/medium |
| Nuclear (imported LWRs) | 800-1,400 MW | 4-5 | 1,500 | Medium/Low | International collaboration | 20 | Many 10s | High/medium |
| Wind | 3 MW (3.5 MW offshore) | 0.5 (longer offshore) | ~1,000* *Wind plants have low PLF | Low | Geographic constraints | 100 | 20–30+ | Low/medium |

**Figure 2: Coal Production in India**

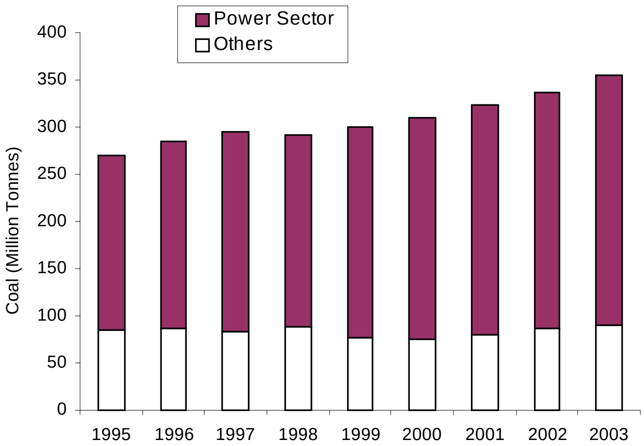
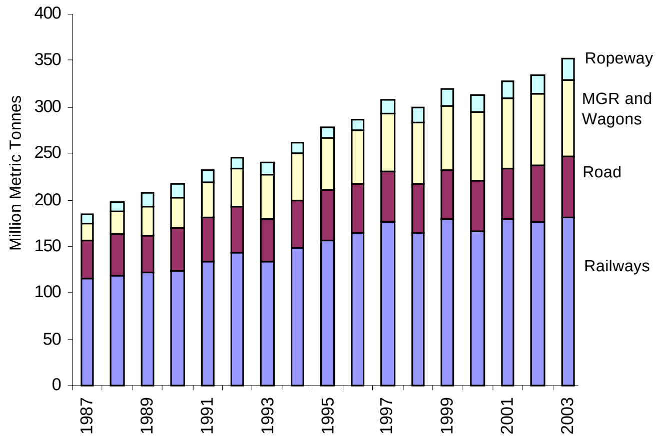



**Figure 3: Modes of Coal Transportation**




was recently reported that the inter-ministerial energy coordination committee headed by the prime minister decided to expedite coal imports to the tune of14 million tonnes to bridge the shortfall faced by power utilities [Anon 2005b]. If coal's share in installed generation capacity continues to be around 60 per cent, then our calculations show that in 2015, for a growth rate of 7-8 per cent, the power sector coal demand is likely to be 520-570 million tonnes. As per the Planning Commission (2002b), power sector coal demand is expected to touch 688 million tonnes by 2020 and even doubling the present coal production will not be sufficient to meet this. Coal India plans to augment coal production by at least 20 million tonnes per annum till 2011-12 and almost the entire additional production will come from open cast mining [Anon 2005c], which has environmental consequences. Even with this, India may not be able to meet the coal requirements of 2015.

Apart from increasing coal production, there is an urgent need for augmenting coal transportation infrastructure as well. Often coal has to be transported more than 1,000 km to the power generating stations. During 2003, 51 per cent of coal (181 million tonnes) was transported by rail and 19 per cent by road (66 million tonnes) (Figure 3) [Ministry of Coal 2004]. The coal carrying capacity of the railways and roads has reached a plateau in the last few years. For nearer consumption, transportation by the Merry Go Round (MGR) system and wagons accounted for about 23 per cent of the coal transported (82 million tonnes) and this steadily increased in the last few years. The coal transportation capacity will call for major upgrades if it has to cope up with a demand of 520-570 million tonnes by 2015. In US, Europe and in Russia coal is transported cheaply by barge. Unlike India, these countries have invested in building and maintaining a network of deep navigable waterways.[4] Indian Railways is planning a dedicated freight corridor (though not specifically for coal) at an expected cost of Rs 22,000 crore.

One possibility could be to locate power plants close to pitheads and hence transport "electrons and not coal". However, there are studies, which show that under typical conditions, energy losses for hauling coal by rail across long distances are lower than the transmission losses of electricity. If the rail lines exist and one compares adding new freight wagons versus a new high voltage direct current (HVDC) long-distance link, even the economics favour coal transportation over power transmission [Bergerson 2003]. However, these calculations may need to be revisited in the Indian context.

Clearly, India's capacity for coal production and transportation is struggling to meet even the present coal demand in the power sector, which is presently growing at less than 5 per cent. If India targets a growth rate of 7-8 per cent, coal will be found severely wanting unless huge investments are made and technologies put in place to increase the production and transport. Even then such a situation may be undesirable from an environmental perspective. The flue gas from a coal power plant comprises of $NO_x$, particulate matter, and $SO_2$ (in some cases),[5] and coal has the highest emissions of $CO_2$ per kWh power generated as compared to other power generation technologies. Particulates are a particularly acute problem, given the high ash in Indian coal; almost 80 million tonnes of ash is generated from coal-based combustion per annum. Present emissions standards in India are relaxed when compared with international norms; only the stack height and particulate matter are regulated.[6] However, if coal consumption continues to grow at the present rate, at some point stricter emission control regulations will have to be enacted, which will increase the cost of generation.[7] A less appreciated fact is that even coal power is not without its release of radioactive emissions due to the small amounts of radioactive materials present in coal coupled with the very high volume of coal throughput in a large power plant. In fact, people living near a coal plant are exposed to higher radiation than those living near a well regulated nuclear power plant [Gabbard 1993]. The tradeoff is that while nuclear power plants are designed to emit very low radiation, the expected radiation emissions are concentrated in the mining and fuel preparation stages of the fuel cycle.

