Developing countries & Global climate change

Electric Power Options in India

Prepared for the Pew Center on Global Climate Change

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Foreword *Eileen Claussen, Executive Director, Pew Center on Global Climate Change*

The electric power sector in India is characterized by low per capita energy use, rapid growth in demand, heavy losses in transmission and distribution, and tariffs well below average costs. Coal dominates usage, which combined with hydropower represents 85 percent of generated power. The power sector is responsible for half of India's carbon dioxide emissions, which were 92 million tons in 1995. Even with the prospect of market and industrial reforms, the "business-as-usual" path for India in 2015 increases both generating capacity and carbon dioxide emissions by around 150 percent over 1995 levels. But the scenarios modeled in this study show that growth in emissions can be reduced to only 60 percent greater than 1995 if progressive sustainable development policies are implemented.

What are the drivers that will influence future technology choices in India?

- The ability of India's power producers to fuel-switch and lower carbon dioxide emissions is heavily dependent on the availability and cost of alternative fuels (especially natural gas). In the scenario simulating stricter local environmental controls, this restriction steers decision-makers to sulfur control equipment and does not necessarily lead to reductions in coal use. On the other hand, striving to attain sustainable development goals can reduce costs and capacity needs, and achieve the most dramatic reductions in carbon dioxide emissions.

- Market reforms can lower costs by 11 percent and carbon emissions by 7 percent through a reduction in the need to build more power plants through increased supply efficiency and earlier availability of new technologies.

- More widespread adoption of cost-effective energy efficiency measures could also reduce carbon emissions by 23 percent and sulfur dioxide emissions by 60 percent, by reducing demand for power by around 15 percent.

Developing Countries and Global Climate Change: Electric Power Choices in India is the third in a series examining the electric power sectors in developing countries, including four other case studies of Korea, China, Brazil, and Argentina. The report's findings are based on a lifecycle cost analysis of several possible alternatives to current projections for expanding the power system.

The Pew Center on Global Climate Change was established in 1998 by the Pew Charitable Trusts to bring a new cooperative approach and critical scientific, economic, and technological expertise to the global climate change debate. The Pew Center believes that climate change is serious business and a better understanding of circumstances in individual countries helps achieve a serious response.

Executive Summary

Electricity consumption in India has more than doubled in the last decade, outpacing economic growth. The power sector now consumes 40 percent of primary energy and 70 percent of coal use. This sector is the single largest consumer of capital, drawing over one-sixth of all Indian investments over the past decade. Despite these huge expenditures, electricity demand continues to outstrip power generating capacity, leaving a 12 percent electricity deficit and a 20 percent peak power shortage.

The government has assumed the predominant role in electricity supply in the post-independence era. State electricity boards (SEBs) and power corporations plan and govern power plants financed with state funds. SEBs in particular are wide open to political influence and tariff distortions. Operational inefficiencies grew in the absence of competition and financial discipline, undermining the power sector's financial health. By the early 1990s, the sector was overdue for sweeping reforms to enhance revenues and mobilize investment in the short run, and to change ownership and the regulatory structure in the long run. Reforms underway fall broadly into the categories of SEB corporatization, privatization of power corporations, unbundling (vertical divestiture), and regulatory restructuring.

Despite enhanced competition from other fuels, coal remains the mainstay of power generation in India. The present power technology mix relies on domestic coal to provide three-fifths of the country's power; large hydroelectric dams provide about one-quarter. Gas-fired power has grown from almost nothing to one-twelfth of total generation in the last decade due to the reduced risk associated with lower capital requirements, shorter construction periods, diminished environmental impacts, and higher efficiencies. Nuclear power contributes less than 3 percent to total generation and renewables (other than large hydro) just over 1 percent. India has a significant program to support renewable power, exemplified by wind power capacity that rose from 41 megawatts in 1992 to 1,025 megawatts in 1999.

Power transmission and distribution has suffered from losses amounting to over one-fifth of generated electricity, more than double the level of most countries. An institutional restructuring process began in 1989 to consolidate various suppliers and distributors under an agency called "Powergrid." Faced with unreliable power supply, many industries have invested in on-site power generation that now accounts for 12 percent of total capacity.

The phenomenal rise in agricultural electricity consumption is due to greater irrigation demand by new crop varieties and the very low price of electricity provided to that sector. The average electricity tariff in India is 20 percent below the average cost of supply. The gap is mainly due to subsidized rates for agriculture. Industrial consumers pay higher costs and provide a cross-subsidy that was worth over US$5 billion in 1997, equal to almost half of power sector investments that year.

Concerns about the environmental impacts of power plant projects have grown in the past twenty years. The power sector contributes about half of India's carbon, sulfur, and nitrogen oxide emissions. Hydroelectric projects also have generated social concerns. Dam construction has forced the relocation of many Indians, a problem the government has handled poorly. Managing environmental and social impacts has therefore drawn considerable attention in policy-making, project development, and operations.

A. Results

This study projects a baseline of current trends, then tests the effects that market reform, efficient technology, local environmental pollution controls, and sustainable development strategies could have on the Indian power sector. The analysis uses a least-cost model that optimizes power demand according to power generation technologies, energy supply, and environmental constraints. Because India may overtake China by 2015 as the world's most populous nation, the results should be of significant interest to climate change policy-makers. The goal of this analysis is to present policy options based on the relative differences between scenarios and other qualitative information about India's power sector.

Baseline. Power capacity in 2015 will grow to two-and-a-half times the 1995 level. Coal technologies will continue to account for the largest share of new additions to capacity, but will decline from 62 percent in 2000 to about 55 percent in 2015. Clean-coal and natural gas technologies will play larger roles, while hydropower will decline slightly. Capital requirements will total $151 billion from 2000 to 2015, more than all other scenarios except a high-growth case. Sulfur dioxide and carbon emissions both more than double from their 1995 levels to 5.9 million and 217 million tons, respectively, by 2015.

Market Reform Scenario. This scenario assumes that India will further liberalize domestic policies and become more receptive to foreign direct investment. The scenario results in minor changes to the power supply mix compared to the baseline. However, less capacity overall is needed due to greater energy efficiency and utilization of existing capacity, thus reducing capital requirements by 11 percent. Carbon emissions decline 7 percent from the baseline by 2015, falling to 203 million tons per year. By 2015, sulfur dioxide emissions fall by 56 percent to 2.6 million tons due to increased use of pollution control equipment with conventional coal technologies.

Efficient Technology Scenario. This scenario simulates the impact of cost reductions in advanced power generation and end-use technologies. Investment requirements in this scenario decline 20 percent below the baseline due to the higher capacity and efficiency factors of advanced technologies. Advanced technologies in the end-use sector reduce total installed capacity from 246 gigawatts to 207 gigawatts, while the power mix shifts from coal to gas and hydroelectric. Carbon emissions total 168 million tons in 2015, about 23 percent lower than the baseline. Sulfur emissions fall by 60 percent in 2015 to 2.3 million tons.

Local Environmental Control Scenario. This scenario simulates stricter control of nitrogen and sulfur oxides and particulates. Capacity additions closely resemble the base case in this scenario, but capital costs increase by 5 percent due to more expensive control technologies. The marginal cost of electricity is 3 percent higher than the baseline and higher than in most other scenarios. Compared to the base case, fitting coal technologies with sulfur control equipment cuts sulfur emissions by 40 percent in 2015. Carbon emissions reach 218 million tons by 2015, similar to baseline emissions, primarily because there is little substitution of gas for coal.

Sustainable Development Scenario. Modelers simulate a combination of progressive policy options in this scenario, including decentralized governance, environmental conservation, efficiency and renewable energy promotion, and regional cooperation. Requirements for capacity additions in this scenario fall 22 percent below the baseline, but still require $117 billion of cumulative investment between 2000 and 2015. Sulfur emissions fall dramatically to about 2.3 million tons. This scenario produces the lowest carbon emissions in 2015 at about 141 million tons, still 60 percent higher than emissions today.

Growth Scenarios. The high-growth scenario, which assumes 7 percent economic growth, requires $218 billion in investments by 2015, more than any other scenario. Surprisingly, high growth cuts sulfur emissions significantly — to 3.3 million tons in 2015 — due to the availability of sufficient funds. This is almost half the baseline level. Carbon emissions reach 225 million tons by 2015, about 2.5 times the 1995 level, though only 4 percent more than the baseline total.

In a low-growth scenario, capital requirements amount to just $97 billion per year by 2015, about 36 percent lower than baseline requirements. Ironically, this scenario produces the second highest level of sulfur dioxide, more than 4.0 million tons in 2015, or 50 percent higher than the market reform case. Carbon emissions in 2015 reach 145 million tons, about one-third lower than baseline emissions, but almost 60 percent higher than 1995 emission levels.

B. Conclusions

This study concludes that near-exclusive government ownership, a supply-side orientation, and tariff distortions led the Indian power sector to an unsustainable path before 1990. The analysis yields three additional insights. First, without low-cost supplies of natural gas, strict control of local pollutants may not necessarily lead to reduced coal consumption. A least-cost option might simply promote early penetration of pollution control equipment suited to conventional coal technologies. Second, high economic growth does not have to lead to excessive coal-fired emissions; instead, stricter emissions control and greater financial resources might cause a shift to cleaner fuels and more energy-efficient coal technologies. Third, the share of natural gas use increases in all scenarios, indicating that enhancing the gas supply is a vital energy policy measure.

