Developing countries & Global climate change

Electric Power Options for Growth

Prepared for the Pew Center on Global Climate Change

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

Understanding the possibilities for greenhouse gas emission reductions in developing countries can inform the debate over long-term equitable commitments and global participation in a climate change regime. This study investigates policy and technology choices in the electric power sector that can lower carbon dioxide and other air emissions, while maintaining or improving economic growth.

The standard projection shows electric sector CO_2 emissions in developing countries nearly tripling over the next twenty years as a result of investments of approximately $1.7 trillion. This sector already represents 10 percent of global emissions. The study presents four alternative paths for new power generation that could maintain economic growth and reduce new emissions to levels below this projection:

- Including the costs of electricity delivery — not just generation — makes planning and investment decisions more efficient and makes distributed renewable energy more viable, decreasing CO_2 emissions by up to 2.5 percent;
- Increasing privatization of the electricity sector could reduce CO_2 emissions by up to 1 percent and boost economic benefits by up to 5 percent;
- Using low-emissions technologies — for example, increasing the use of natural gas and renewables — could reduce CO_2 emissions by almost 25 percent while still allowing economic growth; and
- Increasing the efficiency of electricity supply and demand could reduce CO_2 emissions by up to 10 percent.

These findings were based on an aggregated analysis and may not hold for individual countries. For similar benefits to accrue, specific reforms that account for national conditions would have to be implemented in each country. Countries could also participate in the Clean Development Mechanism to increase the available up-front financing to accomplish these reforms.

This report is the fourth in a series by the Pew Center on Global Climate Change examining policy questions both domestically and internationally. Five case studies — evaluating electric power options in more detail — will be published for Argentina, Brazil, China, India, and the Republic of Korea.

The Pew Center 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 and its Business Environmental Leadership Council believe that climate change is serious business. Better understanding of those sensible actions that reduce emissions without hurting the economy brings us closer to a serious solution.

Executive Summary

In 1995, 34 percent of global carbon dioxide (CO_2) emissions were produced by electric power generation, approximately one-third of which came from developing countries. Between 1995 and 2020, developing countries will invest roughly $1.7 trillion building 50 percent of all new global power generation capacity. If these investments are made according to business-as-usual (BAU) investment trends, CO_2 emissions from developing country power generation will nearly triple their 1995 levels within 20 years.

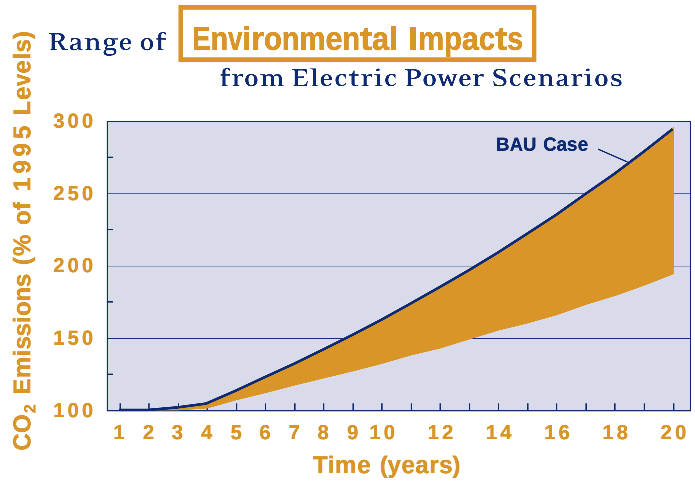
This report presents the results of a RAND study that suggests that BAU investment trends are not the only path to strong economic growth. If developing countries adopt different policies and planning methods for their power generation sectors, technologies other than those included in BAU projections could provide lower local and global environmental impacts and produce similar or even higher economic benefits. This study compared the possible impacts that different policies and technology mixes could have on economic growth, air pollution, and CO_2 emissions from new electric power generation in developing countries.

In order to consistently and quantitatively examine the economic and environmental impacts of different policies and mixes of power generation technologies, this study developed a simulation model that sought to capture the macro-level relationships between electric power generation, economic growth, and capital investment in the world's developing countries. The simulation model was used to compare current forecasts and BAU trends for electric power to several policy alternatives that also met projected capacity needs. The policy alternatives investigated in this study were: the inclusion of infrastructure costs in new capacity investment decisions; the acceleration of private-sector participation in power generation; the use of low-emissions technologies; and improvements in energy efficiency.

Figure ES-1 presents the range of potential CO_2 emissions based on this study's findings. The upper bound of this range shows that accelerated privatization could, under some circumstances, increase new CO_2 emissions up to 20 percent relative to BAU investment trends that include infrastructure costs. Other scenarios could decrease the expected growth. Low-emissions technologies could reduce that growth by almost half.

This study began by examining the potential economic impact of traditional planning tools and analysis methods that typically do not include the non-generation infrastructure costs of electricity supply. By comparing the expected economic benefits of BAU trends with the expected annual benefits these tools and methods yield, this study found that traditional planning tools and methods may overestimate the benefits of new capacity by as much as 10 percent. Furthermore, when the infrastructure costs are included in planning analyses, new distributed technologies, which are often thought to be significantly more expensive, may result in only small or no losses in annual economic benefits relative to BAU investment trends, as well as reduce CO_2 and other local pollutants.

Figure ES-1



This study also found that accelerated privatization of new generation could boost the expected annual economic benefits provided by new capacity up to 5 percent after twenty years. Analysis also shows that unless planning is done properly and regulatory institutions are effective, privatization could increase emissions of local pollutants and CO_2. However, if these conditions are met, accelerated privatization could reduce new CO_2 emissions up to 1 percent. In addition, privatization under these conditions could reduce future increases in power generation-related emissions of sulfur oxides (SO_X) up to 64 percent and emissions of nitrogen oxides (NO_X) up to 46 percent, while providing a small increase in economic benefits.

Next, this study found that, relative to BAU investment trends that include infrastructure costs, there are opportunities to reduce new CO_2 emissions up to 22 percent and local pollutants by similar amounts through the increased use of low-emissions technologies. This finding is particularly important because while electric power may not be the major cause of local air pollution in developing countries, electric power does contribute to these problems. If local pollution problems persist or worsen, reducing power generation emissions could become a larger priority. This study found that if estimates of the infrastructure and environmental costs of new investments are taken into account, power generation investment portfolios that use more low-emissions technologies than currently forecasted could reduce future increases in power generation-related SO_X emissions up to 72 percent and NO_X emissions up to 39 percent, with no long term economic costs.

Finally, this study investigated the opportunities for improved efficiency in both electricity supply and demand. For twenty years, experts have identified opportunities for increased energy efficiency; however, little of this potential has been realized due to a variety of obstacles. While obstacles are likely to persist, this study found that developing countries could benefit both economically and environmentally from improvements that cost less than $3,000 per kW on the supply-side and less than $0.07 per kWh on the demand-side, both of which are common.

This study was based on an aggregated analysis of all developing countries. Accordingly, its conclusions cannot be applied to individual countries. However, the results presented in this report provide insights into the implications of policies that impact new electric power generation — namely, that alternative electric power options can provide similar or even higher levels of economic growth while reducing local and global air emissions relative to BAU trends. These findings suggest that individual countries and the international community have a significant opportunity to guide new investments in electric power generation in ways that capture these benefits.

Specific policy options this study suggests decision-makers consider:

1. Include infrastructure costs in new capacity investment decisions;
2. Accelerate private-sector participation, where appropriate;
3. Consider the use of low-emissions technologies;
4. Consider participation in international mechanisms or markets to aid in providing financing for capital-intensive, lower CO_2 emitting technologies;
5. Create incentives to improve the efficiency of the existing electricity system.

In recognizing the need for each country to consider these concerns in greater detail and under individual circumstances, the Pew Center on Global Climate Change will follow this report with a series of case studies examining power generation in Argentina, Brazil, China, India, and the Republic of Korea.

Introduction

Between 1995 and 2020, roughly $1.7 trillion will be invested in new electric power generation capacity in the world's developing countries, according to forecasts in the International Energy Agency's (IEA) World Energy Outlook 1998 (WEO).[1] This added capacity will enable continued economic growth in these countries while bringing electricity to some of the nearly 2 billion people who currently do not have access to it.[2] The generation equipment acquired with each year's $68 billion investment will have a useful life span of 20 to 50 years; therefore, the investment choices made over the next 25 years could have impacts lasting well past the middle of the 21st century. These impacts will affect, at a minimum, the cost and quality of electricity, its accessibility by different segments of the population, the allocation of its generating costs, and the magnitude of power generation-related carbon dioxide (CO_2) and other air emissions.

The magnitude of power generation-related emissions is particularly important. Power generation currently accounts for over one-third of global annual CO_2 emissions.[3] According to the WEO, the rapid economic growth that is expected in these regions could result in 50 percent of all new increases in global power generation capacity between 1995 and 2020 being located in developing countries. Based on business-as-usual investment trends, this could result in developing country power generation CO_2 emissions increasing to nearly 300 percent of their 1995 levels. More importantly for developing countries, these trends will also lead to significant increases in local air emissions such as sulfur oxides (SO_X), nitrogen oxides (NO_X), and particulate matter (PM) among others. For these reasons, the technologies used to generate electric power in developing countries today and in the near future will affect national economies, global CO_2 emissions, and even the global economy well into the 21st century.

A. Technologies: An Expanding Set of Generation Options

For much of the last 100 years, electricity has been generated by large, centralized power plants using boilers and turbines fired by fossil fuels, hydroelectric dams, and nuclear power plants. These "conventional" technologies are typically built as large capacity units on the order of 100 to 1,000 megawatts (MW) often far from the consumers of the electricity. These large capacities are the result of planners seeking economies of scale that allow generation costs to fall as plant size increases. While planners seek to build new capacity near consumers, specific power plant locations are typically based on natural resource needs (i.e., location of primary energy resource or large water supplies to meet cooling needs), fuel delivery infrastructure (i.e., railroads or shipping ports), land availability, and other factors. As a result of the distance between the site of generation and the site of consumption, these centralized plants require that the electricity they generate be sent to population centers through a transmission and distribution (T&D) system, which typically consists of high-voltage transmission lines, substations, distribution lines, and transformers.

During the last ten years, there have been advances in generation technology beyond the conventional methods described above. In addition, new and expanded access to fuels (e.g., natural gas, oil, low-sulfur coal, and some renewable resources) has opened power generation options that were previously not thought possible.[4] New generation options include natural gas-fired, combined cycle combustion turbines, cleaner coal technologies, biomass gasification, and several distributed renewable technologies such as solar photovoltaics and wind turbines, among others. Taken together, these new and conventional power generation technologies provide numerous options for new electric power generation capacity. However, these expanded options also make comparing one option to another more complex for planners. This is due to wide variations in a number of important factors:

- investment, operating, and maintenance costs for different generation technologies;
- fuel supply cost and availability;
- fuel delivery infrastructure cost;
- transmission and distribution equipment costs; and
- environmental impacts such as air emissions, water discharges, and solid wastes resulting from generation and fuel life-cycle processes.

B. Investment Decisions in Electric Power Generation

Despite the promise of these new technologies and energy sources, the degree to which they will be implemented is uncertain for three reasons. The first and most significant impediment to the installation of new capacity for some of these technologies is the difference in initial investment costs. For example, the direct generation costs of solar photovoltaics can be more than four times as large as that of a conventional coal-fired plant. In the case of intermittent renewables (i.e., those technologies that do not produce electricity at all times, as with solar photovoltaics), low availability can further increase the cost per kWh. A second reason some of these newer technologies may not be used widely is that the costs of emissions from conventional power plants are not well understood. For this reason, the economic benefits of lower emissions technologies are not fully recognized. Third, investment decisions in developing countries have traditionally been made by investing in technologies that could generate electricity for the "least cost" per kWh as determined by capacity expansion models.[5] Unfortunately, traditional approaches to electricity planning and financing typically do not reflect the differences listed above.

While the traditional capacity expansion models used by planners could adequately simulate the operation of an electric system that included conventional, central station power facilities, they are not capable of providing a system-wide approach to electricity planning given the new technologies described above. A system-wide approach should include not only the total cost of generating power from a particular source, but also the transportation cost of fuels, the transmission costs of power, the impact on electric system reliability, and emissions costs, among other factors.[6] To date, many utilities in developing countries use a two-stage approach that first optimizes generation, and then optimizes transmission and distribution. Some analyses then try to simulate options between the two steps, but most do not. These models and analysis methods have not changed significantly since the 1980s, perhaps due to (1) the long-standing tradition of publicly financed electricity, (2) the ability of monopoly providers to pass costs through to consumers, and (3) perhaps most relevant, the fact that until recently, the technology choices had fundamentally similar T&D and fuel infrastructure needs. Fortunately, some countries have begun to address these concerns through integrated resource planning (IRP) methods that use a system-wide approach to energy planning. However, IRP methods have not yet made a significant impact on electricity capacity investment decisions.

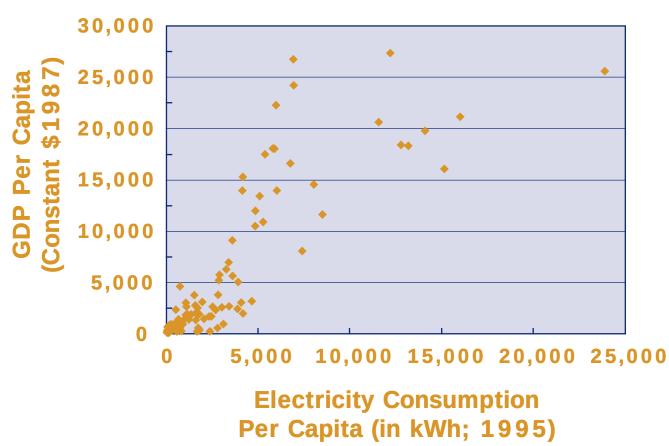
C. Electricity & Economic Growth

Electricity, and energy more broadly, can be a driving force behind economic growth because of the role of electricity in almost every sector of the economy. Many of these benefits result from electricity's convenience in use, ease of transport, safety, and cleanliness. These attributes provide new and existing industries with an energy source that allows them to maintain or increase competitiveness.[7] For example, industry uses electricity to drive motors for industrial processes, to run instruments that monitor, control, and inspect industrial operations, and to power new advanced automatic controls. This results in processes that are more efficient than labor alone while simultaneously increasing the productivity of labor. It is equally important that the commercial sector be provided with electricity, so that it can keep pace with changing computer processing and information technology requirements. In particular, the financial sector relies heavily on information exchange and storage made possible only by high-quality, reliable electricity. Electricity can play a major role in the agricultural sector as well, through improved irrigation and harvesting practices.[8] Bringing electricity to rural areas also creates opportunities for microenterprise. For example, improved lighting can allow for longer working hours or higher productivity in already established household industries, while new small industries requiring electricity, such as machine shops, can be established.[9] Finally, electricity can also benefit households in numerous ways that boost quality of life and household productivity. For additional information on the socioeconomic impacts of electricity see Box 1.