If the business as usual scenario were to continue, coal will still continue to play a dominant role in the power sector. However, if India expects to accelerate electricity generation, the answer may not (and perhaps should not) come from coal under the current trajectory.

## Natural Gas

Natural gas has a number of advantages, due to which it is experiencing the highest growth rate globally amongst major fuels. The capital costs for building combined cycle power plants are relatively low, the erection times are significantly shorter, the plants operate at high efficiencies and are environmentally much less polluting than coal. Globally, the reserves are relatively more plentiful than oil, but India is somewhat limited in its reserves. Natural gas prospects in India brightened with the recent discoveries of major reserves in Bay of Bengal and also with the possibility of imports from west Asia and Bangladesh. Prospects and economic benefits of importing natural gas from west Asia have been discussed in detail [Tongia 1999; Tongia and Arunachalam 2005]. Twenty billion cubic metres of pipeline natural gas imports could feed roughly 16,000 MW of power. A pipeline would take four to five years before full operation, which could be timed to coincide with new gas-fired combined cycle power plants.[8]

Liquefied natural gas (LNG) hauled over oceans in large tankers is fast becoming an alternate and attractive method of gas transport. This option calls for an additional infrastructure for liquefying the gas at the loading port and for re-gasifying at the destination. There has been a significant reduction in the cost of building such quayside infrastructure. It is likely that LNG transportation – because of the option of buying from various competitive sources – may become competitive with overland pipelines.

However, the cost of electric power depends critically on the gas price. In 2004, natural gas power plants (both combined cycle and simple cycle) in the US operated at an average 15 per cent load factor and some filed for bankruptcy because power sector natural gas prices exceeded $ 6/MMBTU.[9] Therefore, any future large-scale capacity addition with natural gas will be subject to the risks inherent in natural gas pricing.

## Hydro-Power

India's estimated hydroelectric potential is 148,700 MW, which the Ministry of Power translates to 84,000 MW based on a load factor of 60 per cent [National Hydro Power Corporation 2004]. The present hydro-based capacity is 32,135 MW. The hydro to thermal ratio, which used to be 35:65 during the first Plan, is presently 25:71. As is the case with coal, options for hydroelectric power are also located mainly in a few areas in the country: Arunachal Pradesh, Sikkim, Himachal Pradesh and Jammu and Kashmir. Of the untapped potential, almost 50,000 MW is estimated to be in Arunachal Pradesh alone. Tapping these sources would critically depend on addressing major environmental issues, possible international agreements on water sharing and building of high voltage transmission lines to distant load centres. As per National Hydro Power Corporation, power projects amounting to over 10 GW are under various stages of construction and will be available within 10 years [National Hydro Power Corporation 2004]. The hydroelectric potential of the north-east is high and so is the possibility of importing hydel power from Nepal. However, large hydro projects have the problem of land acquisition and rehabilitation and resettlement of people, which causes considerable hardship and resentment among the local people.

## Wind

India has a gross potential of approximately 45,000 MW and a technical potential of 13,000 MW from wind[10] [Ministry of Non-Conventional Energy Sources 2004]. The present installed capacity is a little over 3,000 MW, ranking India fifth in the world. Wind recorded spectacular growth in the 1980s and 1990s and the government generously supported these with incentives such as subsidies and 100 per cent depreciation allowance. Most state electricity boards have attractive buy-back arrangements with the wind generators.[11] However, this is only part of the story. Many projects came up without proper planning and site selection just to take advantage of these benefits. The economics of generation critically depends on wind speeds[12] and the capacity factor and therefore it is important to select the site carefully. In general, wind speeds in India are lower than those in European countries and the US. A power density exceeding at least 200 W/m$^2$ at a height of 50m characterises a good wind site. Most wind sites in India are concentrated in parts of Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra and Gujarat and have power densities of 200-300 W/m$^2$. This is modest in comparison with European or US standards. For example, most of Denmark has power densities of 200-500 W/m$^2$ at 50 m heights and the coastal regions have in excess of 600 W/m$^2$.

As per some estimates, the average capacity factor in India is only approximately 13 per cent and consequently the country-averaged cost of generation works out to over Rs 5/kWh [Banerjee 2006]. While some projects have high capacity factors ( approximately 35 per cent), the overall low average capacity factor implies that there are several unviable wind projects and that wind has a negligible share in actual generation.

Wind-based capacity addition will certainly continue and now there is more maturity in site selection and project deployment. The government norms have also improved to incentivise generation instead of mere capacity addition. An optimistic scenario could see an additional 3,000 MW of wind-based generation capacity in the coming decade. At present, the wind-based installed capacity exceeds the nuclear-based capacity. However, there is a huge difference in the actual output (kWh) and the potential from the two. It does not appear that wind could become a dominant player in Indian power sector because the government itself estimates a technical potential of about 13,000 MW, that too operating at an optimistic 25 per cent capacity factor. Further, wind is intermittent and location specific and presents difficulties in grid integration. Contrary to a recent article in this journal, we do not believe that there is any bias against wind power or renewables in general [Reddy 2005]. On the contrary, wind has received (but often not properly utilised) generous public funding support and many wind generators are now defunct as mentioned above.

It appears that offshore wind power has better potential, as the wind speeds are reportedly higher.[13] Wind is also reasonably cheap when the capacity factor exceeds 30 per cent. However, it is relevant to point out that the potential contribution from wind in the next decade (approximately 3 GW) is modest in the overall context of India needing more than 100 GW.