A useful hedging strategy would be to keep the energy and technology mix flexible. Gas is a robust option that meets multiple objectives like low emissions and peak load requirements and multiple constraints like low investment costs and short construction time. Another option is to gain experience with emerging renewable technologies. It would also be useful to integrate regional grids into the national grid to enhance the efficiency and reliability of the power supply. Nepal and Bhutan own hydro resources while Bangladesh and Myanmar possess gas; cooperation with these neighboring countries will help diversify the capacity mix, reduce costs, and improve environmental performance.

India could reduce electricity losses in the power grid by updating technology and management practices. Furthermore, improved grid reliability could lower the need for captive power generation — often inefficient diesel generators — at industrial sites. The costs required to accomplish this would be offset by the savings in building and operating new power plants and the associated reduction of harmful emissions.

The Indian power sector has substantial potential to reduce its carbon emissions from baseline projections. Short-run policies such as promoting clean technologies and reducing energy demand are likely to curb local pollution substantially and reduce carbon emissions by one-quarter by 2015, or a total of 600 million tons between 2000 and 2015. However, measures that control sulfur and nitrogen oxide pollutants such as coal washing, sulfur scrubbing, and integrated gasification combined-cycle plants have little impact on carbon emissions. Climate change mitigation policies for the Indian power sector therefore will have to be crafted for their own sake.

I. The Indian Energy Picture

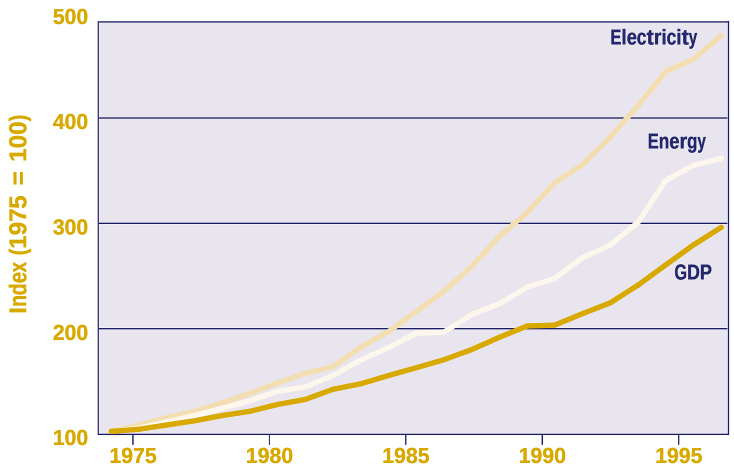
A. Electricity's Role in the Indian Economy

Indian electricity use has more than doubled in the last decade, and has grown faster than gross domestic product (GDP) for 20 years.[1] (See Figure 1.) Industrialization, combined with the modernization of agriculture and a rise in per capita income, have led to this rapid increase in energy consumption. Electricity use per person has increased to over 430 kilowatt-hours (kWh) per year, up from 90 kWh in 1972.[2] Despite this increase, India's per capita electricity use averages only one-sixth that of the world, one-half that of China, and less than one-twentieth that of the United States.[3]

The power sector now represents 40 percent of total primary energy use in India, including nearly 70 percent of all coal use.[4] Power generation has also been India's single largest consumer of capital, drawing over one-sixth of all investments over the past decade. Despite this huge level of investment, electricity demand continues to outstrip power generating capacity, leaving a 12 percent electricity deficit and 20 percent peak power shortage.[5]

Figure 1

Energy and Electricity Demand and the Indian Economy



Source: Government of India, Ministry of Finance, 1999. *Economic Survey (1990–1998).*

Shortly after India won independence from the United Kingdom in 1948, political, economic, and institutional considerations led the government to assume the predominant role in electricity supply. Government policy opposed involving international capital in this core sector of the economy. The absence of competition and the lack of private investment meant the power sector developed as a state monopoly.

Supply was decided by government-allocated investments. Because the power producer and regulator were one entity, regulation seemed unnecessary, hindering the emergence of a regulatory system.

Two forms of public power ownership evolved. Most state governments created state electricity boards (SEBs) to govern power plants financed with state funds. Since the 1960s, the central government has also created government-owned power corporations. These corporations were meant to close the investment gap resulting from the SEBs' tariff distortions and operational inefficiencies. The corporations did expand capacity and enhance operating performance. However, the power gap between supply and demand grew unabated because the central government's "Five-Year Plans" did not provide the needed outlays.

Under this dual ownership, power plant governance was wide open to political influence and tariff distortions, especially in the SEBs. Their operational inefficiencies worsened in the absence of competition and financial discipline. These inefficiencies, along with tariff subsidies, undermined the power sector's financial health. Government ownership and the political attractiveness of large power development projects diminished environmental and social scrutiny. Growing awareness of these issues has emerged as an important barrier to adding power capacity, especially for large hydro projects and coal-fired plants planned in ecologically sensitive areas.

The continuation of "business-as-usual" appeared a grim prospect by the early 1990s. The power sector was overdue for sweeping reforms concerning ownership and competition. Such changes involve lengthy processes, however; the immediate need was to attract investment to bridge the widening gap between supply and demand. The Indian government launched major power sector reforms in 1998 against this background. (See Box 1.)

B. Current Power Dynamics

India increased power generation capacity nearly sixfold between 1970 and 1995, while diversifying its mix of supply technologies.[10] (See Figure 2.) Currently, coal provides about three-fifths of power and large hydroelectric dams about one-quarter. Hydropower is declining in relative importance. In contrast, use of gas-fired power has grown from

Box 1

Power Sector Reform in India

Before 1998, the declining health of the state electricity boards (SEBs), the widening power gap, and yawning inefficiencies in India's power sector suggested the need for major reform. Priorities included the need to enhance revenues and mobilize power sector investment in the short run and to change ownership and the regulatory structure in the long run. Reforms underway fall broadly into the categories of corporatization of SEBs, privatization, unbundling (vertical divestiture), and regulatory restructuring.

Corporatization

Corporatization is the process of changing the SEBs from state ownership and administration to business-like corporations as defined by the Indian Company Act of 1956.[6] Corporatization is expected to increase professionalism, management independence from political interference, and financial accountability. The approach is to enhance operational independence through such means as including private nominees as board members.

Privatization

Amendments to the Indian Electricity Act of 1910 and the Electricity Act of 1948 have permitted private participation in the power sector.[7] Private participation is now open in power generation, distribution, and transmission. Long-term generation licenses are offered to private parties, and the approval process for power generation has been streamlined. Captive power generation and cogeneration have received incentives such as the right to sell surplus power over the grid to a third-party customer. Privatization of power transmission, inherently more difficult, has been encouraged through the recognition of exclusive transmission companies. Control of power distribution by the SEBs, a major barrier to privatizing this link of electricity service, is being reduced. Other incentives to privatization are allowing 100 percent equity ownership by foreign private investors, reduction in import tariffs on power plant equipment, a five-year tax holiday, a liberal power purchasing agreement with performance incentives, and special appropriations for debt redemption.[8]

Unbundling

Separating SEBs into generation, transmission, and distribution companies is part of the reform process. This change rests on the premise that generation is competitive, while transmission is a natural monopoly, and distribution is a local monopoly. Generation and distribution, therefore, must be separated from transmission to promote competition. The State of Orissa passed India's first unbundling initiative.

Regulatory Reforms

Power sector regulations in India formerly centered on creating regulatory institutions and defining rules to govern supply-side investments. Price, quality of supply, and consumer protection were hardly addressed. The central government formulated national power policy, new legislation for energy supply, and technical standards, and allotted energy sources for power generation. Planning and project implementation fell under the jurisdiction of the Central Electricity Authority (CEA), which also was responsible for setting tariffs for power utilities owned by the central government. Only the state governments controlled licensing. The Electricity Supply Act of 1948 (revised 1976) required licensees or generating companies to follow the directions of Regional Electricity Boards for integrated operation. The regulatory performance of regional bodies was poor because the government exercised direct and indirect control over them.

The 1998 Regulatory Commissions Act was a landmark in regulatory reform. This act mandated creation of a Central Electricity Regulatory Commission (CERC) and proposed creating a State Electricity Regulatory Commission (SERC) in each state. The original ordinance also included a provision for introducing floor prices for electricity tariffs at 50 percent of the production cost.[9] Because of opposition from the farming lobby, the tariff proposal was dropped. Due to inadequate support, the provision for establishing SERCs also did not become mandatory. The Act empowers the commission to rationalize or adjust electricity tariffs, create transparent policies on subsidies, and promote environmentally benign policies.

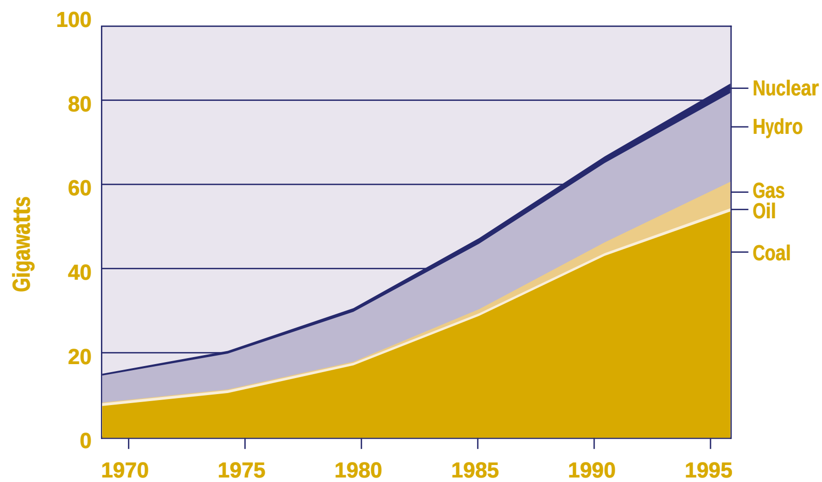
The proposed functions of CERC include: (1) suggesting tariffs for utilities owned by the central government and other generating companies selling power to more than one state; (2) regulating interstate transmission; (3) aiding and advising the central government in tariff policy; and (4) arbitrating in disputes between generation and transmission entities.