The common perception that GDP per capita rises with increasing electricity consumption per capita is illustrated in Figure 1. Despite the positive correlation between these two, however, the large degree of scatter also suggests that growth in one does not necessarily lead to growth in the other. An important issue that is not fully reflected in Figure 1 is that increased energy efficiency, on both the supply and demand sides, can begin to de-couple

Figure 1

Per Capita **Electricity Consumption** is Positively Correlated With Per Capita GDP



(from *World Development Indicators 1998*, The World Bank)

Box 1

Electricity and Socioeconomic Development

Electricity can have positive impacts on socioeconomic development in developing countries, especially among the poor. Electricity can impact the environment, quality of life, rural to urban migration, gender-related opportunities, and health and nutrition among many others.[10] Certainly, electricity has a role in improving each of these factors, though the provision of electricity alone is not sufficient to produce these improvements. Accordingly, the impact of electrification varies significantly from one locality to the next. The role of electricity in advancing socioeconomic development can be illustrated by analyzing the changes it can produce at the micro-level.

Electricity can provide new economic opportunities to poor households in both urban and rural areas, although seizing those opportunities is neither automatic nor easy. Electricity can boost household productivity by improving lighting and increasing working hours. It can improve agricultural productivity by increasing irrigation, improving access to agricultural information, allowing for local processing of agricultural products, and creating rural employment. And it can spur development of small-scale commercial industries.[11] Thus, electrification of an area could increase economic opportunities thereby leading to higher levels of income and economic growth than would have otherwise occurred.

In addition to creating new opportunities for income, electricity can improve overall quality of life for citizens in developing countries. "International experience has shown a positive correlation between access to … electricity services, and education attainment and literacy among both the rural and urban poor. Families lacking adequate energy supplies will tend to limit children's time spent on schoolwork and reading; in extreme cases, families may withdraw children from school systems to spend time on fuelwood and dung collection."[12] The introduction of electricity can improve healthcare. (For example, vaccines must often be refrigerated until administered). Electricity can allow for provision of sanitation, which decreases the risk of disease. It can be used to pump clean water, which can increase food production and ultimately improve nutrition, as well as decrease the risk of gastrointestinal diseases. It can be used for lighting, which could increase literacy by allowing children and adults to study at night. And it can be used to power radios, televisions, and computers, increasing access to information.[13]

Women are most affected by inadequate energy services, so provision of electricity can do much to increase their quality of life. Women are the primary collectors of traditional fuels (wood, biomass, dung), and may spend up to four to six hours travelling to collect enough fuel for one day's worth of cooking and heating.[14] The time spent collecting fuelwood and carrying water takes away from the time women can spend caring for their families, performing agricultural tasks, or working in income-generating activities.

In addition, women and children are the most affected by the health problems associated with the use of traditional fuels for cooking and heating. Women and children spend more time indoors than men, and are thus continually exposed to high levels of indoor pollution that result from cooking and heating with inefficient fuels in poorly ventilated areas. Some estimates contend that indoor air pollution "contributes to acute respiratory infections that kill some 4 million infants and children a year" and decreases the overall health and life expectancy of millions more women and children.[15] In many cases, electricity will not replace cooking or heating fuels because it is relatively expensive and does not meet cultural needs. However, electricity can help provide the economic opportunities that allow households to move up the "energy ladder," permitting them to buy more efficient, less-polluting fuels, stoves and heaters that will reduce indoor air pollution.

It is difficult to quantify the economic benefits associated with these socioeconomic impacts. Rural electrification programs in particular have been difficult to justify on an economic benefit-cost basis, in part because quantification of the benefits has eluded most analysts. In this study, an initial attempt has been made to quantify the economic impacts of electrification. For additional information, see Appendix A.

economic growth from the need to increase capacity. Thus, while an economy can increase electricity consumption, increased generation and consumption alone is not sufficient to promote growth. An additional explanation for the scatter could be the negative impacts that electricity can have on economic growth. These negative impacts are primarily related to low-quality electricity (see Box 2).

Much of the literature that studies the relationship between *energy* and economic growth measures the effect of changes in energy use on industrial output and productivity. Unfortunately, there is little literature that specifically links *electricity* and economic growth. However, since electricity consumption is close to 50 percent of total energy consumption, literature that examines the relationship between energy and economic growth is relevant.[22]

Numerous studies in the 1980s found a strong positive relationship between increases in energy use and economic growth.[23] More recent studies have also observed a positive relationship between energy consumption and economic growth, while studies in Nigeria and Tanzania have found a strong complementary relationship between growth in energy consumption and growth in national income.[24] For example, in Tanzania, where the agricultural sector is the main source of foreign exchange, the importance of energy in economic growth is a result of the energy-intensive needs of fertilizer production and

Box 2

Electricity Quality & Economic Growth

For industry, commerce, agriculture, and households, electricity can boost growth through increased production and productivity. However, unreliable electricity can also impose added costs that equal or even exceed its benefits.

In the past, increased quantity of electricity was the focus of domestically- and internationally-funded efforts to bring economic growth and improved quality of life to the people of developing countries. However, this strategy has begun to change since past efforts were only partially successful due to their resulting in low-quality, intermittent, or unreliable electricity. Common problems included recurring blackouts, brownouts, and voltage fluctuations.[16] These problems were typically caused by capacity shortages, improper maintenance, and related operating factors such as frequent plant repairs and temporary shut downs, aging plants, and lack of adequate preventative maintenance procedures.[17]

Poor-quality electricity can impose large costs on individuals and small companies, for example, by damaging electric appliances and machinery, restricting economic activity, and diverting private resources to purchase individual electricity storage or backup generation systems. In general, information on the costs imposed by low-quality electricity is limited to specific case studies. However, the negative impacts of low-quality electricity can be real and significant. A recent World Bank report estimated that 92 percent of manufacturing firms in Nigeria purchased and operated their own private sources of electric power due to Nigeria's chronically unreliable public power supply.[18] The study found that uncontrolled diesel generators were typically used to meet private generation needs despite their large initial investment costs, high operating costs, noise, maintenance needs, and relatively high air emissions. As an indication of the aggregate impact of this low-quality electricity, a 1998 study estimated that the annual opportunity cost of poor quality electric service in Nigeria's economy exceeded $900 million.[19]

These problems are not unique to Nigeria. Many developing countries have unreliable electricity supplies and as a result, firms are frequently willing to pay high prices for reliable electricity. Two recent World Bank papers describe such high willingness-to-pay by firms in Indonesia that paid generation costs exceeding $2 per kWh to assure high-quality power.[20] (For comparison, costs in the United States for electricity are less than $0.10 per kWh). Related studies in Latin America estimate that power shortages cost the regional economy from $10-$15 billion annually; further, it has been estimated that fuel costs for thermal generating plants are more than $600 million per year higher than they need to be because of poor maintenance.[21]

Clearly, developing countries and their private sectors cannot afford to continue paying these high costs if they are to capture the true benefits of electricity, much less compete in the global economy. This study makes an attempt to incorporate reliability concerns into the economic assessment of different technologies. For additional information, see Appendix A.

the need to transport crops for export. Another study in China found a strong linkage between electricity consumption and economic growth.[25]

In contrast, one recent analysis has not demonstrated a positive relationship between energy use and economic growth. This study, which focused on Brazil, Mexico and Venezuela, found "no causal linkages between energy consumption and economic growth for both Mexico and Venezuela" and only weak causal linkages in Brazil.[26] Clearly this conclusion contradicts those of the other studies. A possible explanation for the lack of correlation between energy and economic growth is that the negative effects such as those caused by low-quality electricity, increased emissions, and displaced public investment can create a drag on the economy that is not fully offset by the benefits of increased energy consumption.

D. Implications

While the traditional processes for planning and investment have served decision-makers well in the past, conditions have changed. Examples of these changes include new power generation technologies, limited public resources, rising debt, recent trends in policy reform, globalization of companies, and rising foreign investment. Furthermore, methods of analysis formulated to meet the needs of developed countries are not necessarily applicable to developing countries. Therefore, developing country decision-makers may benefit from new analytic methods, sensitive to the problems developing countries face, that would aid in identifying the "least cost" means of *delivering* electricity to end-users (as opposed to the least cost means of *generating* electricity).

Continuing to base new capacity decisions on traditional planning methods may result in non-cost-effective power generation investments, lost economic potential, and unnecessarily high levels of locally and globally damaging air emissions. This lost economic potential, also known as opportunity cost, corresponds to the additional GDP that a more efficient use of these and other capital resources could have provided. For example, more cost-effective public investment in electricity supply could allow other public investments to increase (e.g., education, transportation, sanitation, etc.). On the demand side, the provision of a more reliable electricity supply could reduce the private sector's need to purchase backup generation and storage equipment, thereby enabling it to make more profitable investments. In addition, less expensive electricity would benefit all portions of society by increasing savings and investment, which could boost national competitiveness. As the global economy grows and international capital flows increase, developing countries will continue to compete for foreign investment from transnational companies and investors. Under these conditions, those countries that can most efficiently use their capital resources to provide reliable, high-quality, low-cost electricity may grow faster than others.

Finally, since current decision-making processes typically do not include environmental impacts, continued use of traditional planning methods may miss cost-effective opportunities to reduce local and global emissions, thereby causing significant environmental impacts, diminished public health, lower productivity, increased risk of global climate change, and ultimately, lower economic benefits.

II. Study Goals and Approach

This study examined how different policies and mixes of new generation technologies can affect economic growth, local air pollution, and CO_2 emissions in developing countries. The underlying premise was that electricity is not a homogeneous commodity, but rather the result of a series of processes including primary energy extraction, fuel processing, transportation, conversion to electricity, and delivery to end-users. Individual technologies have different attributes in each of these areas, and each attribute has different implications in terms of the costs and benefits of power generation. Specific technologies vary in terms of the costs required to generate electricity, the accessibility they offer, their reliability, the cost-allocation they impose, and the quantity and type of air emissions and other environmental impacts they produce. These differences in turn generate varying degrees of economic growth and environmental impact.

This study began by building a generic simulation model that could be used to consistently and quantitatively examine the economic and environmental impacts of different mixes of new power generation. To quantify the differences, a system dynamics simulation model was developed that sought to capture the macro-level relationships between electricity generation, economic growth, and capital investment. The generic model was then applied to each of five developing regions: Africa, China & East Asia, Latin America, the Middle East, and South Asia. Once the regional models had been completed, several scenarios were developed to represent plausible alternatives to business-as-usual (BAU) expectations of the future. These scenarios were then analyzed with the models, and the five sets of results were aggregated to represent all developing countries. Finally, these results were compared to the economic and environmental impacts of the BAU expectations and to each other. (Throughout the remainder of this report, the five regional models will be referred to collectively as "the model.")

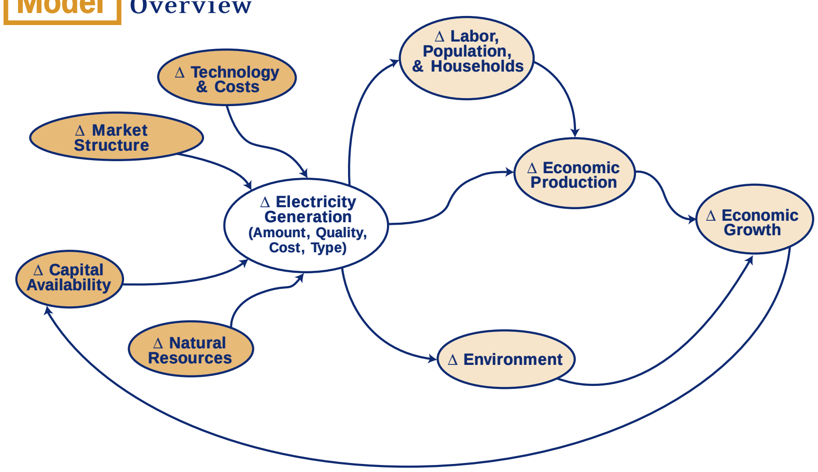
This multi-step approach combined the best aspects of innovative scenario analysis with computer modeling to investigate the direct and indirect impacts of complex relationships. Innovative scenario analyses, such as those employed by Shell International, are based on developing plausible variations from expected trends, but it stops short of quantifying the differences among the scenarios. Using this approach, scenarios are generated as "stories" and expert judgement is used to evaluate the implications of the scenarios. The analyses used in this study take the process one step further and use models to quantify the differences among the various scenarios.