## Biomass

Potential for power generation from biomass is estimated to be approximately 17,000 MW from agro-forest residues and 5,000 MW from bagasse and rice husk-based cogeneration [Ministry of Non Conventional Energy Sources 2004]. There are several advantages of biomass: it is renewable and produces almost no net carbon emissions. Moreover, biomass is available in rural areas and hence there is a good opportunity for generating electricity close to the rural loads. Detailed discussion on biomass conversion technology and economics is beyond the scope of this paper and is discussed elsewhere [Bharadwaj 2002, Ministry of Non-Conventional Energy Sources 2004]. India has done well in the development of atmospheric pressure downdraft biomass gasifiers. These can handle a variety of biomass fuels and can be combined with a diesel or spark ignition engine to give an overall power rating of 10-500 kW. The electric power demand in most Indian villages is 20 kW-100 kW and the locally available surplus biomass is often sufficient to meet the power requirements.

Over the last two decades, more than 1,700 such power plants were sanctioned amounting to an installed capacity of about 35

MW. Thus, the average plant size is approximately 20 kW. The cost of generation is reasonable considering the fact that system transmission and distribution losses are greatly avoided. Despite this, there are few success stories. There is no record available about the performance of these systems and most of them are probably not functioning. Almost all these units received generous subsidies and tax incentives from the central and state governments and there are attractive buy-back tariffs. Many projects misused the subsidies and in many cases, people stopped using the gasifier and switched to an all diesel application. The economics of biomass power is critically dependent on the load factor [Bharadwaj 2002; Banerjee 2006]. Most rural electrification projects suffer from low load factors leading to an unfavourable cost of generation. Such power plants have to be tied up with industrial/commercial applications to enhance the load factor. Based on the experience with bio power in the past two decades, it is unlikely that India will achieve even a fraction of the theoretical potential of 17,000 MW in the foreseeable future.[14]

There is a good potential from bagasse and rice husk-based cogeneration, however. Till recently most sugar mills were using low-pressure boilers that generated just enough steam to take care of the sugar mill's requirements. The use of high-pressure boilers increases the power generated and it can be exported to the grid. Several such projects came up in the last few years assisted by incentives. Recent experimental work by the authors have shown that it is not possible to realise the full calorific value from rice husks in gasifiers and one may have to resort to a fluidised bed that also pulverises the husks to realise the full calorific potential of this resource. Including all these, India will be able to add only up to 2 GW in the coming decade.

## Other Options

In addition to supply-side options, a number of analysts have advocated energy conservation, efficiency, etc, as a means to avoid increases in capacity, including nuclear power. Such efforts are commendable, and should be optimised based on pricing models and value (such as the concept of "negawatts"). However, based on the arguments given previously in the discussion on consumption, user demand is likely to grow, perhaps even higher than GDP growth rates. The analysis of efficiency standards, learning curves, etc, suggest that such initiatives may at best reduce overall consumption growth by 1 per cent; even this amount is significant, when we factor in reduced growth requirements over many years. Similarly, cutting down electricity theft will do more for utility balance sheets than for reducing electricity growth. After all, even stolen electricity is technically consumed.[15] No matter what India does, it needs much more power than what it generates today.

## Overall Energy Scenario and Role of Nuclear Power

Based on the above discussion, the approximate capacity addition from various sources (other than coal and nuclear) is estimated in Table 2.

As mentioned before, for India's growth rate to be at least 6 per cent, the required capacity addition is 90 GW, and it follows from Table 2 that in the coming 10 years coal will have to be the workhorse contributing about 60 GW of new capacity. Our earlier discussions suggest that this appears unlikely (and perhaps even undesirable) because of production, transportation and environmental constraints. If GDP were to grow at 8 per cent instead of the postulated 6 per cent, this problem becomes even more acute requiring an additional new coal-based capacity of 100 GW.

In the following section, we evaluate the role of nuclear power in meeting India's additional power needs. Clearly, nuclear power will not be able to meet all of India's power sector needs. Neither is nuclear power without its share of problems, much like any other source. But these problems are not as acute or as insurmountable as they have been made out to be [Mian 2005, Reddy 2005]. Nuclear power should therefore not be abandoned without deeper analysis, especially when India needs power from all possible energy sources.

A major criticism of nuclear power is that it has always underperformed. Even after years of promise, the present capacity is now 3,260 MW, just under 3 per cent of total installed capacity. To grow from 3 to 10 per cent, nuclear power sector would need to grow dramatically. Our analysis as discussed below suggests that this sector would need to grow even more radically than the past government projections, which were based on domestic uranium resources. In this context, the recent US-India declaration becomes significant. The potential of nuclear power is limited by several constraints, including fissile material availability, site selection and design approval, and industrial infrastructure for reactor construction, financing and waste disposal.

There are several options for building nuclear power stations and we summarise each of these briefly.

*Pressurised Heavy Water Reactors:* India's domestic uranium reserves, estimated at 50-70,000 tonnes, if used in pressured heavy water reactors (PHWRs), can only sustain a capacity of the order of 10,000 MW (10 GW) for about 40 years.[16] However, the present installed capacity is a little under 3,000 MW of PHWR capacities. The fuel for PHWR is natural uranium oxide and this can be run in a "once-through" mode (the spent fuel is discarded) or reprocessed to extract plutonium for fuelling fast breeder reactors.

*Fast Breeder Reactors:* A prototype 500 MW fast breeder reactor (PFBR) is under construction that uses plutonium reprocessed from the spent fuel from PHWR. But this will not be ready for commercial replication in numbers in the coming decade.

Our initial studies showed that it would take a few decades before the widespread commercial deployment of FBR and thorium reactors [Tongia and Arunachalam 1998]. We now believe that if India constructs more reprocessing facilities on a war footing to reprocess the vast amount of spent fuels the country has built up and build its commercial FBRs, almost in parallel with the PFBR with a time lag of just a few years, it may be able to bring on stream its first commercial fast breeder in about nine to 12 years. For thorium usage, the AHWR may also be prototyped and built, but here issues of fuel reprocessing are critical; even with thorium conversion to U233, which will be sustainable, AHWR would need Pu fuel as well. Handling U233 requires

**Table 2: Future Capacity Addition Projection from Various Sources**

| | | Overall Potential (MW) | Present Installed Capacity (MW) | Feasible Capacity Addition till 2015 (MW) |
|---|---|---|---|---|
| Natural gas | | | 12,350 | 16,000 |
| Hydro | | 84,000 | 32,135 | 10,000 |
| Wind | | 13,000 | 3,000 | 3,000 |
| Biomass | (Small) | 17,000 | 35 | – |
| | (Large) | 5,000 | 1,000 | 2,000 |
| Total | | | | 31,000 |

remote processing and managing the FBR fuel cycle might turn out to be easier. In this light, it is conceivable the FBR Pu route may be more expeditious.