Ten states have established SERCs, whose functions include setting tariffs for wholesale, bulk, grid, and retail customers, and for transmission facilities. SERCs also regulate power purchases and procurement for transmission utilities, investment, approval and arbitration of disputes, issue of licenses for transmission and distribution; set quality, continuity, and reliability standards; and promote competitiveness and private sector participation. Some state governments also have begun to implement wide-ranging reforms. Orissa was the first state to take such an initiative. The reform process is new, and it is too early to judge its progress. Isolated success stories like Orissa's lend to optimism, but the slow pace of reform nationwide is a reminder of how far India has to go to transform its regulatory system.

almost nothing to one-twelfth of power capacity in the last decade. Nuclear power provides less than 3 percent and renewables (other than large hydro) just over 1 percent. Power generation capacity (kilowatts) has grown at 4.4 percent annually in the 1990s, though power generation (kilowatt-hours) has grown at 7 percent. This difference is due to increasing capacity factors, the amount of time plants spend actually generating electricity.[11]

Figure 2

Power Generation Capacity



Source: Tata Energy Research Institute, *TERI Energy Directory and Yearbook*, 1998/99.

Coal – The Mainstay of Power Capacity. Coal-based power generation using domestic coal has been the mainstay of electricity generation in India. The country has relatively large reserves of coal but little of oil or gas. Domestic coal has a competitive price advantage over imported fuels, which carry risks associated with the security of supply and payment of foreign currency. A sizable infrastructure in coal mining, power sector manufacturing, and transport has evolved. The heavy engineering industry has developed indigenous manufacturing capability for critical equipment. Coal-fired capacity has risen over the last 20 years, along with the expansion of coal production and restrictions on fuel imports.

Several factors have recently influenced power generation investment, prompting a shift to natural gas. Gas has benefited from inadequate expansion of coal mining capacity, eased restrictions on fuel imports, and foreign participation in the power sector. This shift has been enhanced by the low risk associated with gas-fired power, which enjoys lower capital requirements and shorter construction periods, as well as reduced environmental impacts and higher operational efficiencies.[12] Long-term power purchasing agreements, based on the cost-plus principle that guarantees recovery of investments plus a fixed profit, and incentives for improving operating efficiency have also aided penetration of gas-based power supply.

Clean-coal technologies now being considered do offer opportunities to ameliorate the local environmental drawbacks of coal-based power plants. Particulate control, for example, has improved with mandatory requirements for electrostatic precipitators in new coal power plants. But in the absence of stringent controls for sulfur and nitrogen oxides, penetration of clean-coal technologies has remained marginal.

Large Hydro – Decline in Capacity Share. Hydropower was favored in the early years of independence to bolster self-sufficiency, and India built large-scale projects with capacities ranging between 880 and 2,700 megawatts.[13] But hydropower has declined from 44 percent of installed capacity in 1960 to 25 percent in 1995.[14] Thermal power (coal, gas, oil, and nuclear) expanded as a result of shorter construction time, increased opposition to the social and environmental impacts of large hydro projects, and the greater political risks of relying on hydro due to regional disputes over water and power sharing. Because hydro capacity has traditionally been used for power supply during peak periods, the decline in the proportional contribution of hydro worsened peak power shortages. Pumped storage projects, which pump water to elevated holding reservoirs for later use, now receive greater attention as a means of enhancing peak generating capacity.

Natural Gas – Expanding Power Capacity. Because of its advantages in capital cost and construction lead time, gas is well-suited to meeting peak power demand. This attribute helps account for the 25 percent annual growth rate of gas-fired power in the first half of the 1990s.[15] New capacity is also now being built for base-load operation (plants that run nearly constantly). Domestic gas resources are limited, although production has increased by 150 percent since 1988.[16] Plants are being built in coastal areas near ports with terminals capable of handling liquefied natural gas (LNG). However, inland use of imported LNG remains expensive compared to coal, so natural gas is competitive in these regions only if transported by pipeline directly from the production field. Major supply sources could include the Bay of Bengal off the coast of Bangladesh or across land from Myanmar or Turkmenistan. The lower cost of transporting gas from these locations (compared to LNG) must be weighed against the security risks associated with international pipeline projects, particularly those that cross politically unstable countries. Some power projects hedge this risk by investing in technology capable of burning both gas and liquids, though this adds to the cost.[17]

Nuclear Power – Slow Growth. With assistance from the United States, India launched a nuclear power program in 1969 with two twin boiling water reactors. Subsequent projects have used pressurized heavy water reactor technology (PHWR), built with Canadian assistance and later developed indigenously. India operates 10 nuclear reactors with 2,225 megawatts of total power capacity and energy production of almost ten terawatt-hours per year.[18] It plans to add 11,600 megawatts of nuclear capacity by the year 2012.[19] India has emerged as a leader in reactor development and safety, and thorium fuel utilization technologies. While the nation possesses 8 percent of global uranium reserves and 32 percent of thorium reserves, it has linked the fuel cycle of the pressurized heavy water reactor to a 40-megawatt fast breeder reactor program to maximize use of these reserves.

Regulators have paid increasing attention to nuclear safety and environmental impacts in recent years. Radioactive waste treatment and disposal plants are operated as an integral part of every nuclear facility. An independent agency, the Environment Survey Laboratory, monitors nuclear plant sites and their surroundings for impacts on forests, fauna, marine life, crops, and air. The International Commission on Radiological Protection (ICRP) and the Atomic Energy Regulatory Board set guidelines for the operation of nuclear stations. Nevertheless, public concerns about reactor safety, waste management, and decommissioning hazards have been growing.[20]

Renewable Power Capacity – Emerging New Markets. Twenty years ago, the Indian government initiated a renewable energy program to diversify national energy sources. This program created a renewables market through technical assistance and commercial incentives. At first, the program sought to develop niche applications (in rural areas where grid electricity was unavailable, for example). This focus has shifted to grid-connected commercial applications such as wind power. (See Box 2.) Renewable power technologies in 1997 included 917 megawatts of wind power (which has since grown to over 1 gigawatt), 134 megawatts of small hydroelectric capacity,[21] 42 megawatts of biomass-fired plants, and 2 megawatts of solar photovoltaic units.[22] Significant domestic experience and capability has thus been developed for renewable electricity production, including indigenous biomass gasifier technology[23] and a manufacturing base for wind power and solar photovoltaics. Though the present contribution of renewable electricity is small, existing capabilities offer the flexibility to respond to emerging environmental and sustainable development needs.

Box 2

Wind Power Technology in India

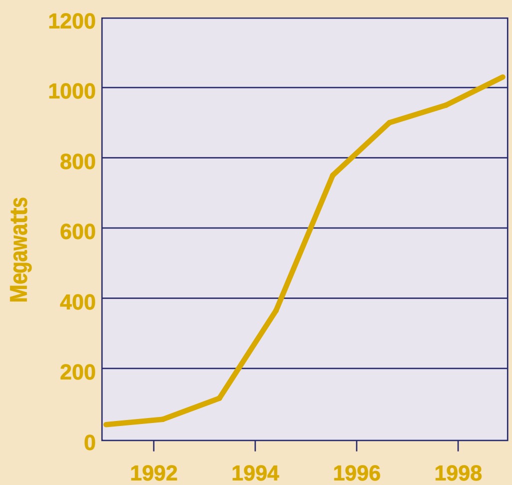
Wind power has expanded significantly over the past five years in India. (See Figure B-1.) For more than two decades, government programs alone drove the demand for renewable energy technologies. Although there were multiple suppliers, the government was the single dominant consumer, fixing technology prices on a cost-plus basis. Price signals therefore did not reflect market conditions. Reform policies have expanded the market's role. Rather than impose development targets, financial incentives such as tax rebates on investment now drive demand. Access to the grid is guaranteed to wind producers via mandatory wheeling (transmission from one region to another via a third). Banking and foreign exchange reforms have also improved the competitive position of the wind power industry by generating significant demand ("market pull") for wind power by the private sector.

Market dynamics also aided technology transfer, as international wind turbine companies (often with generous financial backing from the governments of their home countries) competed to supply technology, and Indian companies formed joint ventures with wind equipment suppliers. Implementation experience has lowered the costs of wind power, and enhanced manufacturing and servicing capacity has lowered the risk. Wind power deployment in India has already contributed to 0.7 million tons of cumulative carbon mitigation.[24]

Rising use of wind power — fueled by tax rebates — has increased tax revenue losses to levels that are financially unsustainable for the government budget. Multilateral finance institutions also have limited resources to promote wind power development. But the reduced cost of wind power, combined with greater awareness of the need to internalize environmental costs from conventional power sources, may enhance wind power market penetration. The future growth of wind power depends on balancing these two factors.[25]

Figure B-1

Wind Power Capacity in India



Source: Tata Energy Research Institute, *TERI Energy Directory and Yearbook,* 1998/99.

Transmission and Distribution Systems. The power transmission and distribution network is comprised of large regional grids. Unfortunately, the share of low-voltage distribution lines increases as the network extends to rural service areas. The ratio of low- to high-voltage lines increased from about 4 in 1965 to 16 in 1996.[26] Because low-voltage lines carry power much less efficiently, this configuration increases power losses and costs, while reducing power reliability and quality.