A. Simulation Model Description

The dynamics of the generic simulation model are shown in Figure 2. The model begins with 1995 regional levels of value added, fixed assets, labor, and electric power consumption for industry, services, agriculture, and households, in both urban and rural areas. Each year begins with a budget for new capacity investment. This budget is a fraction of the previous year's GDP plus a fixed level of foreign investment.[27] For each year, the annual investment funds are allocated according to percentages specified in case-specific technology investment portfolios.[28] (In other words, the model directs a certain percentage of total funds toward each technology type. The portfolio does not specify the percent of constructed capacity that is of a specific technology). Following the initial investment, new plants come on-line after a specified construction time. Simultaneously, these investments affect the average cost and quality of electricity. As electricity generated from new capacity comes on-line, it is allocated to agricultural, industrial, service, and household consumers in urban and rural areas (this allocation reflects anticipated demand based on historical trends).[29] This new electricity then increases economic production, improves household productivity, and impacts the environment through increased air emissions. As total economic output grows, the economy grows and the amount of

Figure 2

Model Overview



Note: Δ refers to the incremental change from the previous year.

capital available to invest in electric power in the next year also grows. The model simulates the above process each year for twenty years.

It is important to understand that the model was created solely for the purpose of comparing the economic and environmental impacts of a variety of alternative electricity technology mixes — it was never intended to forecast economic growth.[30] By focusing exclusively on new power generation and its impacts, this simulation model allows the comparison of different technology mixes without the need to model all aspects of economic growth. For this reason, factors that are unrelated to new power generation (e.g., percent of total workers in agriculture) were assumed to be constant across all scenarios, thereby ensuring that the model only reflected the implications of different types of new electricity supply. In addition, as a result of the study's goal of illustrating the relative differences between the economic and environmental impacts of different technology mixes, the model did not address demand. Rather, the model assumed that the IEA's forecasts reflected the demand for electricity in developing countries.[31] Finally, given the study's goal of performing an aggregated analysis of the entire developing world, the model was not able to reflect the international and intra-regional variability which exists between and within countries. For further information regarding model calculations, refer to Appendix A, and for data refer to Appendix C.

B. Overview of Scenario Analyses

The first scenario modeled in this study was the business-as-usual case for capacity expansion as described by the IEA's World Energy Outlook.[32] Termed the "BAU Case" throughout the rest of this paper, this scenario represents current forecasts of how power generation expansion will occur in the future. Furthermore, it is similar to traditional planning and analysis tools that do not account for the infrastructure costs of new investments. The BAU Case provides a baseline for economic and environmental impacts, as well as a technology investment portfolio (i.e. the percentage of annual funds allocated to building specific technologies) against which other portfolios can be compared. Throughout the remainder of this report, the portfolio used in the BAU Case will be referred to as the BAU Portfolio.

Following presentation of the BAU Case, the remaining analyses focus on feasible alternatives to the BAU Case. Each of these alternative scenarios attempt to identify investment portfolios that provide meaningful bounds of what could actually occur under different policies. Accordingly, the results of the scenario analyses should be interpreted as defining a range of possible outcomes, where the specific portfolio investigated serves to define the outer bound of that range. This allows decision-makers to judge the range of possible effects of different policies, given uncertainties or different expectations of how a given policy may be implemented.

In all cases, the results are presented in both the text and as graphs or tables. The results presented in the text and the tables refer to changes in economic benefits or emissions from new capacity only (i.e., the results do not compare total economic benefits or total emissions), while the graphs show total economic benefits and total emissions relative to conditions at the start of the model (i.e., graphs are plotted with an index equal to 100 at the beginning of the model). Initial $C0_2$ emissions were based on 1995 power generation $C0_2$ emissions as presented in the IEA's World Energy Outlook 1998 Edition. The results are not presented as corresponding to actual calendar years. This format allows easy comparison across scenarios and is consistent with this study's intent to investigate possible futures rather than provide forecasts. Because different scenarios are often founded on alternative assumptions, different baselines are often provided. However, in some cases, additional baselines are presented so that decision-makers can determine how different assumptions impact the results.

The policy options investigated in this study consist of: including infrastructure costs in new capacity investment decisions; accelerating private-sector participation; using low-emissions power generation technologies, and improving energy efficiency.

III. The Business-As-Usual Case

A. Trends

As previously explained, the BAU Case uses IEA projections for capacity expansion and technology investment. This case represents what forecasters expect will occur in the electric power sector of developing countries over the next 20 years, if the following three general trends continue: government ownership of power plants, growth of electricity demand, and little improvement in the quality and reliability of the electricity system.

The majority of new capacity continues to be built and owned by the public sector, though there are exceptions. In most developing countries, the power sector has always been government-planned, -owned and -operated. In the early 1980s, in response to low efficiency, severely limited public budgets, and rising foreign debt, developing countries began to open their power generation markets to private-sector participation. Typically, this participation consisted of government-specified technology and a guaranteed purchase price for electricity. While some countries have given the private sector more freedom to choose their own technologies and capacities, this type of private-sector participation has advanced slowly in many countries. The IEA BAU analysis assumes that among all developing countries, only those in Latin America undergo a substantial degree of privatization by 2020. All other regions are based on power plants that have cost and reliability characteristics that continue the trend of government-planned, -owned and -operated power plants.[33]

In developing countries, the use of electricity will continue to grow faster than total energy use. The IEA reports that electricity's share of total final energy consumption in developing countries increased from 29 percent in 1971 to 44 percent in 1995, and projects that electricity's share of total final energy consumption will further increase to 54 percent by 2020.[34] Indeed, one study has estimated that in a 20-year period, over 40 of the largest developing countries had growth rates of installed capacity that were more than double their individual real GDP growth rates.[35]

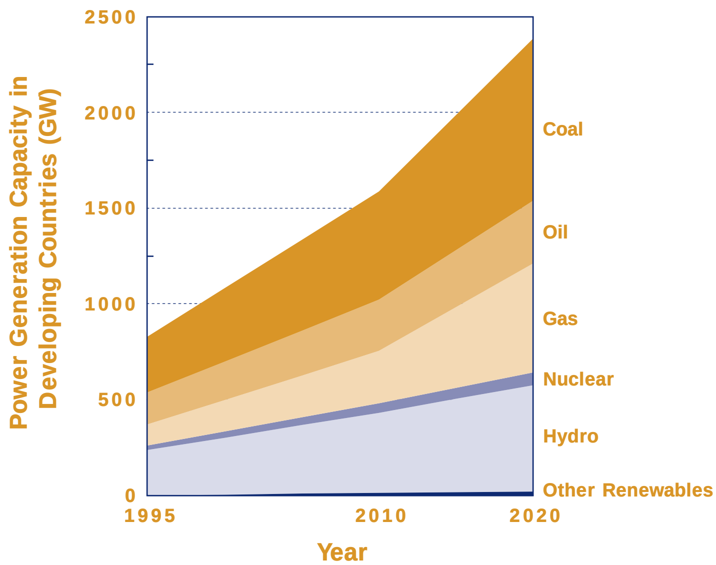
While reliability and quality will improve slightly, they will remain significant problems due to supply and demand growing faster than system efficiency can improve. Similarly, T&D losses will continue to exceed 20–30 percent of total generation[36] in some countries, which is significantly higher than the best practice performance of 5–8 percent obtained in some developed countries.[37]

B. Investment Portfolio

Under BAU assumptions, new capacity will be dominated by large coal-fired plants, with substantial shifts toward natural gas where gas supplies are available (Figure 3). Future investments in hydroelectric power will decrease due to the large costs and rising environmental and social concerns, although these concerns will sometimes be outweighed by non-power needs such as flood protection and year-round storage facilities for irrigation water. Oil-fired capacity investments will continue due to its ease of use in remote areas and its backup potential for other fuel sources. Nuclear power will also see decreasing investments due to rising costs and environmental and safety risks. Finally, investments in renewables will be limited by their high capital costs and low availability. Accordingly, BAU trends suggest that developing countries' new capacity will be roughly 40 percent coal, 35 percent natural gas, 10 percent large hydro, and 5 percent other renewable technologies (e.g.,

Figure 3

Current Trends will Result in New Capacity Primarily from Coal and Natural Gas



(from *World Energy Outlook 1998*, IEA)

solar photovoltaics, solar thermal, wind and small hydro). Using the corresponding investment portfolio, the percent of total GDP invested in capacity expansion by the model was configured to match the IEA forecast.

Figure 4

The Economic and Environmental Impacts of BAU Trends

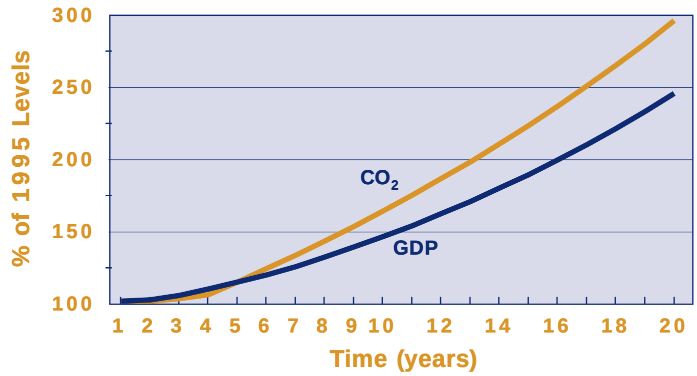


Figure 4 shows that expected annual economic benefits from increased electricity supply could grow to nearly two and a half times current levels within 20 years. Meanwhile, the corresponding expected annual CO_2 emissions could nearly triple current emissions rates within 20 years. In the next section this study evaluates alternatives to the business-as-usual trends and forecast.

Throughout the remainder of this report, each of the scenarios is discussed in greater detail. Specifically, each section begins with a discussion of why the underlying issue or opportunity is important and why policy makers should be concerned with addressing it. Next, underlying assumptions are presented and several specific investment portfolios are described. Then, the model's economic and environmental results are presented and compared to a baseline that is founded on similar assumptions. The findings of each scenario are then discussed. Finally, the paper ends with conclusions and recommendations based on the scenarios investigated in this study.

IV. Alternatives to Business-as-Usual

Prior to presenting and discussing alternatives to the BAU Case, it is important to reiterate that this study did not attempt to forecast the future of power generation or economic growth in developing countries. Rather, it set out to illustrate the potential economic and environmental impacts of different investments in new power generation. Furthermore, the study's goal of performing an aggregated analysis of the entire developing world means that the assumptions and results in the alternative scenarios may not hold for individual developing countries. Based on these goals and caveats, the simulation model was used to illustrate the potential impact of variations from business-as-usual trends on developing countries.

A. Including Infrastructure Costs in New Capacity Investment Decisions

1. The Issue

As described previously, many traditional analysis and planning methods guide investments toward technologies that *generate* electricity for the least cost rather than toward technologies which *deliver* electricity to end-users for the least cost. While historical and institutional circumstances explain this shortcoming, continued use of these tools could mean that investment decisions would continue to be made without considering the infrastructure costs of electricity — such as:

- T&D equipment to deliver electricity from the site of generation to the site of consumption;
- Construction of new pipelines or rail transportation (or retrofit of existing) infrastructures to deliver primary fuels to a generation plant (i.e., natural gas, fuel oil, and coal);
- Backup systems, storage, or other electricity conditioning and delivery equipment for off-grid intermittent technologies; and
- Increased investment costs for reserve generation and reserve T&D capacity to ensure high-quality electricity during periods of peak demand and both planned and unplanned outages.

Unfortunately, estimating these costs is difficult due to limited data and extreme variability at the project level.[38] Nevertheless, these costs can be substantial, as indicated by a 1990 World Bank study that found infrastructure costs[39] to represent up to 40 percent of developing countries' total capital expenditures on new capacity.[40] These additional costs suggest that the BAU Case may overestimate the benefits of new capacity. Once the infrastructure costs of new capacity are included, either less power can be built for a given level of investment or more government spending in electric power must be allocated to achieve the same level of capacity. Both of these result in lower-than-expected economic benefits.

If today's diverse power generation options are to be compared for the purpose of *delivering* electricity to consumers at the least cost and promoting economic growth, the infrastructure costs associated with that new generation should be taken into account in estimating the benefits. In light of these concerns, the cases examined in this scenario investigate the impact of including reasonable estimates of infrastructure costs, based on a variety of sources as described in Appendix C.[41] In order not to double count the costs of fuel transport and delivery, this study used international fuel prices rather than power plant prices that could already include the cost of transport and delivery. While these estimates may not be applicable for specific countries or projects, they allow the costs to be internalized in the model for aggregate comparisons. Given the variability of infrastructure costs, it may be useful to consider the estimates used in this study as an upper bound of the full range of outcomes.

2. Analyses

This study reports on three variations to the BAU Case, all of which include infrastructure costs in capacity expansion. Two of the cases use the BAU Portfolio of investments, while the third case uses an investment portfolio that includes an increase in the use of distributed technologies. The first case, "BAU Portfolio & Capacity Including Infrastructure Costs,"[42] measures the impact of maintaining the BAU portfolio and the BAU level of capacity growth when infrastructure costs are included. In this case, the annual investment is not determined by historical estimates, as is done in the other cases. In the second case, "BAU Portfolio Including Infrastructure Costs,"[43] the annual investment is increased not to match the regional forecast, but rather the average increased costs associated with the infrastructure requirements. This means that a fixed percentage of GDP is made available to spend on infrastructure, but the total investment is determined by the model.

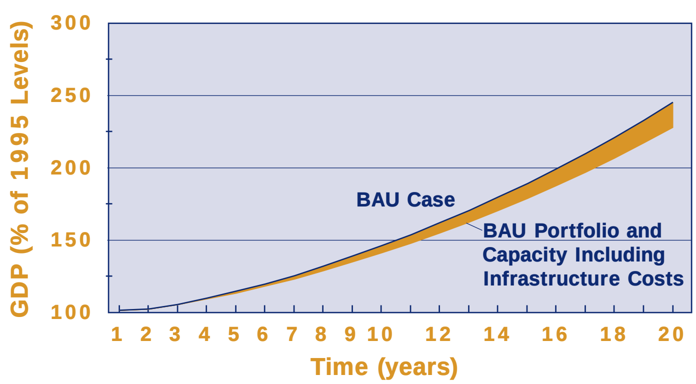
Finally, the third case, "Distributed Technologies for Rural Generation,"[44] is a variation on the second case and measures the impact of shifting, over a 10-year period, 50 percent of the annual investments originally used for coal-fired generation with grid extension (for rural electrification) to a highly capital-intensive mix of distributed renewables.[45] This represents a small shift in investment that displaces 5 gigawatts (GW) of coal and lesser amounts of oil and diesel generation. (Even though small relative to total new capacity, 5 GW corresponds to enough capacity to provide roughly 10 million households with basic electricity service.)