Meanwhile, the gap of about 15 years until FBRs become commercial can be met by imported LWR reactors like the ones the Russians are building at Kudankulam. With appropriate safeguards and agreements, it might even be possible that in the coming years India may also be able to reprocess LWR fuels for its fast breeders.

*Thorium cycle reactors*: As thorium is not a fissile material, it must first be converted to Uranium-233 before being used as a fuel. This is generally done by irradiating thorium fuel rods in reactors. Though conversion through accelerator has been claimed, this is not included in the Indian programme. While there are proposals for advanced heavy water reactors with thorium and plutonium as fuels, these are unlikely to be proven and commercially built at least for the coming one or more decades. Unlike plutonium fuel rods, which can be fabricated in glove-box environments, U-233 calls for special handling and fabrication facilities because of its high gamma activity. While a demonstration plant is likely in the coming decade, commercial production of power from a thorium-based reactor will have to wait for a few more decades.

*Light Water Reactors:* Given India's limited experience with LWRs (Tarapur being the only reactor, commissioned in 1969) that use enriched uranium as fuel, these reactors are likely to come only with foreign collaboration. Two such 1,000 MW reactors are presently under construction at Kudankulam with Russian collaboration. But, these were designed as a one-off project. Without further agreements with the Nuclear Suppliers Group (NSG) and changes in non-proliferation laws of countries that sell nuclear reactors, it is not possible to build more LWRs in the country.

Given short-term difficulties in commercialising FBRs and thorium reactors, a rapid growth of nuclear power is feasible only with imported uranium. While this could be used for fuelling indigenous PHWRs (with a maximum of perhaps 500 or 540 MW capacity), it is advantageous to use this opportunity in constructing a large number of Light Water Reactors with foreign collaboration. The recent agreement between India and the US on civilian nuclear power reactors provides such an opportunity.

Putting aside issues of financing, ownership, and long-term storage/take-back of spent fuel, imported reactors can likely to be built of larger capacity than Indian nuclear plants. If we assume current LWR technology of roughly 1,000 MW (though the French-German consortium claims to build reactors with 1,600 MW capacity), and a five year construction time, and if we begin construction of four such large plants in a given year, and every year thereafter add four more similar plants, the net commissioning of 4,000 MW annually will only commence after five years. In steady state, this means that 20 simultaneous plants will be under construction for a few years in the coming decade; perhaps, more if there are delays.[17] This is an enormous engineering and logistical challenge. Of course, such large investments, estimated at $1,600/kW (including interest during construction; likely higher for new designs in the short term) for LWRs, will be possible only with international collaboration in construction and financing. One option would be for foreign companies to directly finance the plants and even operate them in return for assured off take at affordable unit electricity (kWh) prices. This reduces upfront burdens to India, and also places the onus of performance on the vendor. While such agreements are desirable for minimising domestic funding requirements, it is important to structure the power purchase agreements carefully to ensure that consumer and utility interests are well protected. It is also important to ensure that the Indian atomic energy establishment approves the design and construction technologies, and the operation of such reactors should meet the conditions of the Atomic Energy Regulatory Board (AERB). More agreements such as on accident liability, fuel supply, disposal, and possible spent fuel reprocessing will all have to be negotiated between the vendor countries and India. Japan, China and South Korea had concluded similar agreements in the past with supplier countries.

Even if such a dramatic push for LWRs begins in two years, given the five-year construction times with an annual increase of 4 GW thereafter, the installed capacity will be 32,000 MW by 2020. While it is difficult to predict India's overall capacity in 2020 (see previous section), under such scenarios nuclear power is likely to be around 10 per cent of the total capacity.

## Nuclear Power and Carbon Emissions

In 2003, India's $CO_2$ emissions from fossil fuels combustion stood at 1024 million tonnes, out of which 666 million tonnes were from coal. India is the world's fifth largest $CO_2$ emitter after US, China, Russia and Japan [Energy Information Administration 2005a].[18] Further, India's $CO_2$ emissions grew faster than these countries; an annual compounded growth rate of 5.5 per cent (1980-2003) as against 4 per cent of China, 1 per cent of US and 1 per cent of Japan [Energy Information Administration 2005]. By 2025, China is projected to be the world's largest $CO_2$ emitter followed by US and India [Energy Information Administration 2005b].

India is a signatory to the Kyoto Protocol; however it is not subject to any mandatory cuts in $CO_2$ emissions. The US has taken the stand that Kyoto Protocol is meaningless unless India and China also are required to cut emissions. In July 2005, six countries (US, India, China, Australia, South Korea and Japan) formed the Asia-Pacific Partnership for Clean Development and Climate (AP6). The objective of this initiative is to develop alternate strategies for reducing $CO_2$ emissions by promoting technologies such as clean coal, carbon capture and sequestration, nuclear power and renewables.[19]

In the previous section, we estimated that India should add 90-120 GW of new generation capacity by 2015 to achieve a power sector growth rate of 6-8 per cent. We also estimated that capacity addition from all sources other than coal and nuclear, would be about 31 GW. In the absence of nuclear power, an additional 60-90 GW would have to come from coal-based generation. This requirement more than doubles the coal consumption in the power sector raising it to 520-630 million tonnes from the present 265 tonnes, which would consequently more than double coal-based $CO_2$ emissions also.