Transmission and distribution losses now amount to over one-fifth of generated electricity,[27] though theft accounts for about one-quarter of these losses. Power quality suffers from widening frequency and voltage fluctuations and frequent grid disruptions. These problems are caused by inadequate capacity, inefficient operations, and technological obsolescence. The main source of these problems is the government monopoly on power transport and the inability to recover distribution costs because of political interference. These factors lead to a persistent lack of funds for expanding and improving the transmission and distribution network.

Institutional restructuring began in 1989 to consolidate the various central and government suppliers and distributors under one national agency called Powergrid. This agency now integrates the national power grid system, manages reactive power problems (a type of instability that can affect power quality), provides adequate metering, and enhances load dispatch and communication facilities. The goal is to use technical innovations and enforcement of electricity laws to reduce losses to 15 percent within six years.[28] But reforms in transmission and distribution have developed even more slowly than in the power generation sector. Without strong competition, reform targets are unlikely to be achieved.

Grid Integration. Regional distribution of power generation in India varies significantly due to uneven electricity demand and resource endowment nationwide. Sizable hydroelectric potential is located in the North and Northeast, while coal mines are located in the East and central provinces. The long Indian coastline permits access to imported fuels, however the vast hinterland impedes their penetration. The average transport distance for domestic coal is 1,000 kilometers; the cost of transporting coal such long distances can double its price.[29] The trade-off between fuel transport costs and long-distance power transmission losses is a critical issue for national planners.

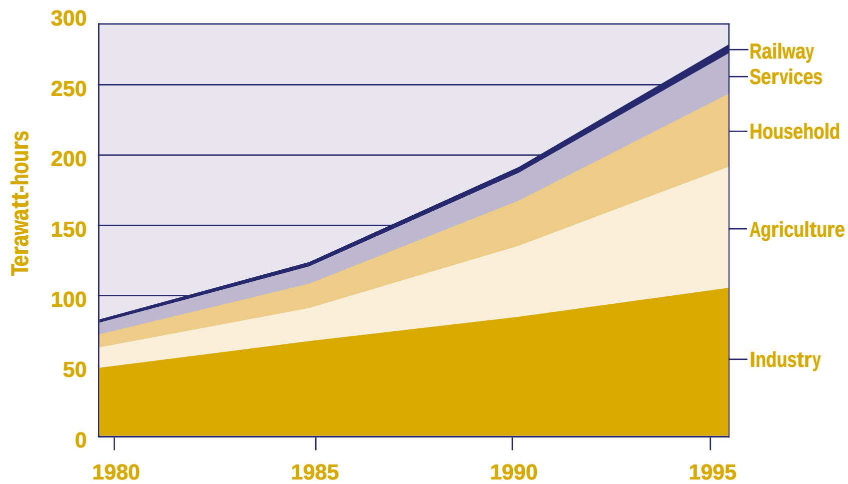
Five regional grids operate in India, with the northern and western grids each connecting 30 percent of power supply capacity.[30] Regional grids connect state transmission networks only within that region, while the national grid remains unconnected. An interconnected national grid could reduce peak capacity problems by evening out load profiles and capacity mixes across regions. Progress in grid integration has been slow due to poor coordination among regional authorities, and technical and financial problems.

Captive Power Generation. Faced with an unreliable external power supply, many energy-intensive industries such as aluminum, steel, and fertilizer have invested in on-site power generation. Industrial, or "captive," power generation has grown from about 1,600 megawatts in 1970 to almost 12,000 megawatts in 1995 (12 percent of the total installed capacity). Captive power capacity continues to grow at an annual rate of 8 percent. Just over half of this capacity is coal, while almost two-fifths is oil. Gas-fired power generation technologies have recently begun to capture the market at the margin, providing 8 percent of captive power.[31] Many captive generating plants have excess capacity that could supply power to the grid given the right policy incentives.

Electricity Consumption Trends. Power demand has grown most rapidly in the agricultural and household sectors over the past two decades. (See Figure 3.) While total power use grew 8.6 percent per year, these two sectors together increased their power use by more than 12 percent annually. Moreover, total power use in the household and agricultural sectors in the same period climbed to 20 and 30 percent, respectively.[32]

Figure 3

Final **Electricity Consumption** by Sector



Source: Tata Energy Research Institute, *TERI Energy Directory and Yearbook,* 1998/99.

Industry's total share of power use over the period therefore fell from almost 60 percent to just under 40 percent. The phenomenal rise in energy consumption from agricultural activities is due to greater irrigation demand by new crop varieties and the very low price of electricity for that sector.

Electricity Costs and Tariffs. Average electricity tariffs in India remained 20 percent below the average cost of supply as recently as 1997.[33] (See Table 1.) This gap stems from subsidized rates to agricultural and domestic consumers, though four-fifths of the subsidy accrues to agriculture. Industrial consumers pay higher costs and provide half of the cross-subsidy, worth over $5 billion[34] in 1997 (nearly half of all electric power sector investments that year).[35] Besides draining public funds, the tariff structure weakens power sector investment incentives and creates widespread inefficiencies. Economic reformers have been unable to alter the tariff structure, which enjoys strong political backing. Changing the power sector probably depends on broader political reform and economic liberalization.

Table 1

Average Cost of Electricity Supply and Tariffs

Year	Cost (cents/kWh)	Tariff (cents/kWh)	Gap (cents/kWh)	Tariff/Cost Ratio
1990	5.1	3.8	1.2	0.75
1994	5.1	4.0	1.1	0.78
1997	5.6	4.5	1.1	0.80

Source: Tata Energy Research Institute. *TERI Energy Data Directory and Yearbook,* 1998/1999.

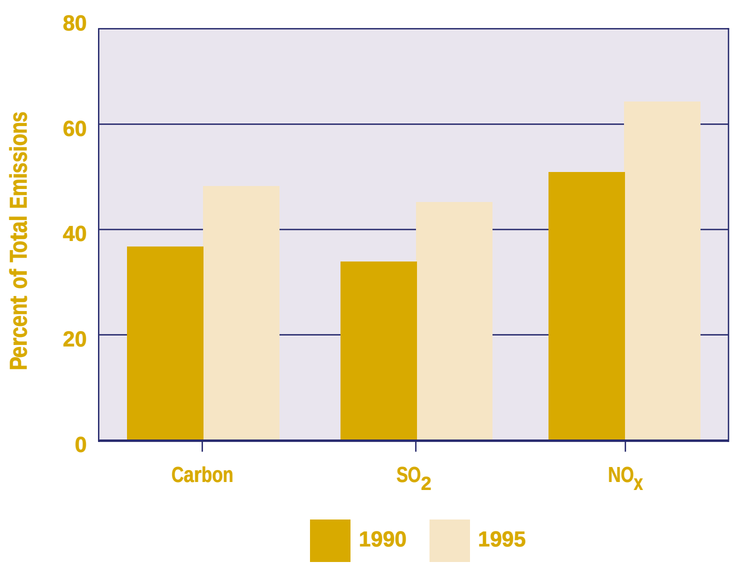
Environmental Issues. Environmental concerns about the Indian power sector relate mainly to coal and large hydro projects, although concern about nuclear power is rising steadily. Environmental problems from coal begin with mining itself. Over the past three decades, surface mining has increased, and poor mining practices have caused significant deforestation and land degradation.[36] However, there is greater environmental concern about the contribution of coal-fired power generation to air emissions. Coal burned in power plants has an ash content of 40 percent and low energy content. Low-quality fuel, together with low combustion efficiencies of 33 percent in pulverized coal plants, generate large amounts of ash, particulates, sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), and heavy metals.

Electrostatic precipitators have been mandatory for the last decade in new coal-fired power plants, a standard that has helped lower emissions of suspended particulates. The relatively low sulfur content of Indian coal has also kept sulfur dioxide emissions in check. But with the rising use of coal, these emissions are now reaching alarming levels. The power sector contributes about half of all carbon, sulfur, and nitrogen oxide emissions in India. (See Figure 4.) The trend of rising emissions from this sector will probably continue without government intervention.

Hydroelectric projects have generated both environmental and social controversy. Opposition to large hydro projects has increased due to conflicts over land and water rights that have been exacerbated by poor government handling of these issues. Environmental impact assessments have been required since 1994 for hydro projects before they can be approved. This assessment now includes attention to displacement of people due to reservoir construction.[37] Opposition to hydro projects remains the focal point of environmental and sustainable development movements in India, however, and therefore is a significant barrier to hydropower project development.

Figure 4

Power Sector Emissions as a Percent of National Totals



Source: Tata Energy Research Institute, *TERI Energy Directory and Yearbook,* 1998/99.

II. The Future of Electric Power in India

A. The Model

Future development of the Indian power sector depends on multiple factors, including economic growth, environmental policy, technology development, energy prices, and power sector reform. This study explores the effect of differences in these variables through scenario analysis. This approach applies a least-cost linear programming (LP) model framework that minimizes the present value of system costs to 2015, while satisfying exogenous (from outside sources) electricity demand forecasts.

The LP model developed first calculates levelized costs[38] for each type of power generation option based on capital, fuel, and operation and maintenance costs. The model then determines the optimal combination of new plants needed to meet given levels of power demand. The model also allows constraints on fuel availability, emissions, investments, and technology improvements that mimic policy measures and sets realistic limits over which values can be obtained. (See Appendix C.) The modeling framework uses a detailed, bottom-up representation of technologies. (See Box 3.)