3. Results

Figure 5 shows the range of possible expected economic benefits that occur when infrastructure costs are included in the model. By including these costs in the analysis, the cost per kW of installed capacity rises. As a result, the amount of capital the government needs to spend is higher, thereby reducing expected benefits. While only one case is shown in Figure 5, both BAU Portfolio cases could reduce the increase in annual economic benefits from new capacity up to 10 percent after 20 years, as compared to analyses that do not include these costs. Once again, the scenario can be viewed as an expected upper bound for infrastructure costs. The inclusion of infrastructure costs has economic implications because the incorporation of these costs in the planning process could cause shifts in installed capacity, displaced public investment, and therefore reductions in economic growth and capacity expansion. In the case of the BAU Portfolio, total investment costs will increase, thereby reducing other investments and increasing the cost of *delivering* electricity to consumers. This will result in reduced savings and investment and therefore less economic growth.

Figure 5

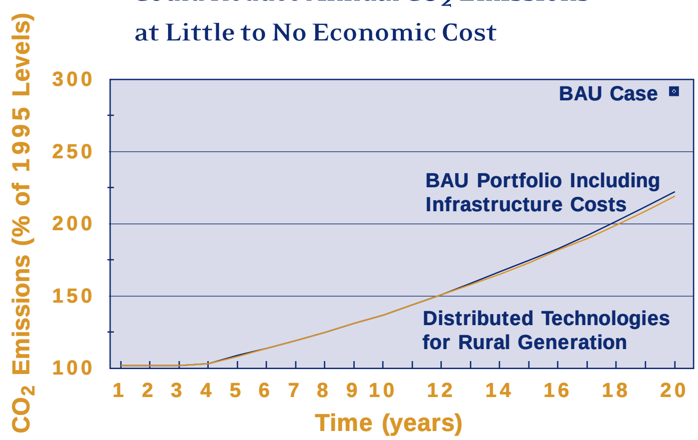
Including Infrastructure Costs May Reduce the Economic Benefits of the BAU Portfolio



In some cases, the infrastructure costs for distributed technologies are not as high as conventional alternatives. Therefore, in the Distributed Technologies for Rural Generation case, the portfolio is shifted slightly so that distributed renewables are substituted for a small amount of the coal-fired generation used for rural electrification (i.e., for grid extension). This change resulted in a 2 percent reduction in annual economic benefits from new capacity after 20 years as compared to the similarly funded BAU Portfolio Including Infrastructure Costs. More important than this finding, however, is that the loss in economic benefits is much smaller than traditional analysis methods suggest. If these economic benefits had been compared to the BAU Case which did not include these costs, planners would have thought that distributed technologies would have reduced new economic benefits over 12 percent, when in actuality there is little to no economic loss associated with this shift if all costs are included. Moreover, if a lower cost renewable portfolio than that used in this analysis could be deployed, there could even be gains in economic benefits. The impacts of distributed technologies will be explored further in scenarios developed in later sections.

Figure 6

Shifting the Source of Rural Distributed Generation Could Reduce Annual CO_2 Emissions at Little to No Economic Cost



The marginal shift away from fossil fuels and toward renewable generation could reduce future increases in CO_2 emissions by nearly 2.5 percent or more (Figure 6). In addition, this shift could result in SO_X emissions being reduced as much as 2 percent and NO_X emissions being reduced by 15 percent, relative to the BAU Portfolio Including Infrastructure Costs case.

These analyses have produced three findings. First, there is an opportunity cost to excluding infrastructure costs from investment decisions. Second, distributed generation is not as expensive as traditional analysis tools lead planners to assume. Third, increased use of distributed renewables can reduce both CO_2 and local pollutants with little or no loss in annual economic benefits.

B. The Acceleration of Private-Sector Participation

1. The Issue

Privatization of power generation is frequently driven by scarce public funds and a desire to simultaneously improve the performance of the power sector while lowering electricity prices. As with other countries, many developing countries have begun to pursue such reforms or are considering them. Examples of these reforms range from commercialization where incentives are created to make existing, government-owned utilities more efficient, to the development of full-scale retail markets and competition for electricity sales. While Argentina has been the first developing country to move aggressively towards a competitive retail market (e.g., competition in selling to individual consumers), through the opening of wholesale markets (e.g., competition in selling to the electricity grid), most developing countries are pursuing a slower pace of reform including commercialization or other combinations of public- and private-sector reform (e.g., independent power producers (IPPs) or build-operate-transfer (BOT)).

It is widely believed that most developing countries will open wholesale power generation markets some time in the next twenty years, although some countries are moving very slowly in this direction or not at all. In these cases, new capacity needs would continue to be determined by government planners, but the private sector would bid competitively to provide new capacity. Unlike other reforms, these wholesale and retail markets would allow the private sector to choose which power generation technologies to use to provide new increases in capacity.

When the private sector is able to make its own investment decisions about new increases in power generation, improved performance and lower electricity prices are typically assumed to occur. This is because competition is expected to reduce (1) initial investment costs through more cost-effective design and construction procedures and (2) operating costs through improved operating and maintenance procedures which will increase conversion efficiency and unit availability. Also, relative to the public sector, the private sector will pursue those technologies which offer the highest returns on their investments in the near term. (This means that the private sector will tend to avoid capital intensive projects with low rates of return.)

For these reasons, especially the last, technology decisions made by profit-driven private companies are expected to be significantly different from those made by the public sector. Private companies typically require high rates of return and rapid payback on their investments, but the desire to minimize risk is also important. Relative to developed countries, many developing countries have more volatile political systems, less robust economies, and fewer skilled laborers and advanced support industries. Each of these concerns, especially since they are only predictable in the near term, will increase the importance of low capital expenditures and rapid payback. Therefore, in the cases presented here, these conditions are likely to result in investment in power generation technologies that are quickly and easily built, and that offer lower technical risk and lower operations and maintenance costs.[46]

For the purposes of this scenario, and based on these private-sector considerations, as well as today's fuel and technology costs and efficiencies, increased privatization will tend to favor new investments in natural gas where available. This is because natural gas can fulfill the private sector's needs for low technical risk and quick returns on investment. Even though gas is more expensive than coal, combined cycle gas turbines are highly fuel-efficient, can be built in smaller increments, and are easy to construct and manage. For countries with no natural gas supplies, the next most profitable option for new generation by the private sector is likely to be coal — a mature and well-understood technology. At present, coal is inexpensive, and the high discount rates used by the private sector reduce the risk associated with rising costs that could result from local environmental regulations or global conventions on climate change. Accordingly, coal will continue to play a significant role in power generation in many developing countries.

While the private sector will likely invest in higher efficiency plants than the public sector (in order to reduce fuel costs), the private sector, if not required to, is unlikely to install the most advanced emissions control technologies. The private sector will avoid these advanced technologies due to their increased costs, technological complexity, energy requirements, and maintenance needs, as well as the lack of skilled labor and advanced support industries in many developing countries. Nevertheless, the private sector may use modest emissions control technologies to lower costs or because they are industry best practice.

Taken as a whole, the changing priorities and incentives brought by privatization will likely result in substantial changes in the mix of new generation technologies. There will likely be decreases in the construction of large hydroelectric plants (due to large capital investments and slow returns). Substantial decreases in nuclear power plant construction would also be expected (due to large capital investments, slow returns, and high technical and political risks). Although some companies are investing in renewable energy technologies, renewables carry increased market risk due to their higher capital costs, long-term infrastructure and repair needs, and slow cost-recovery. Additionally, the perceived risk of renewables is increased by questions as to the ultimate viability of these newer technologies. Therefore, it is currently believed that the private sector will invest less in renewable technologies than is currently expected under public-sector investment.

2. Analyses

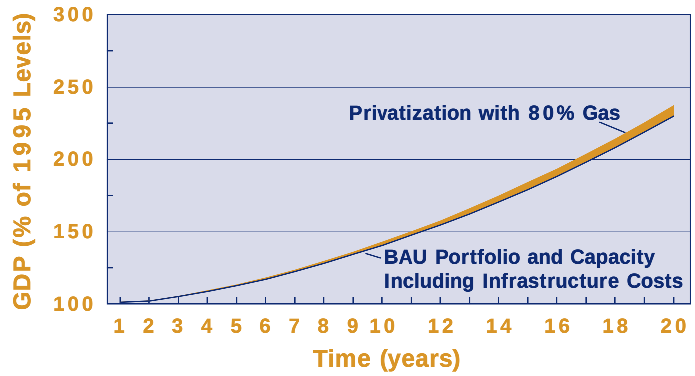
In order to understand the range of potential impacts of an acceleration in wholesale competition, two cases are presented in this scenario. In both cases, wholesale generation was phased in over a 10-year period (in other words, after 10 years, the private sector was able to make its own investment decisions as represented by the generally described investment portfolio presented above). In both cases, the private sector was required to pay all infrastructure costs. Finally, in order to compare privatization to a continuation of public-sector trends, these cases were configured to match the BAU Capacity projections. This allows the cases to be compared on the basis of equal power generation capacity. The two cases examined in this scenario are described below.

The first case, "Privatization with 80 Percent Natural Gas,"[47] consists of the private sector transitioning, over a period of 10 years, from the BAU Portfolio to a portfolio where roughly 80 percent of annual investments are directed toward gas and 10 percent toward coal. In light of increasing supplies of natural gas and reductions in the cost of liquefied natural gas, 80 percent gas was used to represent an upper bound for low-cost private-sector investment.[48] The second case, "Privatization with 50 Percent Natural Gas,"[49] consists of the private sector transitioning, over a period of 10 years, from the BAU Portfolio to a less gas-intensive portfolio where 50 percent of annual funds are invested in gas and 25 percent in coal.

3. Results

Figure 7

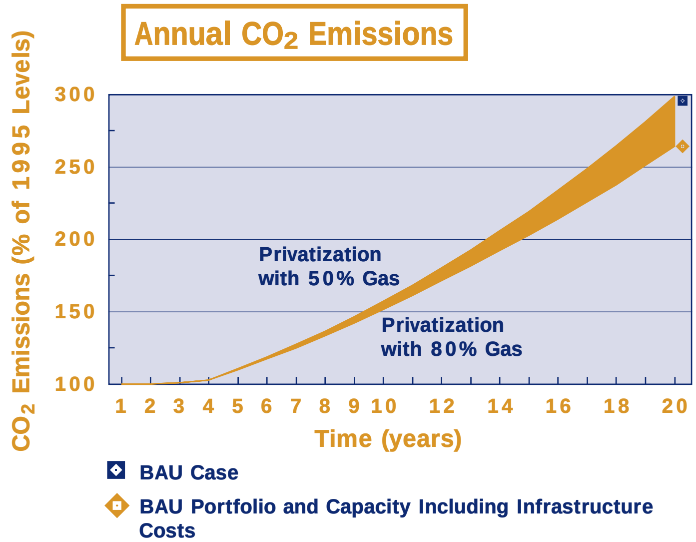
Privatization, Including Infrastructure Costs, Could Boost Economic Growth



As Figure 7 illustrates, if privatization accelerates, and cost reductions due to private sector investment and operations materialize, the Privatization with 80 Percent Natural Gas case yields a 5 percent increase in new annual economic benefits after 20 years relative to the BAU Portfolio & Capacity Including Infrastructure Costs case. However, it is possible that the increased demand for natural gas could exert an upward pressure on natural gas prices, which could eliminate the economic benefits gained from privatization. The Privatization with 50 Percent Natural Gas case provides a more moderate approach to gas investments by continuing significant investments in coal generation. This investment portfolio yields up to a 4 percent increase in new annual economic benefits after 20 years. Taken together these suggest that privatization may boost economic benefits, but the magnitude of the benefits may be influenced by the private sector's relative preferences among coal, gas, and other technologies.

Figure 8

Privatization Could Impact **Annual CO_2 Emissions**



As the curves in Figure 8 show, privatization can have a variety of impacts on CO_2 emissions depending on the specific investment portfolio. If, over the course of ten years, the private sector aggressively increases its use of natural gas relative to coal, new annual CO_2 emissions after 20 years could decrease by 1 percent relative to continued public-sector management (i.e., BAU Portfolio and Capacity Including Infrastructure Costs). However, if the private sector continues to make substantial investments in coal, new annual CO_2 emissions could increase, up to 20 percent or even more after 20 years, which brings emissions back to the level estimated by the BAU Case.

Clearly, the bounded range in Figure 8 shows that privatization could increase CO_2 emissions relative to public-sector trends. These increases are the result of a private-sector investment portfolio that shifts away from low-emitting but capital intensive technologies such as large hydro, nuclear, and renewables and focuses almost exclusively on coal and gas technologies.

Potentially more important to developing countries than CO_2 emissions are the reductions in conventional pollutants relative to public-sector trends. As Table 1 shows, the Privatization with 80 Percent Natural Gas case could reduce future growth in SO_X emissions by up to 64 percent and NO_X emission by almost 46 percent. Given the increase in emissions of SO_X, NO_X, and CO_2 between these two cases, it seems reasonable that if the private sector's investments in coal were to increase much beyond 25 percent, local pollution could possibly worsen rather than improve. This scenario illustrates that the economic, CO_2, and local pollution implications of privatization are dependent on the private sector's relative preferences among coal, gas, and other technologies.