Large-scale deployment of nuclear power could partly be a solution to the $CO_2$ problem. As discussed in the previous section,

**Table 3: Estimates of Present and Future Power Sector Coal Demand and $CO_2$ Emissions**

| Year | Scenario | Coal Consumption in Power Sector (Million Tonnes) | $CO_2$ Emissions from Coal in Power Sector (Million Tonnes) |
|---|---|---|---|
| 2005 | Present | 265 | 477[20] |
| 2015 | No significant nuclear | 520-630 | 930-1,160 |
| 2015 | 20 GW of nuclear capacity | 420-500 | 780-1,000 |
| 2020 | No significant nuclear | 640-770 | 1,160-1,380 |
| 2020 | 32 GW of nuclear capacity | 500-640 | 910-1,140 |

aggressive nuclear capacity addition could see India adding about 20,000 MW by 2015 and 32,000 MW by 2020. Consequently, India will reduce its reliance on coal to that extent. Table 3 shows the demand for coal and $CO_2$ emissions for this scenario. The detailed procedure for estimating $CO_2$ emissions from various fossil fuel sources is explained in [IPCC 1997, Energy Information Administration 2005c].

With the addition of 20 GW of nuclear capacity, the coal requirement can be reduced by about 100 million tonnes, which would reduce $CO_2$ emissions by at least 150 million tonnes per annum. If this trend of building nuclear power stations continues, then by 2020, India would reduce about $CO_2$ emissions by at least 250 million tonnes per annum. This amount is not small considering that the present annual $CO_2$ emissions from France and UK are 409 and 564 million tonnes respectively [Energy Information Administration 2005a].

In this calculation, we assume that there are almost no $CO_2$ emissions during the operation of a nuclear power plant. Of course, $CO_2$ is emitted during other activities such as plant construction, ore extraction, transportation, waste disposal and decommissioning [Reddy 2005]. However, the same is true for any power generation technology: coal, wind, solar PV and biomass. Several independent studies have estimated the "life cycle" emissions of $CO_2$ from various power generation technologies [Koch 2000; White and Kulcinski 2000; Meier 2002; Meier et al 2005] (Table 4). These cover $CO_2$ emissions during entire life of the power plant. They suggest that even on a life cycle basis, emissions of $CO_2$ from nuclear power plants are lower than those from coal and natural gas power plants.[21]

Large-scale nuclear power can play a vital role in $CO_2$ mitigation as explained in Figure 4 and Table 5. France and Japan are two countries that have a large dependence on nuclear power. Nuclear-based capacity in France is 63.2 GW (57 per cent of total installed capacity) while that of Japan is 45.9 GW (19 per cent of the total installed capacity) [Energy Information Administration 2005a]. The share of nuclear in France went up from 25.3 per cent in 1980 to 78 per cent in 2003. In Japan, though the share of nuclear power increased from 14.3 per cent in 1980 to 23 per cent, thermal power still dominates at 63.7 per cent. As a result, the $CO_2$ emissions in France have declined over the past two decades. In Japan, the emissions have gone marginally up reflecting its greater reliance on thermal power.

## Economics

In the past, the Indian nuclear power sector was linked to atomic energy pioneer Bhabha's statement, "No power is as costly as no power." However, planners today recognise the importance of economics, and nuclear power must be cost-effective to be deployed in larger scale.

Like all power technologies, there are fixed costs and operating costs, and their inherent uncertainties. Such calculations also depend on the assumptions. Fixed costs depend significantly on the chosen design/technology. And to some extent, operating costs also depend on this. In our analysis, we project costs for state of the art LWRs based on imported designs and foreign collaboration.

We present a hypothetical LWR economic analysis based on actual numbers from existing plants or figures from personal discussions with technology suppliers from the US and Europe [UBS Investment Research 2005]. In these calculations we have not included the liability costs for power producers and the government in case of any accident. There have been a few conventions (Vienna, 1997 and Paris, 1998) to discuss the amount of liabilities, and the US enacted the Price-Anderson Act to cover such nuclear accidents.[22] However, India has not enacted such legislation. A unified international liability regime, under discussion, may soon emerge that provides for an acceptable upper limit of liability and also creates an international funding mechanism. India may have to join such conventions.

This is the nominal cost, and appears quite competitive for plants being built out in India. For comparison, DAE's numbers for costs are often "overnight construction costs" and do not factor in many of the components shown. Even if certain costs end up being higher, there is adequate margin to accommodate such increases.

Is the model realistic? As a first cut analysis, it appears to be feasible given that we have been conservative in some calculations, e g, interest during construction and decommissioning. Estimates for decommissioning vary, but these costs are significantly out into the future, even more than the operating life of the plant due to a cooling period of multiple years. Thus, setting aside a fraction of the capital costs (which we estimate as, say, $100/kW additional), into an interest bearing fund is likely to cover the costs of decommissioning 50 or 60 years hence, even if the real prices in the future were to be double than estimated [UBS Investment Research 2005].

It is difficult to predict the exact costs of construction for imported plants, in part because it depends on the exact design, technology and local manufacture. European estimates of today (not projections) are approximately 1,680 $/kW (overnight

**Figure 4: $CO_2$ Emissions from Burning of Fossil Fuels in India, Japan and France 1980-2003**

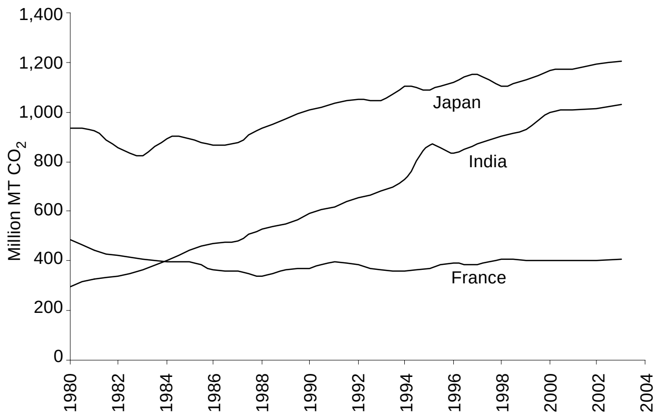



**Table 4: Life Cycle $CO_2$ Emissions from Various Sources**

| | $CO_2$ Emissions (g/kWh) |
|---|---|
| Coal | 800-1,200 |
| Natural gas | 390-510 |
| Nuclear | 2-59 |
| Wind | 7-124 |
| Solar PV | 13-730 |
| Biomass | 15-100 |