The results indicate an optimal mix of supply technologies, along with details on generation costs, investment requirements, and environmental emissions. The levelized, or annualized, cost of power generation technologies is the critical criterion for competitiveness. The study estimated levelized costs for feasible candidates of power supply based on Indian costs and conditions. Cost and performance characteristics for each technology are presented in Appendix B.

All modeling has limitations. Optimization models like this one have finite ability to mirror the reality of consumer behavior. Furthermore, although they provide realistic technical and performance characteristics, they tend to overestimate the impact of the single cheapest alternative. Finally, optimization models can neither account for investor preference, such as risk mitigation or financial guarantees, nor ensure that energy security and diversity issues are addressed without input from the modeler.

Box 3

A Guide to Linear Programming for Power Sector Analysis

Analysts use linear programming (LP) models to optimize combinations of inputs whose values are valid only over specific ranges. For example, power planners and electric utilities use LP models to determine types of power plants required to meet least-cost power demand over time while meeting limitations in pollution emissions, energy sources, and manufacturing capacity. Models can help planners analyze alternatives, but non-quantitative factors must also be considered when designing real-life systems.

Researchers use two classes of models to analyze energy systems. LP models are often called "bottom-up" models because they contain detailed information about technology and costs. They have rich engineering detail and rely on user input to simulate broader economic conditions. "Top-down" models, on the other hand, begin from a higher level of economic reality by simulating the interaction of supply and demand in the main sectors of an economy. While top-down models have less detailed information about energy technologies and costs, they capture the reality of consumer behavior better than bottom-up models. Some models, like MARKAL-MACRO, try to integrate the economic reality of top-down models with the engineering detail of bottom-up models.

Researchers at Battelle created a generic LP model which each of the country teams in this study modified to analyze least-cost power options according to the conditions in their specific countries. The model can choose among 17 different types of power plants (coal, petroleum, natural gas, nuclear, hydroelectric, and renewable) to meet power demand. The model divides the country into as many as five regions to capture the variation in energy availability, fuel cost, and environmental limitations. Simulation begins with a base year (1995) and then determines the amount of new capacity from each type of power plant needed to meet demand over 5-year intervals.

After analysts enter technology and cost characteristics of the power plant options, the model calculates the levelized, or lifecycle, costs of power generation. Levelized cost analysis accounts for all the costs of building, fueling, operating, and controlling pollution from power systems and spreads them out over the economic life. In this way, the costs of delivering power to users from nuclear plants (with high construction and low fuel costs) can be compared directly with the costs of providing power from combined-cycle plants (low construction costs and high fuel costs). Analysts also enter the power demand over time and regions. These values are calculated separately according to estimates of economic growth and power demand intensity.

The actual linear program will then find the minimum cost combination of power plants needed to meet the demand. Additional constraints can include emission caps on pollutants such as sulfur dioxide, manufacturing limitations for power generation equipment such as nuclear reactors, energy supply limitations such as hydropower capacity, and transmission line characteristics that limit the amount of power that can be sent from one region to another. For a given time period, the LP will choose the cheapest power source available and continue to use that technology until a constraint prevents its use. LP models need expert input to define when constraints are needed to simulate reality.

Still, the model can be a useful tool to weigh policy alternatives, especially when other qualitative information about India's power sector is considered.

B. The Scenarios

The study presents six scenarios. Important exogenous model specifications for these scenarios include the electricity demand trajectory, investment constraints, energy supply limitations, energy prices, technology costs, and technology performance parameters. The baseline scenario presumes continuation of current energy and economic dynamics and provides a reference for comparing the impacts

Table 2

Key Scenario Drivers and Model Parameters

Scenario	Key Drivers	Implications on critical parameters of the model
Market Reform	Competition, access to global finance and technology	Fuel price (↑), technology cost (↓), efficiency (↑), investment capacity (↑)
Efficient Technology	Technology R&D, transfer and capacity building	Technology cost (↓), efficiency (↑)
Local Environmental Control	Strict local pollution control, emission standards, clean fuel and technology choices	Supply of clean fuel and technology (↑), emission limits (↓)
Sustainable Development	Environmental integrity, consumption changes, dematerialization, cooperation	Environmental constraints (↑), energy and materials content of goods/services (↓), electricity consumption (↓), efficiency (↑)
Growth	Economic growth rate	Sectoral demands (↑↓), investment limits (↑↓), fuel supply (↑↓)

of policies or alternate futures. (See Table 2 and scenario descriptions for key assumptions.) The other five scenarios are market reform, efficient technology, local environmental control, sustainable development, and growth. These scenarios represent those factors most likely to affect the future of electric power in India noticeably. They may differ somewhat from issues affecting other nations.

Baseline. Assumptions used in the baseline scenario are important because they serve as a point of comparison for the other policy scenarios. Investments, energy prices, and technology improvements are assumed to follow past trends and the most likely future developments, as perceived by the experts participating in this study.[40] The baseline scenario assumes moderate annual economic growth of 6 percent between 1995 and 2015. Because India's GDP elasticity of electric power demand has long been greater than one, this rate of economic growth corresponds to a 7.5 percent annual rate of growth in electricity demand. These assumptions closely follow those used by the Central Electricity Authority in developing India's fifteenth electric power survey. For other assumptions, see Appendix B. Also important to note is the assumption in all the scenarios that emission regulations are enforced and that investments and pricing are determined transparently and according to rule of law. Therefore, the results given below are likely idealized.

Market Reform Scenario. This scenario assumes accelerated progress in ongoing market reforms in the electricity sector compared to expectations in the baseline scenario. The context for this alternative future is economic globalization and liberalization. Accelerated market reforms would spur more rapid improvements in technological efficiencies and earlier availability of new technologies. Reforms would lower investment risk in India, thereby stimulating increased levels of foreign direct investment. Constraints on natural gas availability are relaxed by 20 percent due to accelerated development of domestic gas resources and international investment, but prices also rise by an equal percentage. Beginning in 2005, new technologies such as combined-cycle and cleaner coal systems are available five years earlier than in the baseline case. (See Appendix B.)

Efficient Technology Scenario. This scenario tests additional assumptions about technological progress over the baseline and reform scenarios. Accelerated technological improvements are presumed in electricity supply and demand technologies. These improvements would accelerate cost reductions in new and renewable technologies. The scenario incorporates domestic policy measures that would lead to enhanced penetration of efficient technologies, including higher levels of investment in technological research, development, and capacity building through pilot projects and development of local manufacturing capabilities. The model incorporates these factors through exogenous parameters for power generating efficiencies, capacity utilization, reduced power demand, and lower technology costs. New technologies are available ten years earlier than in the baseline case beginning in 2005. The efficiency of combined-cycle plants, for example, increases to 53 percent by 2015 compared to the baseline of 47 percent. (See Appendix B.) Meanwhile, technology improvements on the user-side lower demand by 1 percent annually compared to the baseline beginning in 2005.[39]

Local Environmental Control Scenario. This scenario evaluates the impact of stricter local pollution control. This future would impose measures for reducing health and property damage from particulate and sulfur and nitrogen oxide emissions and the cost of land degradation due to mining. Pollution control measures would be implemented to impose environmental standards, mandatory use of sulfur control technologies, and greater use of clean fuels such as washed coal. The model incorporates these policies through exogenous assumptions for technology costs, relative fuel prices, fuel availability, and investment constraints. After 2005, for example, all new pulverized coal power plants are fitted with sulfur and nitrogen oxide controls, and the availability of washed coal is increased by 20 percent compared to the baseline. This scenario does not include intervention to reduce greenhouse gas emissions or directly assume the cost of environmental externalities (estimated damages to the environment that are typically not monetized).

Sustainable Development Scenario. This scenario assumes policies that contribute to "sustainable development." Such policies include decentralized governance, strong environmental and conservationist values, emphasis on renewable resources and technologies, demand-side measures (such as increased use of energy-efficient technologies and lowered consumption patterns), policy integration, and regional cooperation. Compared to the baseline scenario, the sustainable development scenario requires different model inputs for demand trajectories, a wider range of technology alternatives, cleaner fuel supply, stricter environmental constraints, and electricity trade within the country and among its neighbors. Thus, electricity demand declines by 1.5 percent annually after 2005 compared to the baseline. The capacity for renewable energy sources also increases by 40 percent. Natural gas and washed coal supplies increase by 20 and 35 percent, respectively, and sulfur and nitrogen controls are again required on all new pulverized coal plants. (See Appendix B.)

Growth Scenario. This scenario demonstrates the sensitivity of different economic and electric power growth rates and the resulting impact on fuel consumption and emissions. High- and low-growth, respectively, refer to economic growth above or below the base case. A high-growth case assumes average GDP growth of 7 percent from 1999 to 2015. A low-growth case assumes 5 percent growth over the same period. Model inputs were adjusted to match changes in electricity demand, availability of surplus funds for investment, and energy supply constraints in proportion to changes in assumed economic growth. The high- and low-growth scenarios assume a 1.5 percent increase and decrease, respectively, in annual power consumption compared to the baseline. Baseline electricity demand of 1,285 terawatt-hours in 2015 grows to 1,670 terawatt-hours in the high-growth case and falls to 900 terawatt-hours in the low-growth case.

C. Results

In the baseline scenario, Indian power-generating capacity increases 4.8 percent per year through 2015 – reaching two-and-a-half times the 1995 level. Coal-fired technologies remain dominant, although their share in the total capacity declines from 62 to 55 percent. (See Figure 5.)