Table 1

Change in Annual Emissions from New Generation, After 20 Years, Relative to the BAU Portfolio

	Privatization with 80% Natural Gas	Privatization with 50% Natural Gas
SO_X	–64%	–18%
NO_X	–46%	–10%

C. The Use of Low-Emissions Technologies

1. The Issue

Under the BAU assumptions for new power generation capacity, power sector air emissions will continue to increase, along with emissions caused by rising industrial activity and motor vehicle usage. The combined increase in pollution will degrade ambient air quality, thereby harming human health and imposing other costs. According to one study, mortality from respiratory infections may be five times higher in developing countries than in developed countries (which have strong environmental and public health protection laws).[50] The resulting health care costs for treating respiratory illnesses, as well as lost days at work and diminished worker productivity, can be substantial. For example, the total health cost of air emissions in Cairo may exceed $1 billion per year.[51] Yet diminished public health is only one aspect of the damage caused by air emissions. Other damages include reduced visibility, decreased agricultural production, and damage to the “built” environment.

Given the substantial growth that is expected in developing countries in the future, decision-makers may wish to consider options that could meet their power generation needs with less local environmental impact. Prior to being able to assess these options, though, decision-makers will need to estimate the costs associated with these pollutants. Determining these costs is very difficult, however, because power generation is only one source of such emissions. Even when specific sources and pollutant concentrations are known, the presence of other pollutants can lead to different synergistic effects.

While it is sometimes possible to estimate the environmental costs of pollution from market data, it is often necessary to use surveys or other means to collect “willingness-to-pay” (WTP) data for environmental amenities that are not directly addressed in markets, such as air quality. Two methods are often employed to place an economic value on such pollution externalities. The first employs estimates of damage costs, and the market and WTP approaches. A second method recognizes the inherent difficulties in quantifying and monetizing damages, and instead uses more accessible data about the costs of existing pollution control as indicative of a society’s “revealed preferences” for environmental amenities.[52] This report uses a hybrid of the two approaches to estimate values for SO_X, NO_X, and PM-10. Specifically, this study used European data for direct damage estimates and US data for the pollution-control preference estimates.[53] The European data were employed to estimate the economic differences between urban and rural impacts. Finally, the resulting hybrid data were modified to reflect lower incomes in developing countries.

There are, of course, other environmental costs associated with power generation. These include land impacts (e.g., large renewable installations, ash disposal), water discharges (e.g., thermal pollution), and other air emissions due to generation and fuel lifecycles (e.g., methane leaks from natural gas pipelines and/or coal bed releases). These impacts are important, but they were beyond the scope of this study. Accordingly, the pollution-cost estimates used in this study provide a first-order approximation of the environmental impact of power sector emissions. For further information on the estimates of pollution costs used in this study, refer to Appendix B.

2. Analyses

This scenario presents three analyses based on different investment portfolios, each of which seeks to investigate a feasible option for future power generation. For all three cases, the impact of infrastructure costs and pollution are included in the analyses. These analyses are based on the approach used in the second infrastructure case, BAU Portfolio Including Infrastructure Costs, which assumes that the annual investment is increased to match the average increased cost of infrastructure requirements. Since all three analyses are financed similarly, the three investment portfolios can be compared to determine their relative impact on economic and environmental benefits.

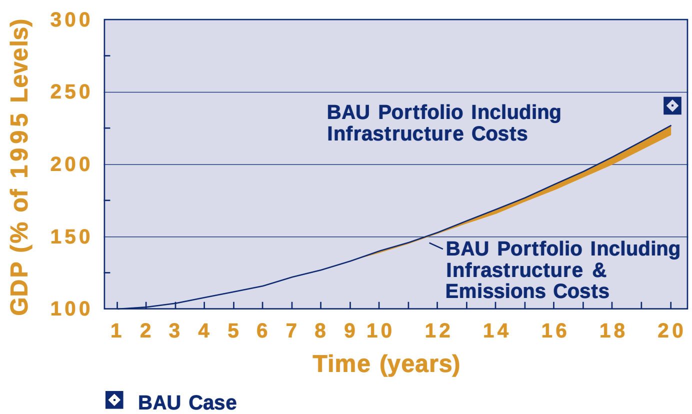
The first case, “BAU Portfolio Including Infrastructure and Emissions Costs,”[54] investigates the impact of including pollution costs on the BAU Portfolio. The second case, “Cleaner Fossil Fuel Technologies,”[55] begins with the BAU Portfolio, but investments are gradually shifted over 10 years from technologies with no or low levels of emissions controls toward technologies which have higher efficiencies and more stringent emissions controls.[56] Finally, a third case, “Gas and Renewables,”[57] consists of shifting, over 10 years, 50 percent of the BAU Portfolio’s new coal investments to natural gas and renewable technologies, with the increase split evenly between the two. The renewable technology portfolio was a mix of small hydro, biomass, and solar photovoltaics (including battery storage).

3. Results

By including estimates of the cost of emissions, the model reveals that the impact of emissions on the BAU Portfolio Including Infrastructure Costs case decreases the annual economic benefits from new power at the end of 20 years by as much as

Figure 9

Including **Air Pollution Costs** May Reduce the Economic Benefits of the BAU Portfolio



6 percent (or 17 percent relative to the BAU Case) (see Figure 9). However, prior to assuming that the BAU Portfolio of technology investments results in only a 6 percent decrease after 20 years, it is important to recognize that the pollution cost estimates were limited to SO_X, NO_X, and PM-10. In reality there are other pollutants that could impose added costs and would therefore lower economic benefits even further.

When the estimates of pollution costs are accounted for, as Figure 10 illustrates, the technology portfolios that represent cleaner alternatives (i.e., cleaner fossil fuel technologies and the combination of gas and renewables) result in similar and even slightly higher levels of annual economic benefits as those from the BAU Portfolio.

Figure 10

Lower CO_2 Emitting Technologies Result in Similar Levels of Economic Growth

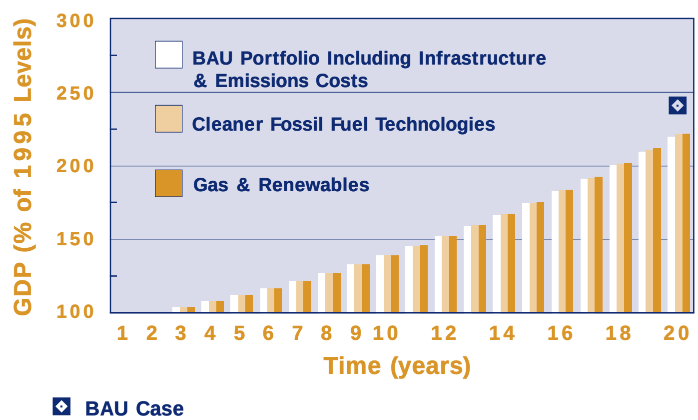


Figure 11 shows that these three analyses result in varying levels of CO_2 emissions. Relative to the BAU Portfolio Including Infrastructure Costs case, new annual CO_2 emissions after 20 years could be reduced up to 17 percent by investing in cleaner, more fuel-efficient fossil fuel technologies. Increased use of natural gas and renewable technologies, however, could reduce new CO_2 emissions by up to 22 percent relative to this same curve. In addition to reduced CO_2, these alternative technology investment portfolios also result in decreased emissions of local pollutants as shown in Table 2. For example, the Cleaner Fossil Fuel

Figure 11

Cleaner Generation Sources Could Reduce Annual CO2 Emissions

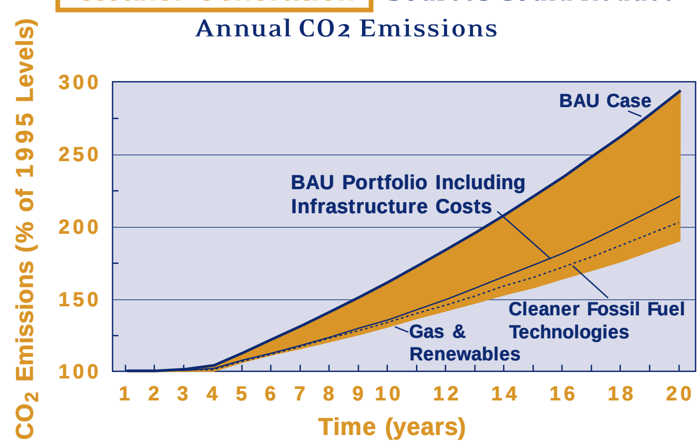


Table 2

Change in Annual Emissions from New Generation, After 20 Years, Relative to the BAU Portfolio

	Cleaner Fossil Fuel Technologies	Gas and Renewables
SO_X	–39%	–72%
NO_X	–25%	–39%

Technologies portfolio could reduce future increases in SO_X emissions by 39 percent and NO_X emissions by 25 percent. However, even further reductions are possible as shown by the Gas and Renewables portfolio that reduces future SO_X emissions by 72 percent and future NO_X emissions by 39 percent.

The results from this scenario reveal that alternative technology mixes could reduce both local and global emissions at no long-term economic cost to developing economies. Moreover, in the case of Gas and Renewables, developing countries could even experience an increase in long-term economic benefits, relative to the BAU Portfolio of investments. The technical possibility of such reductions, however, does not mean that shifting away from BAU trends will be easy for developing countries. There are many barriers (i.e., financial, technological, political, institutional) to choosing a path in which the direct power plant costs are higher than the alternatives, as is the case for the Cleaner Fossil Fuels and the Gas and Renewables portfolios presented in this scenario.

In order to begin to overcome these barriers, many developing countries will need up-front financial assistance to be able to invest in these more expensive technologies. In the context of climate change, the Clean Development Mechanism (CDM) — given its project-based, CO_2-reduction focus — is one obvious vehicle for such financing. Alternatively, some developing countries could benefit by participating in an international emissions trading program (should one occur). By selling the rights to future emissions as part of such a program, participating countries would be able to finance new investments in cleaner technologies, thereby reducing both CO_2 emissions and local pollutants, which would likely boost economic benefits.

D. Improvements in Energy Efficiency

1. Issue

Energy professionals have long argued that the most cost-effective way to increase "effective" power generation capacity and reduce emissions is to improve the efficiency of the existing electricity system. While a large number of studies have identified cost-effective ways to increase efficiency, and consequently to increase the effective capacity of the electricity supply system,[58] institutional and market barriers have prevented these investments from occurring or even being seriously considered. Examples of supply-side efficiency improvements include higher fuel-to-electricity conversion efficiencies and reduced T&D losses. In the case of public sector generation, however, utilities have no incentives to undertake such activities, and inefficiency may be compounded by government subsidies. While the private sector may not be subject to these institutional challenges, lack of incentives, information costs, and other market barriers typically limit private-sector supply-side efficiency improvements as well.

Similar to the supply side, opportunities for demand-side energy efficiency improvements have not been realized, though for different reasons. Impediments to greater deployment of demand-side energy efficiency improvements include subsidized electricity prices, flat electricity tariffs (which are often used to simplify billing when electricity meters are either not present or too costly to install), information barriers, and low-quality electricity. (Energy efficient equipment is often more susceptible to damage from low-quality electricity.)

In addition, for many industrial customers, even though there will be a positive payback on efficiency improvements, there are other investments that can improve competitiveness more cost-effectively, particularly if electricity is subsidized. Furthermore, companies often have one division that makes design and capital investment decisions, while another division is responsible for operations. As a result, initial capital investment may not be made in a manner that minimizes life-cycle costs.[59] The result can be substantially more expensive to society and produce much larger CO_2 emissions than would be required by more energy-efficient technologies.

2. Analysis & Results

While the model used in this study focused on the costs and impacts of new generation, it also allowed an analysis of how large the benefits of efficiency improvements could be. Because information on the costs of improved efficiency measures are limited and varied, the model was used to determine how much society benefits (measured as an increase in GDP) from increases in effective electricity generation. This benefit was determined by increasing plant availability and decreasing T&D losses to feasible levels.[60] The resulting increase in "effective" capacity produced additional GDP through increased economic activity made possible by this new electricity. By dividing this increase in GDP by the increase in electricity consumption, the model suggests that developing countries could increase their economic growth by investing in supply-side efficiency measures that cost less than $3,000 per kW, on average. (For reference, the capital and infrastructure costs of a coal-fired plant are roughly $3,500 per kW). Furthermore, if developing countries were to invest in such improvements, the increase in effective capacity could be roughly 50 GW. If these investments had been made in the BAU Portfolio & Capacity Including Infrastructure Costs case, CO_2 emissions could have been decreased by as much as 10 percent.

The model's supply-side analysis also allows an estimate of the economically beneficial level of investment in demand-side efficiency improvements. This was accomplished by annualizing the supply-side investment estimate over a 10 year period[61] and converting the cost to an hourly basis. Known as the cost of conserved energy (CCE), this analysis revealed that economic growth could increase if demand-side efficiency improvements that cost less than $0.07 per kWh were implemented. Recent studies have identified numerous opportunities for end-use efficiency improvements that cost $0.01 to $0.10 per kWh.[62] Since these costs are generally below the price of electricity in most developing countries,[63] there are clear opportunities to improve end-use efficiency if ways can be found to overcome the institutional and market barriers. Finally, as with the supply-side analysis, savings in demand-side efficiency will also increase effective capacity and thereby reduce emissions relative to what would have occurred if these improvements had not been made.

V. Conclusions and Recommendations

The analyses presented in this report demonstrate that business-as-usual trends are not the only way to provide new increases in electric power generation in developing countries. Decision-makers have a broad menu of policy options that can shift the mix of generation technologies from "conventional" technologies to other combinations having different economic and environmental impacts. While the analyses performed in this study do not discuss all of the policy measures that can yield such changes, they do illustrate several significant problems with traditional planning and investment methods.

A. Include Infrastructure Costs in New Capacity Investment Decisions

Traditional analysis methods have focused on identifying the "least cost" means of generating electricity even though there are substantial non-generation infrastructure costs (e.g., pipelines and transmission and distribution equipment) associated with delivering electricity to consumers. This study suggests that continued use of these methods could, by ignoring these substantial costs during the planning stages, reduce the annual economic benefits of new capacity by 10 percent compared to what traditional analysis methods suggest. Moreover, this study finds that if infrastructure costs are included in the decision-making process, renewable technologies are more economically viable than current analysis tools suggest. Therefore, by modifying the planning and decision-making processes to include infrastructure costs, it is likely that scarce resources can be used more cost-effectively, possibly leading to higher economic growth and lower emissions. This change could be brought about by governments requiring that competitive bids for new power generation include an assessment of the fuel delivery infrastructure costs, the cost of additions to and expansion of the T&D system, and the impact of the plant on system reserve and reliability.