**Table 5: Share of Thermal and Nuclear Generation in France, India and Japan, 1980 and 2003**
*(in per cent)*

| | Thermal Generation | | Nuclear Generation | |
|---|---|---|---|---|
| | 1980 | 2003 | 1980 | 2003 |
| France | 47.0 | 10.3 | 25.3 | 78.0 |
| India | 58.5 | 84.3 | 2.5 | 2.9 |
| Japan | 69.5 | 63.7 | 14.3 | 23.3 |

construction costs) [UBS Investment Research 2005), and there are indications that with scale and some new designs, this could decrease measurably. Suppliers for new design plants indicate overnight construction costs as low as $1,100/kW. Today's higher costs for nuclear power estimated in the US or even parts of Europe reflect long (actual or estimated) construction times, higher capital costs than feasible with current state of the art, higher costs of capital, and high operating costs. Reducing these alone would make nuclear power competitive against traditional fuels.

While calculating these costs, some observations are in order. Nuclear power is capital intensive. Thus, one may wonder whether there are sufficient funds for so many new nuclear power plants. The imported LWRs are perhaps the best option for garnering international funds for the Indian power sector. Because of the absence of large markets for nuclear power in the US, LWR manufacturers will be interested in selling such power plants to India, if necessary even with attractive financial packages. This will be a new source of money that is unlikely to be substitutive. In addition, the corollary of the high capital costs is low operating costs, especially for fuel. Thus, while fossil fuel prices may increase rapidly in the coming years, even if nuclear fuel prices rose similarly (which projections indicate they would not), the impact on net power costs would be on the order of half, or lower compared to gas plants.

We propose that the best model may be for the foreign partner, perhaps in collaboration with an Indian power corporation, to undertake to build the power plant, supply fuel, and produce power, which Indian power utilities can buy at reasonable rates. Given some uncertainty in various factors in Table 6, the nuclear operator (which may entail an Indian partnership, of course), would take on the risks of uncertainty, in return for a slightly higher price by 10-20 paise/kWh. This would differentiate the model from the Enron one, where the risks and costs were passed through to the Indian side.

## Indigenous R and D and Imported Reactors

There have been fears from some quarters that indigenous R&D would be demoralised and dwarfed by the import of LWRs. Actually, the situation is quite opposite: this would enable the Indian Atomic Energy Establishment to focus all its energy and resources on building more PHWR, proving fast breeder reactors for commercial electricity generation and exploring the thorium option by building a sizeable nuclear reactor and specialised reprocessing facilities. All these take decades and thus require long-term planning and effort, in contrast to the more immediate power needs in India. Previous work has shown that breeder reactor technologies will not be able to power significant capacity in the coming one to two decades [Tongia and Arunachalam 1998]. While some solutions may not turn out to be feasible or optimal, new fuel cycles and sources and are going to be very relevant in the future when the world runs out of cheap fossil fuel and even of uranium resources. The once through uranium option that ignores the presence of plutonium is advocated by the US because of its fears about proliferation. In the long run, this argument may not be sustainable as the technology uses a mere few per cent of one isotope of uranium ignoring the rest of this energy-rich resource; there are also options that mitigate proliferation risks. If many countries opt for nuclear power – already the UK having expended a large fraction of its North Sea fossil fuel resources is veering back to nuclear power – the uranium resource may get tighter. Fast reactor technology is then going to be critical.

If India perseveres in these areas, it may then end up as a pioneer in plutonium and thorium technologies that may meet its growing power needs not in the immediate decades, but a few decades later. India will then turn out to be global leader in these technologies. An embargoed nation, long denied its due, would rise to become the global resource for these technologies. Already, a few western scientists having despaired of the difficulties inherent in fusion power have concluded that fast reactor technologies are going to be necessary for the coming many centuries [*MRS Bulletin* 2005].

In addition to direct economic competitiveness, nuclear power may offer benefits as and when carbon credits are monetised. Already, the clean development mechanism and other financial instruments are affording a modest effective carbon tax on many projects (or credit for "green" power). Carbon emission credits

**Table 6: Economics of Potential Imported Nuclear Plants (LWRs)**

| | | | |
|---|---|---|---|
| *Capital Costs* | | | |
| Plant Size | 1,000 | MW (net) | Indian power plants are quoted as *gross* capacity |
| Overnight construction costs | 1,300 | $/kW | This is higher than the projected *n*th of a kind costs for new designs, but lower than today's numbers. |
| Plant Load Factor | 80 per cent | Lifetime | |
| Weighted Average Cost of Capital | 10 per cent | Nominal | Assumes some fraction as debt at a lower rate, remaining equity; typically this is 70:30 debt:equity. International borrowings are likely to be less expensive than domestic capital markets |
| Lifetime | 30 | Years | The actual operating lifetime is projected at 50 years, but fiscally, we assume a more conservative estimate for financial calculations. |
| Decommissioning charge | 100 | $/kW | This is the upfront extra capex, which yields significantly more money towards the end of life due to time value of money (due to compounding) |
| Interest during construction multiplier | 25 per cent | On capex | This is the net effect of debt during the construction phase; assumes a logistic curve for cumulative expenditure (equivalent to a bell-curve for expenditure over time) |
| Net Capital Costs | 1,725 | $/kW | |
| Capital costs normalised per kWh | 2.61 | Cents/kWh | |
| *Operating Costs* | | | |
| Fuel | 0.5 | Cents/kWh | This is based on (MIT 2003) and includes additional transport to India |
| Other operating | 0.6 | Cents/kWh | This is on the lower end of actual costs; assumes new, standardised designs |
| Waste disposal | 0.1 | Cents/kWh | This is an estimated charge (UBS Investment Research 2005), towards disposal; fuel supplier should integrate this into fuel supply obligations |
| Total costs | 3.81 | Cents/kWh | |
| | or 1.70 | Rs/kWh | @44.5 Rs/$ |

would push nuclear to the forefront in terms of economics, either through a carbon tax or effective means such as caps and trading mechanisms [MIT 2003]. A plant with a foreign collaborator is more likely to be able to avail such credits, and thus could become even more cost-competitive.