Gas-fired systems double their capacity to 14 percent, while nuclear rises to almost 6 percent over the period. Hydroelectric power declines slightly to around 20 percent, while renewable capacity (excluding large-scale hydro) rises from its small base of 1 percent to 3 percent in 2015. The share of integrated gasification and combined cycle (IGCC) systems increases significantly to one-quarter of the total new capacity installed between 2010 and 2015. Actual power generation shares are similar, as expected. (See Figure 6.)

Power Plants. According to this analysis, coal continues to be the main energy source, but stricter air pollution controls considered in some alternative scenarios help promote a shift toward washed coal, clean-coal technologies, and natural gas. (See Figure 7 and Table 3.)

Figure 5

Power Capacity in the Baseline Scenario

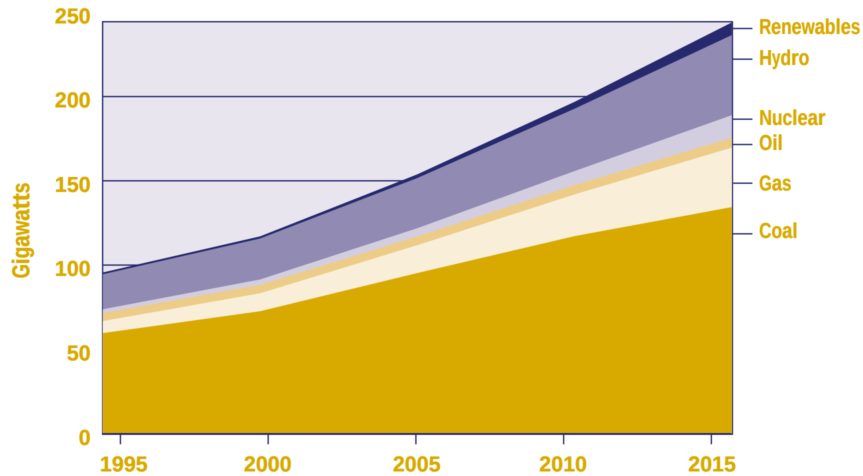
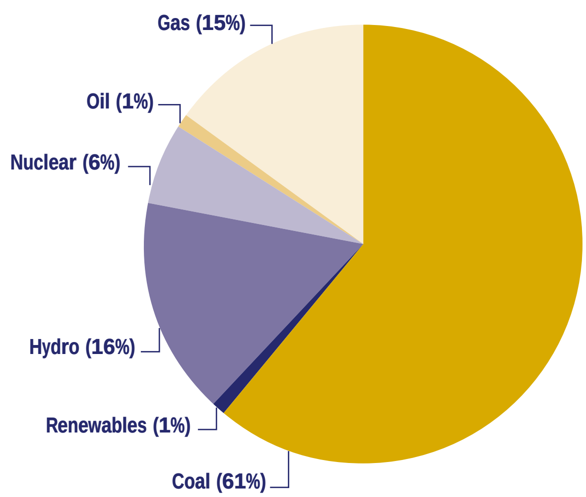


Figure 6

Power Generation in the Baseline Scenario, 2015



Coal use grows by 2.5 times in the baseline. Perhaps surprisingly, strict local environmental controls do not cut coal consumption because conventional pulverized coal technology can be fitted with controls for sulfur and nitrogen oxides at a lower cost than any other option. Higher economic growth raises coal consumption by 4 percent, but cleaner, more efficient coal-burning and utilization technologies penetrate the market more rapidly due to the greater investment capital available in a more prosperous economy. These technologies would lower SO_2 and NO_x emissions by 44 and 70 percent. Simply stated, economic growth generates enough financial resources to offset some of the environmental problems it causes.[41]

Natural gas combined-cycle plants account for higher percentages of the capacity mix in the market reform and efficient technology scenarios. Limited availability of low-cost gas, rather than the costs of other alternatives, constrains the role of natural gas in these scenarios. Natural gas-fired power generation — like the most advanced clean coal technologies — virtually eliminates sulfur dioxide and particulate emissions; carbon emissions, however, are only about half as much as those from coal. Expanding the supply of natural gas is thus a critical variable in India's future energy equation given favorable circumstances for its selection as a fuel for power generation. Accelerating research and development of gas turbines within India to improve their efficiency is also critical unless the country chooses to rely on imported equipment.

Figure 7

Generation Capacity Mix in 2015

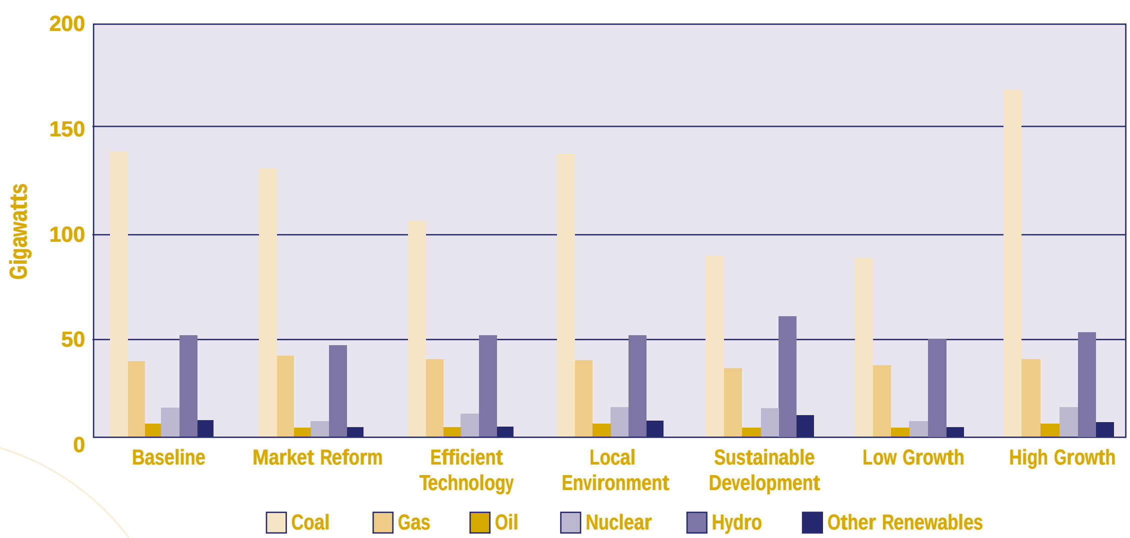


Table 3

Total Discounted Costs, Emissions, and Fuel Consumption in 2015

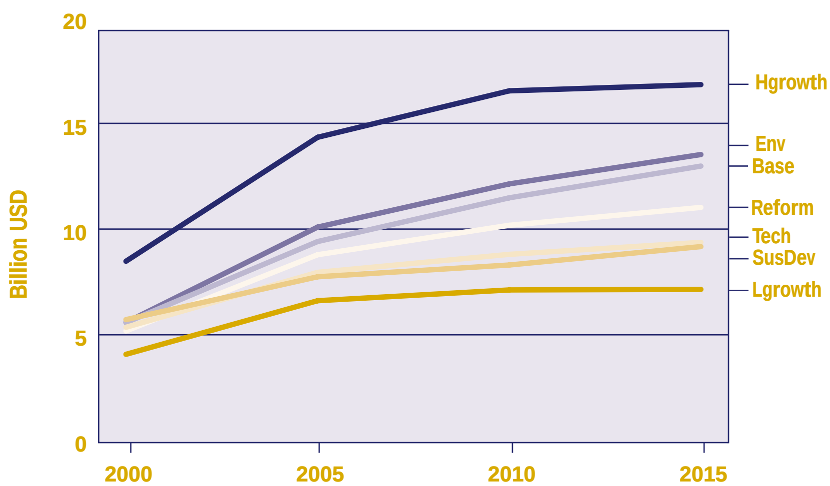
	Cost ($B)	SO_2 (Mt)	CO_2 (MtC)	NO_x (Mt)	Coal (Mt)	Oil (Mt)	Natural Gas (BCM)
Baseline	411	5.9	217	2.6	490	2.9	41
Market Reform	462	2.6	203	1.6	439	0.8	45
Efficient Technology	349	2.3	168	1.2	329	1.0	43
Local Environment	431	2.5	218	1.8	490	2.9	43
Sustainable Development	351	2.3	141	1.0	290	1.0	37
High Growth	631	3.3	225	0.8	509	2.9	43
Low Growth	263	4.0	145	1.8	305	0.8	39

Note: Costs include investment requirements, fuel, and operation and maintenance components for new plants. BCM means billion cubic meters.