B. Acceleration of Private-Sector Participation

Accelerating the rate of private-sector involvement in power generation may offer significant benefits to developing countries through lower generation costs, and increased efficiency. In addition, privatization that includes infrastructure costs will increase the availability of public funds for other investments, while simultaneously encouraging the private sector to identify cost-effective means of providing electricity at the "least cost" of delivery. Despite these advantages, many governments remain hesitant to relinquish their control over electricity generation due to equity and social concerns. Indeed it is important to realize that increased private sector participation will not fix all of the electricity sector's problems. For example, privatization would not provide the incentives needed to reduce T&D losses and increase effective capacity, or to improve grid reliability and quality.

Specifically, this study found that depending on how government-led investment decisions are made and the private sector's relative technology preferences, privatization could increase the economic benefits of new capacity by 4–5 percent, while either increasing or decreasing air emissions. For example, privatization could either increase CO_2 emissions by 20 percent or decrease them by one percent, relative to current trends. Large variations are also possible in terms of local pollution. Accordingly, decision-makers should not minimize the potential long-term negative consequences of privatization. If countries do not develop adequate regulatory regimes, including environmental enforcement mechanisms, privatization may shift the technology mix in directions that could have long-term negative environmental consequences.

C. Use of Low-Emissions Technologies

As air quality in developing countries continues to deteriorate, it will become more important to consider the impact that new power generation sources have on emissions and the environment. This study found that a conservative estimate of emissions costs, together with infrastructure costs, could reduce new economic benefits 17 percent below BAU projections. Furthermore, this study investigated the possibility of increasing emissions controls and building higher efficiency fossil fuel technologies. These improvements were found to reduce SO_X and NO_X emissions by 39 and 25 percent relative to BAU trends, while yielding roughly the same economic benefits. A second low-emissions option that focused on increased reliance on gas and renewable sources was also investigated. This analysis revealed that shifting generation toward gas and renewables could reduce future SO_X and NO_X emissions by 72 and 39 percent relative to BAU trends, again for a very similar level of economic growth. This scenario also found that cleaner fossil fuels reduced CO_2 emissions by 17 percent, whereas the increased use of gas and renewables reduced CO_2 emissions up to 22 percent relative to BAU trends.

While all of these options yielded similar levels of long-term economic growth, the increased costs of the low-emissions options mean that developing countries may need assistance, financial and otherwise, to implement changes that would encourage investments in non-conventional technologies and shifts away from large natural resource endowments. International mechanisms — such as the Clean Development Mechanism — that aid developing countries in financing technologies with reduced CO_2 emissions would result in a cleaner environment, higher quality of life, a stronger economy, and reduced risk of global climate change.

D. Increased Energy Efficiency

Improving the performance of the T&D system and increasing end-use efficiency may offer developing countries another way to expand capacity and deliver more electricity to consumers, without the high cost of building new plants and with lower future CO_2 emissions. The resulting savings could be used for other infrastructure projects, thereby boosting economic growth. Furthermore, unlike the construction of new power plants, the increased effective capacity of an improved electric system would lower electricity prices and avoid increases in emissions that would otherwise be produced.

This study determined that developing countries would benefit economically and environmentally if they implemented supply-side efficiency improvements costing up to $3,000 per kW, as well as demand-side efficiency improvements up to $0.07 per kWh. While there are many technical opportunities for increasing efficiency on both the supply and demand sides that meet these values, the policy challenge lies in lowering the transaction and information costs and removing institutional barriers that are preventing these improvements. For this reason, if governments reduce barriers and perhaps even provide incentives to encourage energy efficiency improvements, then the economy may grow without a corresponding growth in emissions. Possible means for accomplishing these goals include allowing companies to claim tax breaks or accelerated depreciation for efficiency investments, providing innovative financing to end-users, or promoting the use of energy service performance contractors. Under these or similar reforms, investing in efficiency improvements will bring profits to the private sector, while benefiting the public at large through avoided air emissions.

E. Recommendations

Changing the policies guiding the next 20 years of power generation investments in developing countries provides an excellent opportunity to reduce CO_2 emissions while also reducing local pollution for little or no reduction in long-term economic benefits. This report has shown that policy-makers in developing countries have a variety of options to do just that. These alternatives to the business-as-usual, however, will not occur automatically. They will require a strong and concerted effort by developing countries and by the international community. While the results of this analysis cannot be applied directly to an individual country, governments might benefit from instituting reforms such as:

1. *Including infrastructure costs in new capacity investment decisions;*
2. *Accelerating private sector participation, where appropriate;*
3. *Considering the use of low-emissions technologies;*
4. *Considering participation in international mechanisms or markets to aid in providing financing for capital-intensive, lower CO_2 emitting technologies; and*
5. *Creating incentives to improve the efficiency of the existing electricity system.*

If developing countries are to provide electricity to 2 billion more people while promoting economic growth and improving quality of life, then the processes and tools used for increasing power generation capacity must improve the ability of decision-makers to balance market-based principles, policy goals, and social needs.

Appendix A: Description of the Generic Model

Overview

The generic model that formed the basis for the regional models did not attempt to capture all of the diverse impacts of electricity. Rather, it attempted to reflect the most significant electricity-related drivers of economic growth including electricity cost and quality. The generic model uses a conventional economic formulation to estimate changes in economic growth due to new electricity supply. Changes in economic growth (represented in the model by changes in GDP growth) are determined by three factors: capital investment in the economy, human capital (labor), and electricity supply. Changes in each factor have a different impact on the rate of economic growth. Each factor was measured empirically using cross-sectional time series data for developing countries.

Underlying Assumptions

For the past 20 years, economists have attempted to develop estimates of the impact of changes in energy prices and supply on economic growth. (Several examples of this work were discussed in "Electricity & Economic Growth.") While they have used different methods of empirical estimation, most studies were based on a conventional economic formulation where economic output was determined by growth in human capital (labor), produced capital (investment), and energy services.[64] This literature provides a strong argument for a positive relationship between electricity supply and economic growth.

Based on these arguments, the simulation model used in this study assumed that there is a direct relationship between changes in electricity supply and growth of GDP. Changes in electricity supply are determined by the amount of capital available for electricity investments and the technology investment portfolio. Quantifying the relationship between economic growth, capital formation, and electricity supply is relatively straightforward. It is assumed that there is a positive relationship between economic growth and capital formation. Capital formation is assumed to be positively related to electricity supply, because as electricity supply increases, economic output will increase, which will in turn increase the amount of capital available for investment and so on.

Impact of Price on Economic Benefits

This model assumed that all sectors of the economy will be affected by the price and quality of the electricity provided. (In this model, price was assumed to be correlated with cost; for that reason cost was used as a proxy for price.) For example, in comparing two mixes of electricity, the mix that is less expensive and/or more reliable should have a greater economic impact than an equal amount of capacity that is more expensive and/or less reliable. This study performed an empirical analysis of cross-sectional time series data for developing countries and found that a 1 percent reduction in the price of electricity is associated with a 0.11 percent increase in investment. Because the intention of the model is to capture changes in economic growth that result from different technology mixes, capital formation is modeled to vary with changes in price and reliability of electricity. In the model, the change in capital is determined by the capital in the previous period, the rate of growth in GDP from the previous period, as well as the change in the price and reliability of electricity.

Impact of Household Electricity Consumption

Electricity can have significant impacts on socioeconomic development and quality of life (see "Electricity and Socioeconomic Development"), but it is very difficult to determine the precise circumstances under which this will occur or how large the economic benefits may be. Rather than attempt to quantify how electricity is used and how it can improve quality of life and worker productivity, the model drew on previous studies that sought to estimate the relationship between energy and labor[65] and between new energy supplies and household impacts.[66]

Specifically, the model attempts to capture the fact that increased electricity supply can increase the number and extent to which individuals contribute to the formal economy. This increase in labor participation in the formal economy is the result of the provision of electricity services to previously non-electrified populations, as well as increases in electricity consumption by those who already have electricity. While both of these forms of expanded electric service (i.e., new service and increased service) increase the role of these populations in the formal economy, it is assumed that the rate of change of labor participation diminishes as the supply of electricity per capita increases. Thus, electricity supplied to areas that currently have no electricity will have a larger increase in labor participation than areas that already have electricity. Accordingly, increases in per capita electricity consumption will lead to a growing labor pool and eventually an increase in the rate of economic growth. The empirical analysis of developing countries found that a 1 percent increase in electric power supply is related to a 0.17 percent increase in the contribution of labor to economic growth. While it would have been desirable to capture the role of electricity in improving quality of life and increasing labor productivity, this simplification provides a reasonable estimate of the economic impacts of increased household electricity consumption.

Model Development

The generic system dynamics simulation model used in this study was developed using High Performance Systems' *ithink* programming environment. The system dynamics programming environment was chosen due to its transparency, ease of use, and rapid adaptability.[67]

Most of the simulation model's internal economic relationships were based on regression analyses of electricity and economic data for developing countries aggregated into five different regions: Africa, China & East Asia, Latin America, the Middle East, and South Asia. These analyses and complementary data were then used to calibrate a different version of the model for each region. One challenging aspect of these regression analyses, as well as of other parts of the model, was that data from developing countries is often limited. The World Bank, United Nations, IEA, the US Agency for International Development, the US Energy Information Administration, the former US Office of Technology Assessment, and the Electric Power Research Institute, among others, were able to provide reasonable data for the majority of the required analyses and model inputs. Nevertheless, there were cases where less than ideal data were averaged or reasonable estimates, based on published literature and/or personal discussions with experts, were used. For example, determining reasonable estimates of cost and technical data for a variety of power generation technologies in developing countries was difficult, since published estimates are often based on a small number of observations or on average costs in developed countries. Similarly, determining emissions coefficients for these technologies was difficult, since many cost sources do not provide emissions information, and those that do are not necessarily current. These problems were addressed by surveying several sources and choosing estimates that provided a reasonable approximation of technologies currently being constructed in developing countries. Appendix C provides more detail on the data used and its sources.

Key Model Relationships

The main purpose of the model is to capture the effects that different generation technology mixes have on economic growth. At the macroeconomic level, these differences affect labor participation, factor productivities, and gross domestic investment (i.e., savings) as determined by changes in the price of electricity and the reliability of the distribution system. (The results of the econometric analysis based on panel data of developing countries show that these effects are non-negligible.) The amount of resources invested in electricity at time t is defined exogenously at the beginning of each simulation as a percentage of available GDP. Future investments are determined by the growth of GDP and foreign investment.

Equation 1. $E(t) = \gamma GDP(t-1) + F$

where GDP is gross domestic product, F is foreign investment, E is the amount of investment in the electric sector and γ is the fraction of GDP to be invested.[68] This equation is based on the assumption that economic development is necessary to yield increased investment in the power sector.[69] Resources are distributed across different regions (throughout this section of the appendix, region refers to differences between urban and rural locations, not between different aggregations of developing countries) and economic sectors and are invested in the construction of electric power generation. The total generation capacity of each region depends on the capital costs that are associated with each technology.

Equation 2. $Se_{gi}(t) = M_j\left(E(t);\theta_{gi}\right)$

where Se_{gi} is the total supply of electricity in region g and economic sector i, and M_j is a function that depends on the type of technology mix j chosen as well as a fixed set of parameters θ_{gi} used to distribute E across regions and economic sectors. These parameters are based on historical percentages of the share of electricity used by different consumers in both rural and urban regions.

The total value added, Q_{gi}, in each region and sector was determined by assuming a Cobb-Douglas production function.

Equation 3. $Q_{gi} = AL_{gi}(t)^{\alpha}K_{gi}(t)^{\beta}Se_{gi}(t)^{\gamma}$

where L is human capital, K is produced capital, Se is the supply of electricity, α, β, and γ are estimated parameters and A is a constant set to equilibrate value added on the left-hand side with the product of the terms on the right-hand side. As previously stated, this equation represents a conventional model of economic growth as determined by labor, capital, and electricity. In this model it is assumed that non-electric components and other economic factors are constant across scenarios and thus, this analysis focuses only on the electricity-based portion of economic growth. The dynamics of each of the components of this function are defined below.

As described previously, it is assumed that electricity will increase the participation of labor in the economy. In this case the participation in labor is increased by lagged increases in the supply of electricity as shown in Equation 4.

Equation 4. $$L_{gi}(t) = L(t-1)^{*}\left\{1+\left(\frac{\varphi_{gi}Se_{gi}(t-1)^{\varphi_{gi}}}{L(t-1)}\right)\left(\frac{Se_{gi}(t-1)}{Se_{gi}(t-2)}-1\right)\right\}$$

where φ is estimated. This functional form uses a logistic factor that ensures that consumption of electricity has a marginal diminishing effect on labor productivity.[70]

Equation 5 shows that the total stock of capital at time t is given by the sum of the stock of capital in the previous time period and the investments in that period. Hence:

Equation 5. $$K_{gi}(t) = Z\left\{K(t-1)(1-\delta) + I(t-1);\ \Theta_{gi}\right\}$$

where Θ_{gi} is the set of parameters used to distribute capital between the regions and sectors described above and δ is the discount rate which was assumed to be 10 percent.

The price charged to consumers of electricity is an important component of the dynamics of the model since it will affect the level of current investment in the economy. (In this model, price was assumed to be correlated with cost; for that reason cost was used as a proxy for price.) In addition, the cost of electricity will affect profits and therefore the rates of return on capital. The price of electricity will also affect household consumption and savings patterns. Indeed, it can be shown that, other things being equal, a reduction in the price of electricity will increase household savings, thus having positive effects on domestic savings and therefore investments.