Of course, nuclear power, to scale, must move beyond any special status and compete with other fuels. In this light, imported reactors must be gauged in terms of their techno-economic merit, and our analysis indicates they appear competitive and worth further examination.

## Conclusion

Nuclear power needs to be placed in perspective for meeting India's power requirements, and we can see that the other fuels are unlikely to close the gap between desired growth and business as usual growth. We do not claim nuclear power is the panacea to India's energy challenges, rather, suggest that nuclear power is a worthwhile option to pursue. India stands to benefit from imported nuclear fuels and reactors to significantly augment its indigenous capabilities. The economics may also turn out to be favourable, especially if there is foreign investment. While nuclear plants are capital intensive, operating costs are relatively low, and fuel costs are unlikely to escalate similar to rises seen for fossil fuels. The recent US-India declaration on civilian nuclear power and cooperation should be viewed not with suspicion or alarm but rather as an opportunity for India to increase its power generation using nuclear and also as recognition for its outstanding nuclear non-proliferation practices. This will also free the Indian Atomic Energy establishment to focus on the development of advanced fEPW cycle reactors based on thorium and plutonium that may yield a large payoff in an increasingly carbon-constrained future.

Email: anshu.bh@gmail.com

## Notes

[The authors are grateful to L V Krishnan for his comments and criticisms and Anand Patwardhan for reviewing the manuscript. The authors, however, are responsible for the contents. The opinions and views expressed in this paper are those of the authors and do not reflect the position of the institutions to which they belong.]

1 For a detailed analysis of such issues, see Tongia (forthcoming).

2 This in itself is a tall order. In the last several years, India has added a maximum of about 5,000 MW. This, however, dwarfs when compared with China's achievements. China added 51 GW last year to take its installed capacity up to 440 GW.

3 Thermal power plants are required to maintain coal stocks of 30 days. However, due to shortage in production, many generating stations are reportedly operating with stocks of less than a week.

4 The criticality of river transport for hauling raw materials can be seen from the fears expressed over hurricane Katrina's devastation of the port of New Orleans. It appears that there are no efficient and cheap alternatives to river transport to pass through the New Orleans transport corridor. A writer compared the devastation and the resulting damage to the economy as equal to that of an atomic bomb attack over that city! (George Friedman, *The New York Review of Books*, p 4, October 6, 2005).

5 Indian coal is low in sulphur and therefore $SO_2$ emissions are not a major issue unlike in other countries, such as the US.

6 The stack height for a 500 MW power plant should be 275 m and particulate matter limit for a 210 MW (or more) power plant is 150 mg/$Nm^3$.

7 For an assessment of how the various environment control technologies impact capital costs and cost of generation, see the Integrated Environment Control Model (IECM) developed at Carnegie Mellon University. It can be downloaded from: www.iecm-online.com

8 For recent developments, see Tongia (2005).

9 As per one estimate, especially for base load production of power, natural gas prices should be roughly $ 3.5/MMBTU for it to be cost competitive with coal.

10 As per the Ministry of Non-Conventional Energy Sources, gross potential assumes 1 per cent land availability in potential areas and technical potential assumes 20 per cent grid penetration. It is not clear how these potentials were estimated. These numbers have been quoted by the Ministry of Non-Conventional Energy Sources for some years and may not be based on robust long-term data.

11 The Ministry of Non-Conventional Energy Sources laid down several recommendations for buy-back, wheeling and banking of electricity produced by renewable sources. It recommended that the utilities buy back the electricity at Rs 2.25/kWh with 5 per cent escalation with effect from 1994-95. This is an attractive rate for most renewable sources. However, often the State Electricity Boards do not honour the power purchase agreements and delay payments to generators by several months.

12 Power of a wind turbine varies as the cube of the wind velocity.

13 Most European countries are going in for offshore wind power development. In some cases, the distance from the shore is 30-40 km. The turbine power output is proportional to the cube of wind speed and hence higher wind speeds allowed for developing wind turbines of power rating in excess of 3 MW.

14 Besides, it may not be advisable to have a large number of biomass-based power plants since in many cases the residues have alternate economic applications in the villages and provide nutrients to the soil.

15 The full amount of stolen electricity would not be paid for, as demand would come down slightly. But, compared to the growth projected in Table 2, this is a very small potential. Even assuming 20,000 MW of stolen electricity today (not all the T and D losses of today are stolen), and if half this load decreases when users have to pay, this represents only on the order of 0.5 per cent growth rate of capacity.

16 The peak PHWR capacity depends on the rate at which plants can be built. If more are built quickly, a higher peak can be reached, but sustained for shorter period of time, such that with the end of life of the last unit, the last domestic uranium is used [see Tongia and Arunachalam (1998), pp 549-58 for more details].

17 France, for a short period, had 30 simultaneous plants under construction, and commissioned nine reactors in 1980, but this was preceded by only two in the previous year and six and two in the following years. US growth in nuclear capacity was as high as 9.7 GW in a single year, but the average over the 20 years of "boom" construction was less than 5 GW.