Investment and Cost. About $151 billion is required to finance the baseline scenario cumulatively between 2000 and 2015. This sum is required for power generation alone and does not include fuel, operation and maintenance, or transmission and distribution costs. Capital requirements would be about one-fifth lower in the efficient technology and sustainable development scenarios. (See Figure 8.) In the efficient technology scenario, higher efficiencies, improved capital utilization rates, and reduced power demand lead to lower requirements for additional capacity and therefore for investment. In the sustainable development scenario, less investment is required mainly due to reduced power demand and improved technologies. Market reforms would reduce investment requirements by 11 percent as a result of improved technology performance and a greater reliance on natural gas, which has lower capital costs. The environment scenario would require 5 percent greater investment due to the need for sulfur control technologies. However, some of this

Figure 8

Investment Requirements for Generation by Scenario



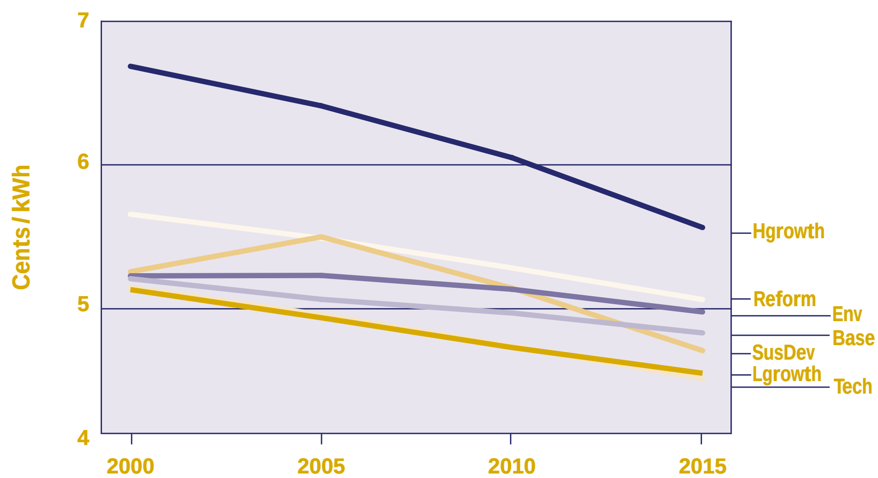
Note: Investment refers to capital costs only. It does not include fuel or operation and maintenance costs.

expense is offset by greater use of combined-cycle systems that have lower capital costs. Finally, investments in the low growth scenario are 36 percent less and in the high growth scenario 44 percent more than the baseline case mainly due to the demand for different amounts of electric power over the period.

The marginal cost for electric power — the total cost of building and operating the power plants divided by the kilowatt-hours of electricity generated — declines with time in all scenarios due to technological and operational improvements. (See Figure 9.) In the baseline, costs steadily decline from US $0.052 per kWh in 2000 to $0.048 in 2015. Coal- and gas-fired power costs decline by 10 percent each over this period, while nuclear power costs decline by 25 percent due to greatly improved plant capacity factors. Raising the nuclear power capacity factor by this much will be difficult, but the current level in India is very low.

Figure 9

Marginal Costs for Electricity Generation



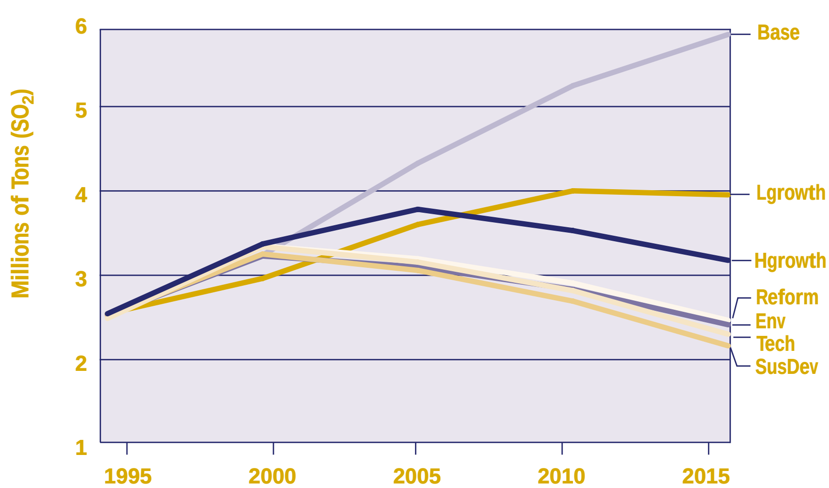
Marginal costs in the market reform scenario are higher than in the baseline because removal of subsidies and higher environmental standards shift hidden costs to the price of electricity. Also, because this study is limited to the electric sector, the analysis does not capture the overall — and potentially larger — positive economic and environmental impacts of market reforms. However, higher sectoral costs (in agriculture, for example) indicate the origins of political resistance to sectoral reforms and also the gradual nature of the market reform process.

The sustainable development scenario increases costs through 2005 because it requires the early penetration of capital-intensive technologies, including renewables, and stricter environmental controls. However, costs start to fall after 2005 as advanced technologies enhance system performance. Marginal costs in the high growth scenario are significantly greater in the early years due to the assumption that environmental control technologies will be used, but they then decline more rapidly than in any other scenario.

Emissions. Local pollutants including sulfur and nitrogen oxides vary in interesting ways across scenarios in their reductions below the baseline. (See Figure 10.) Not surprisingly, local environmental control, efficient technology, and sustainable development measures curb these emissions by almost two-thirds. However, local emissions are also relatively low under high economic growth because this scenario assumes greater financial resources available for investment in clean and advanced technologies. The finding is justified on the observation that rising income results in greater demand for a cleaner environment. Market reforms also enhance access to advanced technologies, lowering emissions. These results do not imply that growth and market reform are panaceas for environmental protection, but they do indicate that growth and reform policies can — along with appropriate environmental policies and measures — provide sustainable solutions to local environmental pollution problems.

Figure 10

SO_2 Emissions from the Power Sector



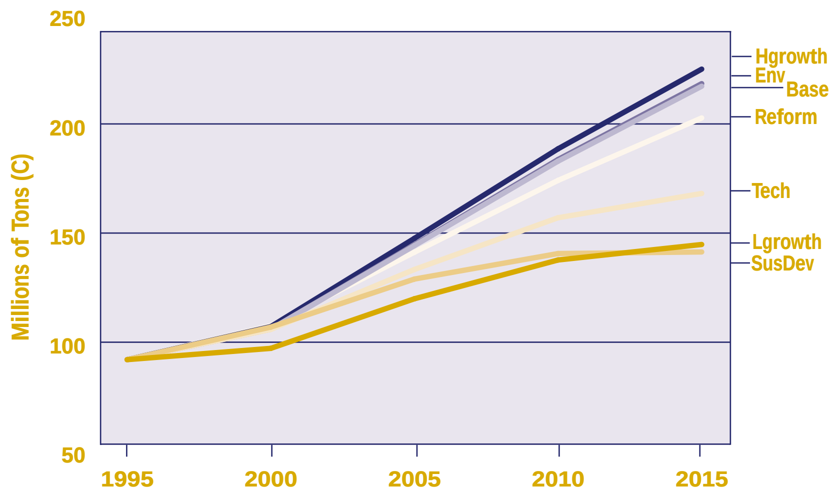
Power sector carbon emissions growth is disconcerting in the base scenario, increasing by two-and-a-half times over the next 20 years. Carbon emissions vary widely across scenarios, however. (See Figure 11.) Higher growth and local environmental control reforms have little impact on carbon emissions because they do not result in substitution of gas and renewables for coal. Instead, they lead to higher penetration of clean-coal technologies such as sulfur scrubbers that increase carbon emissions or of IGCC systems that slightly lower carbon emissions. On the other hand, even a small increase in natural gas use in the market reform scenario could have a noticeable impact on emissions.

Efficient technologies and sustainable development measures produce marked reductions in carbon emissions. Compared to the base scenario, these measures reduce carbon emissions by 23 and 35 percent, respectively, by 2015 (49 and 76 million tons of carbon). Cumulative carbon mitigation between 2000 and 2015 in the latter scenario thus reaches about 600 million tons.

Mitigation of carbon emissions may require special policies that directly influence fuel use.[42] A series of carbon tax scenarios were also modelled, but the impact on emissions was small until the tax level rose significantly. High carbon tax levels (up to $100 per ton of carbon) can change the trajectory of carbon emissions. Policies that encourage advanced technologies and shift demand through sustainable development measures will be needed in conjunction with direct carbon emissions mitigation policies to stabilize emissions in the long run — the ultimate objective of the United Nations Framework Convention on Climate Change.[43]

Figure 11

Carbon Emissions from the Power Sector



III. Conclusions and Recommendations

This study provides three important insights for improving primary energy use by the power sector. First, in the absence of adequate supplies of low-cost natural gas, strict control of local pollutants does not necessarily reduce coal consumption, but might promote early penetration of pollution control equipment and washed coal suited to conventional coal power technologies. Second, high economic growth does not have to lead to excessive emissions of local pollutants. Instead, high growth causes a shift to cleaner fuels and efficient coal technologies due to larger financial resources and greater availability of clean fuels. Third, the share of gas increases in all future scenarios, indicating that enhanced gas supply is a vital energy policy measure.

India's lowest cost options are pollution control technologies such as desulfurization that are fitted with conventional coal power technologies. Switching fuels is more expensive, but provides flexibility if carbon mitigation becomes necessary.

By 2015, carbon emissions rise from 60 to 150 percent across the various scenarios, relative to the 1995 level of 92 million tons. Policies followed in the efficient technologies and sustainable development scenarios could reduce carbon emissions by up to 70 million tons per year by 2015. Further mitigation of carbon emissions will require more direct measures, such as investments from the Clean Development Mechanism, regional cooperation on natural gas supply, carbon taxes, or emissions limitations.

The analyses reveal that carbon taxes are unrealistic and have limited impact on carbon emissions in the short term up to 2015. A high carbon tax changes the trajectory of carbon emissions, but even high taxes are inadequate to stabilize those emissions. Policies that promote advanced technologies (like gas, clean coal, and pumped storage hydro) and sustainable development are more effective for mitigating emissions in the short run. These measures are vital to create the early transition of emissions to a lower path. In the long run, these transition strategies and direct mitigation measures like carbon taxes or emissions limitations will have to be implemented together to stabilize emissions from the Indian power sector.

Market reform and restructuring would help eliminate the demand-supply power gap by using private competition to provide new investments and efficient operation. This strategy would keep electricity costs low to enhance economic competitiveness and support national development goals. It would be wise to keep the energy and technology mix flexible. Gas-fired systems, in particular, help reduce emissions, satisfy peak load requirements, come on-line quickly, and reduce capital costs. If India accelerated efforts to manufacture gas turbines domestically, it could gain the benefits of combined-cycle systems without relying on imported equipment. Gaining experiences with emerging renewable technologies also would increase flexibility.