To capture all of these effects, panel data on developing countries was used to estimate the following investment function:

Equation 6. $$\log I_t(t) = \xi_0 + \xi_1 \log GDP(t) + \xi_2 \log \bar{p}_e(t) + \xi_3 \log L_e(t)$$

In this equation $\bar{p}_e$ is the average electricity cost for each region and economic sector and L_e is the fraction of T&D losses. This last variable has been included as a proxy for reliability of the electricity generation system. Lower reliability imposes other economic costs not incorporated in the price of electricity that have negative effects on investment. In theory, the interest rate would be included in this equation, but since it is assumed that the interest rate is constant across years and between scenarios, it is not included.

Estimation of Parameters

The equation parameters described above were estimated using panel data for countries from the sources listed in Appendix C. The results of the empirical analysis are summarized in the adjacent table.

Parameter	Result
Contribution of electricity to the change in the labor participation — φ	0.17
Contribution of GDP to investment — ξ_1	1.08
Impact of changing electricity price on investment — ξ_2	–0.11
Impact of transmission and distribution losses on investment — ξ_3	–0.13
Average contribution of labor participation to economic growth — α	0.36
Average contribution of capital to economic growth — β	0.48
Average contribution of electricity to economic growth — γ	0.16

Appendix B: Environmental Externalities

This appendix and the underlying estimates of the cost of air emissions were provided by Dr. Roger Raufer, Adjunct Professor, University of Pennsylvania.

This analysis is designed to address the economic impacts of air emissions over a wide range of technological, geographical, and socioeconomic settings. While there are numerous means of quantifying these impacts, the US National Renewable Energy Laboratory has identified seven alternative approaches to incorporating environmental externalities into the utility planning process,[71] but three of these methods are especially relevant.

The first, qualitative treatment, does not try to monetize emissions, but instead identifies and describes them. This approach is easy to apply, but it does not lend itself to quantified economic analysis. The other two approaches, "estimation of damages" and "pollution control costs as revealed preferences," are utilized in the report. The data used are described below.

Environmental externality data for electricity generation are often characterized by "top-down" and "bottom-up" determinations.[72] The former addresses impacts at a national or regional level, summarizing environmental impacts and attempting to estimate the contribution of various fossil fuels to this total. The latter type is usually project-specific, estimating environmental impacts of individual activities, applying physical and dose-response models to estimated project emissions. It has been suggested that "top-down" analyses may be especially relevant for broad policy efforts, since they provide average cost values. The "bottom-up" analyses, on the other hand, are more relevant for considerations involving newly added electrical capacity, since they provide marginal estimates of impacts. The estimates presented at the end of this appendix are based upon "bottom-up," and thus marginal, analyses.

Externality impacts of new electric power generation capacity, however, tend to be very site-specific, as a true "bottom-up" approach indicates. Given the need for aggregated values that are still appropriate for the task, a combination of sources and approximations were used. Base estimates were gathered from the Tellus Institute's estimates of the "revealed preference" found in emissions control costs in the United States, while the European Commission's ExternE analysis formed the basis for the damage valuation estimates. The latter analysis indicated that human health had played a particularly important role in the valuation, and that the values varied according to the size of the population affected. These results were thus employed to estimate the relative effect of urban and rural conditions for each pollutant. Data from each of the two principal data sources were then reviewed, as well as the basis for these individual determinations. Appropriate values for this analysis were then estimated for each pollutant, based upon either average values or individual results. For all values, the resulting US and European estimates were reduced by the ratio of OECD/World per capita income to provide worldwide externality valuation estimates.

The resulting environmental externality valuations represent a "best estimate" of the worldwide economic damage associated with increased emissions of SO_X, NO_X, and PM-10 from new electric power generation in developing countries. Considerable care must be taken in using these estimates for the following reasons:

1) These are not the only emissions emitted; carbon monoxide, volatile organic compounds, heavy metals, polycyclic aromatic hydrocarbons, etc. are all emitted from power generating facilities, and are not addressed in these valuations.
2) All impacts are site-specific, but these reported values represent highly aggregated, worldwide estimates.
3) The techniques supporting the base estimates contain numerous assumptions about physical, technological, and economic processes, and all of these assumptions are subject to considerable uncertainties; and
4) There are numerous normative and methodological concerns about the economic valuation process itself.

Despite these caveats, these values represent a "best estimate" for the proposed modeling analysis.

The cost estimates used in this study were as follows:

Pollutant	Urban Cost Estimate (1999 US $/ton)	Rural Cost Estimate (1999 US $/ton)
SO_2	420	130
NO_X	2,200	430
PM-10	1,130	170

The data used in these analyses were obtained from the following sources:

Tellus Institute, *Valuation of Environmental Externalities for Energy Planning and Operations*, Boston, MA, May, 1990 rev.

European Commission, DGXII Science, Research and Development, *ExternE, Externalities of Energy*, JOULE Programme. http://externe.jrc.es/

European Commission, ExternE: National Implementation Programme, Newsletter No. 6, June, 1998.

Appendix C: Model Data and Sources

Data sources and methods are discussed briefly in the following section. Key data is included in a table at the end of this appendix.

Country Groupings

The IEA's WEO 1998 groupings of developing countries (i.e. non-OECD and non-transition economy countries) were used in this study. Specifically, the following regions were modeled: Africa, China & East Asia, Latin America, Middle East, and South Asia.

Regional Data

Country and regional data was obtained from the following sources:

Heidarian, J. and Wu, G. *Power Sector Statistics for Developing Countries, 1987–1991*, World Bank: Industry and Energy Department, December 1994.

International Energy Agency, *World Energy Outlook 1998 Edition*, 1998.

Moore, E. and Smith, G. *Capital Expenditures for Electric Power in the Developing Countries in the 1990s,* Energy Series Paper No. 21, Industry and Energy Department Working Paper, The World Bank, 1990.

Population Division, United Nations. *World Urbanization Prospects: The 1996 Revision,* publication forthcoming, http://www.un.org/Depts/unsd/social/hum-set.htm

Statistics Division, United Nations. *Energy Statistics Database 1996*, 1998.

United Nations, *National Accounts: Statistics, Main Aggregates, and Detailed Tables*, 1992.

World Bank, *World Development Indicators 1998 CD*, 1998.

Power Generation Technology Data

Fuel Costs

In order not to double-count the costs of fuel transport and delivery, this study used international fuel prices rather than power plant prices that could already include the cost of transport and delivery.

Technological Progress

Estimates of technological progress (i.e., change in capital costs and heat rate) were estimated from the following sources:

US DOE and EPRI, *Renewable Energy Technology Characterizations*, December 1997.

US Energy Information Administration, *Annual Energy Outlook 1999*, 1999.

Sources

Cost and technical data for power generation technologies were gathered from the following sources:

IEA, *Projected Costs of Generating Electricity-Update 1998*, 1998.

IEA, *Greenhouse Gas Technology Information Exchange (GREENTIE),* http://www.greentie.org/aboutgrn.html

US Agency for International Development, *The Environmental Implications of Power Sector Reform in Developing Countries,* 1998.

US Department of Energy and Electric Power Research Institute, *Renewable Energy Technology Characterizations,* 1997.

US Energy Information Administration, *Annual Energy Outlook 1999*, 1999.

R. Taylor, National Renewable Energy Laboratory, Personal Communication, March 31, 1999.

Calculation of Levelized Cost

Levelized costs of generation were based on a 10-percent discount rate and 30-year cost recovery. The standard levelized cost formula shown in Equation 1 was used for those cases where infrastructure costs were not included. In those scenarios where infrastructure costs were included, this equation was modified to include those costs (see Equation 2). The formula for the Capital Recovery Factor is shown in Equation 3.

Equation 1:

Levelized Cost ($/kWh) = { { [Capital Cost ($/kW)] * [Capital Recovery Factor] } + { [O&M Costs (mills/kWh)] + [Fuel Costs (mills/kWh)] } * 8760 * Availability / 1000} / { 8760 * Availability }

Equation 2:

Levelized Cost with Infrastructure Costs ($/kWh) = { { [Capital Cost ($/kW) + Infrastructure Cost ($/kW)] * [Capital Recovery Factor] } + { [O&M Costs (mills/kWh)] + [Fuel Costs (mills/kWh)] } * 8760 * Availability / 1000} / { 8760 * Availability }

Equation 3:

Capital Recovery Factor = { Discount Rate * [1 + Discount Rate] ^ [Time for Cost Recovery] } / { { [1 + Discount Rate] ^ [Time for Cost Recovery] } – 1 }

Emissions Factors

Emissions factors were determined from the following sources:

US Environmental Protection Agency, *AP42/CHIEF Database*, http://www.epa.gov/ttn/chief/ap42.html

IEA, *Greenhouse Gas Technology Information Exchange (GREENTIE),* http://www.greentie.org/aboutgrn.htm

Infrastructure Costs

Methodology

Infrastructure costs were estimated using the following guidelines.

- All fuel-based technologies included fuel delivery infrastructure costs.
- All grid-connected generation technologies included transformers and on-site administrative support costs.
- Grid-connected technologies serving urban consumers included 20 miles of high voltage lines to connect the power plant to the grid.
- Grid-connected technologies serving rural consumers (i.e., via grid extension) included 100 miles of low voltage lines.
- Grid-connected intermittent renewable technologies did not include backup generation or storage facilities. Under these conditions, intermittent renewable technologies were assumed to have low availabilities.
- Distributed intermittent renewable technologies serving rural consumers included batteries, chargers, inverters, and other equipment needed to provide reliable, high-quality electricity. Under these conditions, intermittent renewable technologies were modeled with high availabilities.

Cost Estimates and Sources

Estimates of infrastructure costs were taken from the following sources:

IEA, *Greenhouse Gas Technology Information Exchange (GREENTIE)*, http://www.greentie.org/aboutgrn.htm

Office of Technology Assessment (OTA), US Congress, *Fueling Development: Energy Technologies for Developing Countries,* Washington, DC: US Government Printing Office, 1992.

R. Taylor, National Renewable Energy Laboratory, Personal Communication, March 31, 1999.

Technology Parameters

Power Generation Technology	Capital Cost ($/kW)	Availability (Fraction)	Fuel Cost (mills/kWh)	Variable O&M Cost (mills/kWh)	Heat Rate (MMBtu of fuel/ kW-year)	CO_2 Emissions (kg/MMBtu of fuel)	SO_X Emissions (kg/MMBtu of fuel)	NO_X Emissions (kg/MMBtu of fuel)	PM-10 Emissions kg/MMBtu of fuel)	Infrastructure Costs–Urban Grid Delivery ($/kW)	Infrastructure Costs–Rural Grid Delivery ($/kW)	Infrastructure Costs–Rural Distributed ($/kW)
Pulverized Coal with Particulate Matter (PM) Controls	985	0.8	20.2	3.7	65.3	114.3	1.664	0.246	0.009	2,581	2,658	N/A
Pulverized Coal with PM and NO_X Controls	1,094	0.8	19.2	4.5	62.1	114.3	1.664	0.055	0.009	2,580	2,656	N/A
Pulverized Coal with PM NO_X, and SO_X Controls	1,342	0.8	17.9	7.5	62.1	114.3	0.166	0.055	0.009	2,578	2,655	N/A
Fluidized Bed Combustion with PM Controls	985	0.8	24.6	15.4	79.7	114.3	1.664	0.043	0.009	2,587	2,663	N/A
Fluidized Bed Combustion with PM and SOx Controls	1,342	0.8	24.6	24.4	79.7	114.3	0.166	0.043	0.009	2,587	2,663	N/A
Oil Boiler	894	0.8	22.6	5.0	79.7	73.3	0.541	0.078	0.022	2,645	2,849	N/A
Oil Boiler with PM, SO_X, and NO_X Controls	1,018	0.8	22.6	6.0	79.7	73.3	0.054	0.064	0.003	2,645	2,849	N/A
Gas Boiler	894	0.8	18.3	5.0	64.6	53.4	0.0003	0.00004	0.003	2,641	2,718	N/A
Combustion Turbine-Gas	310	0.8	23.6	1.3	83.4	53.4	0.0003	0.029	0.002	2,739	2,943	N/A
Combustion Turbine- Distillate	310	0.8	23.6	1.3	83.4	74.8	0.137	0.132	0.028	2,651	2,854	N/A
Diesel Generator (uncontrolled)	1,697	0.8	117.6	5.0	59.6	74.4	0.132	2.0	0.141	2,702	3,007	17
Combined Cycle Combustion Turbine-Gas	419	0.8	15.9	2.5	56.3	53.4	0.0003	0.029	0.002	2,630	2,706	N/A
Combined Cycle Combustion Turbine- Distillate	419	0.8	15.9	2.5	56.3	74.8	0	0.132	0.028	2,570	2,647	N/A
IGCC	1,514	0.8	18.3	5.1	59.4	96.5	0.129	0.0013	0.006	2,579	2,655	N/A
Biomass Boiler	1,852	0.8	23.6	17.8	107.1	21.6	0.001	0.0133	0.05	2,904	3,514	44
Solar Photovoltaics	4,713	0.25	0	0	0	0	0	0	0	2,000	2,000	3,000
Biomass Integrated Gasification/ Gas Turbine	1,981	0.7	36.0	15.5	61.3	21.6	0.001	0.0133	0.05	2,772	3,179	N/A
Wind	943	0.3	0	14.6	0	0	0	0	0	3,208	4,429	3,000
Solar Thermal	5,279	0.3	0	10.8	0	0	0	0	0	3,092	4,109	3,000
Small Hydro	2,850	0.8	0	1.8	0	0	0	0	0	21,695	2,519	0
Large Hydro	2,356	0.8	0	0.1	0	0	0	0	0	2,860	3,470	N/A
Nuclear	1,388	0.8	5.5	4.8	72.9	0	0	0	0	2,528	2,559	N/A

Notes: All costs are in 1995 US dollars. $1 equals 1000 mills. Availability refers to the amount of time a technology provides electricity. N/A means this estimate was not applicable because this technology was not used under these conditions.