18 The energy related $CO_2$ emissions of other countries in 2003 were (million tonnes $CO_2$): US (5802), China (3540), Russia (1600) and Japan (1205). Western European countries combined accounted for 3895 million tonnes. Within Western Europe, leading emitters are Germany (842), UK (564), Italy (465) and France (409).

19 This group had its inaugural meeting in Sydney on January 12, 2006.

20 In 2003, total $CO_2$ emissions from coal were 666 million tonnes from 355 million tonnes of coal. However, this includes both power sector and non-power sector emissions. As per EIA data, we estimate $CO_2$ emissions (kg) per kg of coal to be about 1.8 in power sector and 2.3 in other sectors.

21 Better accounting of all stages in life cycle assessment may change the estimates, as well as dynamics in the technology and fuel cycle. For instance, recent studies at Carnegie Mellon University, Pittsburgh, show that life-cycle analysis for natural gas systems significantly underestimates the greenhouse gas emissions as greater fractions of natural gas are transported as LNG. Liquefaction and transport of natural gas has energy requirements as well as venting of natural gas, which has a greater greenhouse effect than $CO_2$.

22 The Price Anderson Act, originally passed by US Congress in 1957 and most recently amended in 1988, requires nuclear power plants to show evidence of financial protection in the event of a nuclear accident, but commercial insurance is limited in availability. The Act pools money paid by all the nuclear power plants into a fund, but provides a cap on operator liabilities.

## References

Anon (2005a): 'Thermal Plants' Coal Shortage Worsening', *The Hindu*, April 4. http://www.thehindubusinessline.com/2005/04/04/stories/

2005040401750500.htm
– (2005b): 'Coal India Slips on Target', *The Telegraph*, August 18. http://www.telegraphindia.com/1050818/asp/business/story_5125608.asp
– (2005c): 'Coal India Plans to Augment Production by 20 Million Tonnes Annually', *The Hindu Business Line*, June 12. http://www.thehindubusinessline.com/2005/06/12/stories/2005061202210400.htm
Banerjee, R (2006): 'Comparisons of Options for Distributed Generation in India', *Energy Policy*, 34: 101-111.
Bergerson, J, Lester Lave (2003): 'Transport Coal or Transmit Electricity? A Hybrid Life Cycle Analysis', *Conference on Life Cycle Analysis and Modelling*, Seattle, WA.
Bharadwaj, A (2002): *Gasification and Combustion Technologies of Agro-Residues and Their Applicability to Rural Electric Power Systems in India*, PhD Thesis, Departments of Engineering and Public Policy and Mechanical Engineering, Carnegie Mellon University, Pittsburgh.
Energy Information Administration (2005a): 'World $CO_2$ Assessment from the Consumption and Flaring of Fossil Fuels (1980-2003)', US Department of Energy, Washington DC.
– (2005b): 'Emissions of Greenhouse Gases in the United States 2004, DOE/EIA-0573(2004)', US Department of Energy, Washington DC.
– (2005c): 'Documentation for Emissions of Greenhouse Gases in the US 2003, DOE/EIA-0638 (2003)', US Department of Energy, Washington DC.
Gabbard, A (1993): 'Coal Combustion: Nuclear Resource or Danger?', *Oak Ridge National Laboratory Review*, 26(3/4).
IPCC (1997): 'Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories', Intergovernmental Panel on Climate Change.
Koch, F H (2000): 'Hydropower-Internalised Costs and Externalised Benefits', International Energy Agency (IEA), Ottawa, Canada.
MIT (2003): 'Future of Nuclear Power: An Interdisciplinary MIT Study', Massachusetts Institute of Technology, Cambridge MA
Meier, P J (2002): 'Life Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis', University of Wisconsin-Madison.
Meier, P J, P P H Wilson, G L Kulcinski, P L Denholm (2005): 'US Electric Industry Response to Carbon Constraint: A Life Cycle Assessment of Supply Side Alternatives', *Energy Policy* 33: 1099-1108.
Mian, Z, M V Ramana (2005): 'Feeding the Nuclear Fire', *Economic and Political Weekly*, August 27.
Ministry of Coal (2004): *Annual Report*, Government of India, New Delhi.
Ministry of Non-Conventional Energy Sources (2004): *Annual Report*, Government of India, New Delhi.
Ministry of Power (2004): *Annual Report*, Government of India, New Delhi.
*MRS Bulletin* (2005): European MRS Spring Meeting, November, Strasbourg, France.
National Hydro Power Corporation (2004): *Annual Report*, Government of India, New Delhi.
Planning Commission (2002a): 'The Working of State Electricity Boards and Electricity Departments', Government of India, New Delhi.
– (2002b). 'India Vision 2020', Government of India, New Delhi.
Ramana, M V, Antonette D'Sa, Amulya K N Reddy (2005): 'Nuclear Energy Economics in India', *Energy for Sustainable Development*, IX(2), pp 35-48.
Reddy, A K N (2005): 'False Assumption of Nuclear Deal', *Economic and Political Weekly*, pp 3812-15.
Tongia, R (forthcoming): 'Political Economy of India's Power Sector', *The Political Economy of Electric Power Market Reform: The Experiences of Five Major Developing Countries*, D G Victor, T Heller, Cambridge University Press.
– (2005): 'Natural Gas Imports for India Revisited', *Economic and Political Weekly*, May 11, pp 2032-36.
Tongia, R, V S Arunachalam (1998): 'India's Nuclear Breeders: Technology, Viability and Options', *Current Science*, 75(6).
– (1999): 'Natural Gas Imports for South Asia: Pipelines or Pipedreams?' *Economic and Political Weekly*, 34(18).
UBS Investment Research (2005): 'Future of Nuclear'.
White, S W, G L Kulcinski (2000): 'Birth to Death Analysis of the Energy Payback Ratio and $CO_2$ Gas Emission Rates from Coal, Fission, Wind and DT-Fusion Electrical Power Plants', *Fusion Engineering and Design*, 48(248), pp 473-81.