Integrating regional grids into the national grid would enhance the efficiency and reliability of the power supply. Cooperation with neighboring countries when possible will help diversify the capacity mix, reduce costs, and improve environmental performance.

In the short run, the best climate emissions mitigation strategy is to promote efficient technologies, combined with market reform and sustainable development measures to reduce carbon emissions. The best medium-run strategy is to employ direct mitigation measures, like carbon taxes or emissions limitations. But power sector dynamics have implications for the next half-century. Long-term considerations are to develop a wider range of energy options including nuclear, solar photovoltaic, and advanced biomass; enhance research and development, infrastructure and indigenous manufacturing; and develop a regional cooperation regime.

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Appendix B: Selected Cost and Performance Assumptions for Power Generation Technologies

Technology	2000	2005	2010	2015
Coal-based Technologies				
Sub-critical PC Combustion[a]				
Capital cost ($/kW)	1,000	975	950	925
Capacity factor (%)	64	66	68	70
Efficiency (%)	35.5	36	36.5	37
Super-critical PC Combustion[b]				
Capital cost ($/kW)	1,150	1,100	1,080	1,045
Capacity factor (%)	65	67	69	71
Efficiency (%)	36.5	37	37.5	38
AFBC				
Capital cost ($/kW)	1,470	1,405	1,380	1,340
Capacity factor (%)	65	68	71	75
Efficiency (%)	38.5	39	39.5	40
PFBC				
Capital cost ($/kW)	1,215	1,160	1,140	1,105
Capacity factor (%)	65	68	71	75
Efficiency (%)	40.5	41	41.5	42
IGCC				
Capital cost ($/kW)	1,480	1,415	1,390	1,350
Capacity factor (%)	65	68	71	75
Efficiency (%)	45	47	49	50
Gas-based Technologies				
Open Cycle Gas Turbine[c]				
Capital cost ($/kW)	720	700	685	670
Capacity factor (%)	38	40	40	40
Efficiency (%)	38.5	39	39.5	40
CCGT[d]				
Capital cost ($/kW)	815	795	775	755
Capacity factor (%)	72.5	75	77.5	80
Efficiency (%)	44	45	46	47
Oil-Based				
Capital cost ($/kW)	765	750	730	710
Capacity factor (%)	71	72	73	74
Efficiency (%)	43.5	44	44.5	45
Nuclear[e]				
Capital cost ($/kW)	1,630	1,590	1,550	1,510
Capacity factor (%)	60	65	75	80
Hydro[f]				
Capital cost ($/kW)	1,395	1,360	1,325	1,295
Capacity factor (%)	51	52	53	54

Technology	2000	2005	2010	2015
Pumped Storage[g]				
Capital cost ($/kW)	1,440	1,405	1,370	1,335
Capacity factor (%)	61.5	63	64.5	66
Small Hydro[h]				
Capital cost ($/kW)	815	790	770	755
Capacity factor (%)	41	42	43	44
Wind				
Capital cost ($/kW)	1,045	1,020	995	970
Capacity factor (%)	21	22	23	24
Biomass Electricity				
Capital cost ($/kW)	815	795	775	755
Capacity factor (%)	51	52	53	54
Efficiency (%)	28.5	29	29.5	30
Solar Photovoltaic				
Capital cost ($/kW)	4,675	4,205	3,790	3,410
Capacity factor (%)	20.5	21	21.5	22

[a] Sub-critical pulverized coal technology is the most commonly used electricity generation technology in India. The present operating efficiency of this technology is around 35 percent. A significant cause of low efficiency is the low quality of coal. Poor maintenance and operating practices are other causes.

[b] Efficient and clean-coal technologies such as super-critical pulverized coal (PC) technology, atmospheric fluidized bed combustion (AFBC), pressurised fluidized bed combustion (PFBC), and integrated gasification combined cycle (IGCC) are not currently operating in India.

[c] Open cycle gas turbine technology is used mainly for meeting peak load requirements.

[d] Combined cycle gas turbine technology (CCGT) is used for base load requirements.

[e] Nuclear power plants, although currently performing at lower load factors, are assumed to operate at higher capacity utilization in the future. In India, these reactors average a capacity factor of about 0.43, or 43 percent of the time, but are rising as experience builds.

[f] Hydro projects in India are constructed for dual purposes of augmenting irrigation water supply and electricity generation. Hydro power is mainly used for meeting peak load.

[g] A large potential for pumped storage is available, which can add to peaking capacity if necessary.

[h] Hydro capacities with less than 15 MW capacity are called small hydro.

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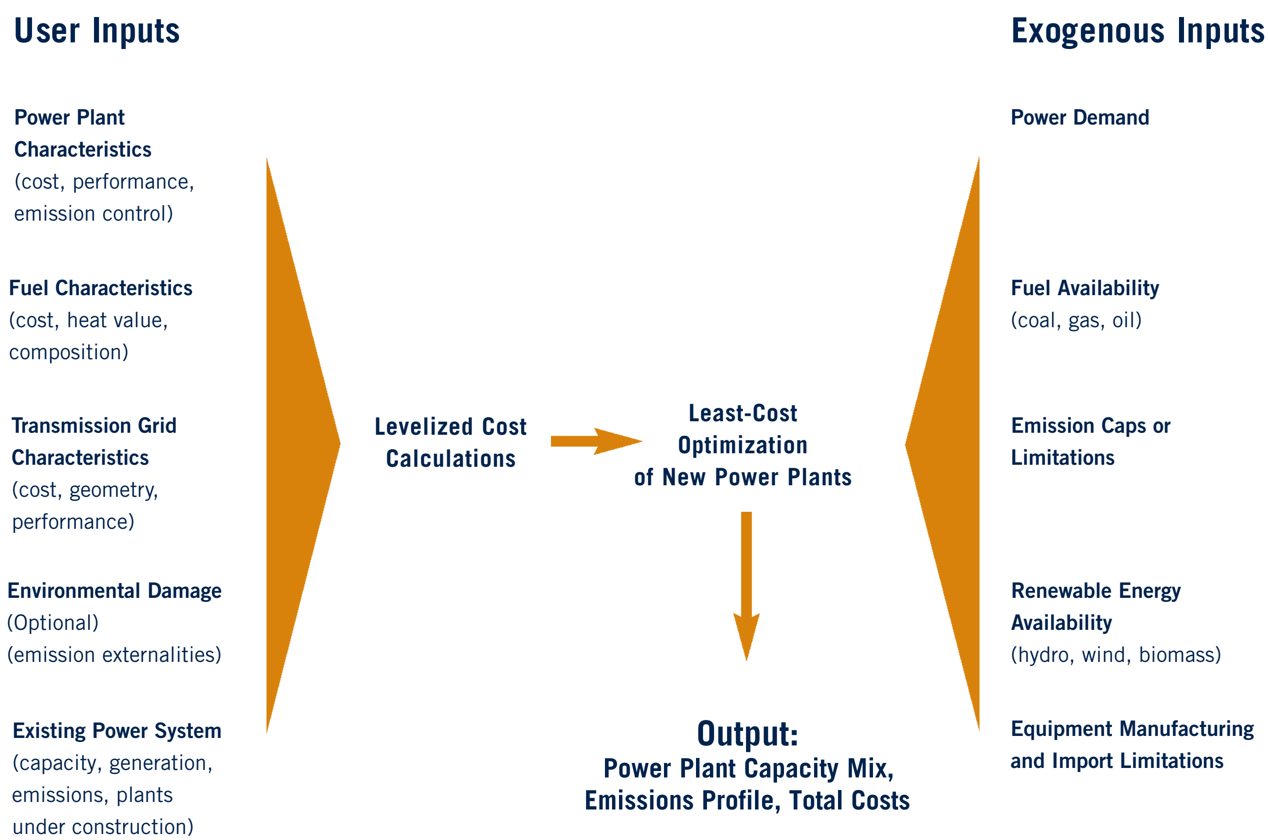
Appendix C: The Linear Programming Model



Endnotes

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38. Levelized cost analysis, also referred to as lifecycle costing, spreads costs out over the economic lifetime of a plant, allowing direct comparisons of cost per kilowatt-hour of delivered power.

39. Demand-side improvements can often be achieved using a combination of simple technology and market or institutional reforms. In this scenario, the authors consider the transaction costs of demand-side policies and the ancillary benefits to be nearly balanced in India.

40. For background on electricity demand projections, see Central Electricity Authority. 1995. *Fifteenth Electric Power Survey of India.* For assumptions used in projecting energy prices, see Shukla, P.R. ed. *Climate Change Mitigation: Shaping the Indian Strategy,* 1999. Discussions of other energy-economic trends in India can be found in Shukla P.R. 1996. “The Modelling of Policy Options for Greenhouse Gas Mitigation in India.” *AMBIO.* 25(4): 240-248.

41. The World Bank believes that only under a scenario of strong economic growth will China be able to achieve greater environmental protection. See *China 2020: Clear Water, Blue Skies*. 1997. Washington, D.C.: The World Bank.

42. For example, a larger gas supply is assumed under the market reform scenario, but at higher prices. A comparison of electricity generation cost under various carbon mitigation policies reveals that an investment, or tax, of $30 per ton of carbon can make windpower competitive against fossil fuels. Costing externalities at 25 percent of capital cost, nuclear power can compete with fossil technologies at carbon tax levels above $45 per ton of carbon. But a carbon tax would have limited impact on carbon emissions in the short term, including the period through 2015.

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