Endnotes

1. International Energy Agency (IEA), *World Energy Outlook 1998 Edition*, Paris, 1998.

2. World Bank, *Rural Energy and Development: Improving Energy Supplies for 2 Billion People*, Washington DC, 1996.

3. IEA, 1998.

4. For example, known reserves of natural gas have increased substantially since the early 1980's, thereby making natural gas a more viable fuel source for power generation. D. Unger, *Energy Policy and Environmental Technology: The Development of Natural Gas Turbine Technology in Power Generation*, Masters Thesis, Cambridge, Massachusetts Institute of Technology, 1999.

5. The most commonly used models have been the Wien Automatic System Planning model –WASP, Electric Generation Expansion Analysis System –EGEAS, and the National Investment Model –NMI; Integrated Energy Planning: A Manual, Asian and Pacific Development Centre, 1985.

6. World Bank, *The Bank's Role in the Electric Power Sector,* Industry and Energy Department Paper, Washington DC, 1992.

7. N. Rosenberg, "The Role of Electricity in Industrial Development," *Energy Journal* 19(2), 1998.

8. D. Barnes, *Electric Power for Rural Growth*, Boulder, Westview Press, 1988.

9. B. James, *The Impacts of Rural Electrification: Exploring the Silences*, Energy Development and Research Center, Cape Town South Africa, 1995. D. Barnes, 1988.

10. J. Goldemberg and T.B. Johansson, Eds, *Energy as an Instrument for Socio-economic Development*, New York, United Nations Development Programme (UNDP), 1997; A.K.N. Reddy, R.H. Williams, T.B. Johansson, *Energy After Rio: Prospects and Challenges*, New York, UNDP, 1997.

11. Barnes, 1988.

12. Reddy et al., 1997.

13. World Bank, 1996.

14. World Bank, 1996.

15. World Bank, 1996.

16. World Bank, 1992.

17. In addition, a major factor in the problems faced by developing countries is theft of electricity which makes planning reliable systems difficult.

18. World Bank, *World Development Report 1994: Infrastructure for Development*, New York, Oxford University Press, 1994.

19. O.A. Uchendu, "Economic Cost of Electricity Outages: Evidence from a Sample Study of Industrial and Commercial Firms in the Lagos Area of Nigeria" *CBN Economic and Financial Review* 31(3); cited in AF Adenikinju, "Productivity Growth and Energy Consumption in the Nigerian Manufacturing Sector: A Panel Data Analysis" *Energy Policy* 26(3), 1998.

20. A. Anas, K.S. Lee, M. Murray, "Infrastructure Bottlenecks, Private Provisions, and Industrial Productivity: A Study of Indonesian and Thai Cities." *Policy Research Working Paper 1603*, Washington DC, World Bank, 1996; K.S. Lee, A. Anas and G.T. Oh, "Costs of Infrastructure Deficiencies in Manufacturing in Indonesia, Nigeria and Thailand,"

Policy Research Working Paper 1604, Washington DC, World Bank, 1996; K.S. Lee, A. Anas, S. Verm, M. Murray, "Why Manufacturing Firms Produce Some Electricity Internally," *Policy Research Working Paper 1605*, Washington DC, World Bank, 1996.

21. World Bank, 1992.

22. IEA, 1998.

23. A sampling of the literature includes: B.W. Ang, "A Cross-section of Energy-output Correlation," *Energy Economics* 9(4), 1987; D. Desai, "Energy-GDP Relationship and Capital Inventory in LDCs," *Energy Economics* 8(2), 1988; J. Dunkerely, "Estimation of Energy Demand: the Developing Countries," *Energy Journal* 3(2), 1982; Leach, Jarass, Obermair and Hoffman, *Energy and Growth: A Comparison of 13 Industrial and Developing Countries*, London, Butterworths, 1986.

24. O. Ebohon, "Energy, Economic Growth and Causality in Developing Countries: A Case Study of Tanzania and Nigeria," *Energy Policy* 24(5), 1996; cited by A. Adenikinju, "Productivity Growth and Energy Consumption in the Nigerian Manufacturing Sector: A Panel Data Analysis," *Energy Policy* 26(3), 1998.

25. J. Huang, "Electricity Consumption and Economic Growth: A Case Study of China," *Energy Policy* 21(6) 1993.

26. B. Cheng, "Energy Consumption and Economic Growth in Brazil, Mexico and Venezuela: A Time Series Analysis," *Applied Economics Letters* 4(11), 1997.

27. Annual investments are a combination of domestic and foreign funds. Domestic funds are a fixed percentage of the previous year's GDP while foreign funds are determined from historical estimates (See E. Moore and G. Smith, *Capital Expenditures for Electric Power in the Developing Countries in the 1990s,* Energy Series Paper No. 21, Industry and Energy Department Working Paper, The World Bank, 1990). In subsequent analyses, the fixed percentage of GDP used for domestic investment was set to reflect the scenario-dependent capacity expansion goal.

28. The simulation model did not include construction that was already underway at the beginning of the simulation. For that reason, new capacity begins to be built in the first year but it may take several years to come on-line and generate benefits.

29. As described previously, the simulation model was intended to compare the impacts of different power generation technologies only. For this reason, changing electricity consumption trends would not affect the results. Historical trends were determined from World Bank, *World Development Indicators 1998*, 1998.

30. This model's focus of estimating the relationship between the quantity and quality of electricity supply and economic growth for the developing world differentiates this simulation model from other models. This model is different from the Tellus Institute's Long-range Energy Alternatives Planning (LEAP) System, which includes all forms and uses of energy and assists in forecasting actual behavior. In contrast, the model used here focuses only on electricity, and contains additional detail regarding electricity sources, consumption, and economic growth. This model also differs from the Millennium Institute's Threshold 21 model, which attempts to capture all of a nation's economic, social, and environmental resources. Compared to Threshold 21, this model contains more detail regarding electricity generation and is more easily applied to aggregate regions of the world.

31. IEA, 1998.

32. IEA, 1998.

33. IEA, 1998.

34. IEA, 1998.

35. World Bank, 1992.

36. The worst known case of T&D losses, 46 percent, occurred in Bangladesh in the mid 1980s. World Bank, 1992.

37. World Bank, 1992 and Office of Technology Assessment (OTA), US Congress, *Fueling Development: Energy Technologies for Developing Countries*, Washington, DC: US Government Printing Office, 1992.

38. These differences are due to local and regional conditions such as differences in terrain, weather patterns and extremes, land value, and natural resource availability.

39. Non-generation infrastructure costs include transmission, distribution, and other general costs including vehicles, communications, buildings, general tools and equipment, and miscellaneous costs.

40. Moore and Smith, 1990.

41. In many cases, fuel delivery infrastructure can be used by other consumers (e.g., industry) or for other purposes (e.g., railroads transport many other goods). Since the benefits of such infrastructure would accrue to more than the power sector, the costs should also be shared more widely. For this reason, the estimates of fuel delivery costs were taken from a report which focused exclusively on power generation in developing countries. See OTA, 1992.

42. The "BAU Portfolio & Capacity Including Infrastructure Costs" case results in the construction of 458 GW of coal-fired plants, 225 GW of gas-fired plants, 163 GW of large hydro, and 117 GW of other renewables.

43. The "BAU Portfolio Including Infrastructure Costs" case results in the construction of 343 GW of coal-fired plants, 149 GW of gas-fired plants, 120 GW of large hydro, and 84 GW of other renewables. It is important to note that this and the next case have roughly one-third less power than the "BAU Portfolio & Capacity Including Infrastructure Costs" case but has the same level of economic benefits. This reflects the fact that even though more capacity is added, the increased capacity required larger public investments which had an opportunity cost to the economy and thereby reduced economic benefits.

44. The "Distributed Technologies for Rural Generation" case results in the construction of 338 GW of coal-fired plants, 149 GW of gas-fired plants, 113 GW of large hydro, and 90 GW of other renewables.

45. The capital-intensive mix of renewables consisted of 90 percent solar photovoltaics, 5 percent wind, and 5 percent small hydro. This mix was chosen not because it is a probable deployment, but because solar photovoltaics are among the most expensive renewable technologies available. Hence 90 percent reliance on this technology provides a conservative estimate of the cost of deploying renewables. Since wind turbines and small hydro will likely represent more than 5 percent of actual renewable deployment, this case represents a conservative estimate of the costs of renewable generation. (As shown in Appendix C, wind turbines have initial investment costs which are roughly one-fifth of the cost of solar photovoltaics, making them competitive with coal-fired generation).

46. These insights were formulated by interviews of managers in eight firms — six US-based and two European-based — that invest and build power generation facilities in developing countries. All the companies build coal and gas plants, and three of the companies have renewable energy subsidiaries. The interviews were made under the condition that no attribution would be made.

47. The "Privatization with 80 Percent Natural Gas" case resulted in the construction of 160 GW of coal-fired plants, 996 GW of gas-fired plants, 55 GW of large hydro, and 90 GW of other renewables.

48. Given the assumptions set forth in this section, 80 percent gas is an upper bound for the use of this fuel. The peak rate of natural gas consumption corresponding to this level of investment was estimated to be technically feasible using US Geological Survey estimates of remaining recoverable reserves in non-OECD countries. IEA, 1998.

49. The "Privatization with 50 Percent Natural Gas" case resulted in the construction of 335 GW of coal-fired plants, 645 GW of gas-fired plants, 66 GW of large hydro, and 140 GW of other renewables.

50. D. Pearce, "Economic Valuation and Health Damage from Air Pollution in the Developing World," *Energy Policy* 24(7) 1996.

51. Pearce, 1996.

52. The use of control costs as a surrogate for the anticipated benefits can significantly understate the actual benefits to human health and the environment. One study by D. Burtraw, et al ("The Costs and Benefits of Reducing Acid Rain," *Discussion Paper 97-31-REV,* Resources for the Future, 1997) found benefits exceeding control costs by roughly an order of magnitude.

53. Tellus Institute, *Valuation of Environmental Externalities for Energy Planning and Operations*, Boston, MA, May, 1990 rev.; European Commission, DGXII Science, Research and Development, *ExternE, Externalities of Energy*, JOULE Programme. http://externe.jrc.es/

54. The "BAU Portfolio Including Infrastructure & Pollution Costs" case results in the construction of 343 GW of

coal-fired plants, 149 GW of gas-fired plants, 120 GW of large hydro, and 84 GW of other renewables.

55. The "Cleaner Fossil Fuel Technologies" case resulted in the construction of 317 GW of coal-fired plants, 159 GW of gas-fired plants, 120 GW of large hydro, and 85 GW of other renewables.

56. It was assumed that developing countries, as a whole, were not likely to build super-critical coal-fired plants.

57. The "Gas and Renewables" case resulted in the construction of 208 GW of coal-fired plants, 235 GW of gas-fired plants, 120 GW of large hydro, and 148 GW of other renewables.

58. Interlaboratory Working Group, US Department of Energy, *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond*, 1997. Michael Philips, *The Least Cost Energy Path for Developing Countries*, International Institute for Energy Conservation, Washington, DC, 1991.

59. A good illustration of this situation is the "landlord-tenant" problem. In this case, the owner is not the renter. As a result, the builder is not concerned with operating and life-cycle costs of a building and its equipment. Thus, builders often minimize the initial investment costs thereby requiring the renter to pay higher fuel and operations costs for the life of the building.

60. For the purposes of the efficiency analysis, infrastructure costs were included but environmental costs were not.

61. The annualization calculation assumed a 10 percent discount rate. In addition, the efficiency improvement was assumed to result in energy savings 80 percent of an average day.

62. Interlaboratory Working Group, 1997. M. Bernstein. *Costs and Greenhouse Gas Emissions of Energy Supply and Use*, Report to the Environment Division of the World Bank, University of Pennsylvania, Philadelphia, PA, 1993.

63. Electricity prices in developing countries, (which are often heavily subsidized), range from $0.04/kWh to $0.28/kWh. See World Bank, 1996; J. Heidarian and G. Wu, *Power Sector Statistics for Developing Countries, 1987-1991*, Washington DC, World Bank, 1994.

64. There is insufficient space in this paper to provide a significant review of the economic literature on the subject. Literature reviewed included Berndt, "Energy Price Increases and the Productivity Measurement," *Annual Review of Energy*, 3, 1978. Berndt and Wood, "An Economic Interpretation of Energy-GDP Ratio", in M. Macrakis, ed., *Energy: Demand, Conservation and Institutional Problems*, MIT Press, Cambridge, MA, 1974; Gollop and Jorgenson, "U.S. Productivity Growth by Industry 1947-1973," in D. Kendrick and B. Vaccara, eds. *New Developments in Productivity Measurement and Analysis*, University of Chicago Press, NY, 1980; Mountain, "The Contribution of Changing Energy and Import Prices to Changing Average Labor Productivity", *The Quarterly Journal of Economics*, V.100, No. 3, August 1985; Shaeeldin, "Sources of Industrial Growth in Kenya, Tanzania, Zambia and Zimbabwe", *Eastern Africa Economic Review*, Vol. 4, No. 2 ,1988.

65. Mountain, 1985.

66. World Bank, 1996.

67. Discussion of system dynamics models are beyond the scope of this paper, but useful background information can be found at High Performance Systems website (http://www.hps-inc.com/), the MIT Systems Dynamics Group website (http://sysdyn.mit.edu/sd-group/home.html), and the Systems Dynamics Society website (http://www.albany.edu/cpr/sds/).

68. The fraction of GDP invested in the power sector and foreign investment in the power sector varied by region and was based on estimates for all developing countries. See Moore and Smith, 1990.

69. Goldenberg and Johansson, 1997.

70. See for example, M. Deleau, P. Malgrange and P.A. Muet (1982). "A Study of Short Run and Long Run Properties of Macroeconometric Dynamics Models by Means of an Aggregative Core Model". *Working Paper. No. 8107* bis. Commisariat General du Plan.

71. National Renewable Energy Laboratory, *Issues and Methods in Incorporating Environmental Externalities into the Integrated Resource Planning Process*. Golden CO, NREL/TP-461-6684, 1994.

72. L. Schleisner, *Review of Externality Valuation*. Roskilde, Denmark, Riso National Laboratory, 1998.