

example, could put large numbers of efficient electric vehicles into many urban markets; in some of those markets (e.g., California) both the overall emissions effects and the greenhouse gas emissions effects could be extremely positive. Similarly, breakthroughs in on-board storage technology for natural gas might allow substantial penetration of natural gas vehicles into many markets, although the positive greenhouse gas emissions impact of such vehicles would likely be substantially less than for EVs or fuel cell hybrids.

5.4.2 Freight Trucks and Locomotives

The diesel cycle engine will dominate the freight truck sector at least until 2020 because of its high thermal efficiency, potential fuel flexibility, and durability. DOE's Office of Heavy Vehicle Technologies (OHVT) within the Office of Transportation Technologies is attempting to develop the enabling technologies needed to achieve fuel flexibility, ultra-low emissions, and high fuel efficiency in all classes of trucks, buses, and other heavy vehicles such as off-highway vehicles. The typical new Class 8 tractor trailer in 2020 is expected to achieve an on-road fuel economy of over 10 MPG, compared to about 7 MPG today, assuming a high-efficiency/low-carbon, low emission diesel cycle engine (thermal efficiency of at least 55% at rated speed and load at the flywheel) and other technologies such as reduced aerodynamic drag, low rolling resistance tires, and lightweight materials (such as magnesium) become an economic reality.¹⁴ While many of these technologies have already been demonstrated to a limited extent, a key enabler is a durable highly efficient NO_x catalyst capable of operating at high-efficiency/low-carbon in an oxidizing atmosphere.¹⁵ Fuel reformulation is envisioned, as well as nonpetroleum fuels, during this period (2000-2020).

However, as the efficiency of the diesel cycle becomes fully exploited (thermal efficiencies of over 63% will be highly unlikely), the hydrogen fuel cell, unconstrained by the Carnot cycle, may be the next powerplant of choice for freight trucks, locomotives, and passenger cars. Significant R&D efforts at DOE have enabled the demonstration of methanol-fueled fuel cell buses and other vehicles. However, significant development of the fuel cell itself, power management strategies, and hydrogen fuel production, distribution and storage are required, and economical solutions are hard to envision before 2020. Particularly problematic are the low cost, efficient production, delivery, and storage of hydrogen fuel (carbon-containing fuels significantly degrade fuel cell thermal efficiency - in many cases to efficiencies below that of current-production diesel engines). The fuel cell powerplant, combined with low aerodynamic drag, low rolling resistance tires, and lightweight materials may raise Class 8 tractor trailer fuel efficiency to 15 MPG or more. Locomotive engines may be an ideal test bed and an early entry for fuel cell powerplant technologies, because sizes needed (4000 hp-equivalent) are on the scale of smaller stationary electrical power generation plants which are already commercial. In addition, locomotives are already driven by computer-driven electric motors for traction control.

5.5 SUMMARY

Cost-effective or near cost-effective technologies and alternative energy sources have the potential to significantly restrain the growth of the U.S. transportation sector's greenhouse gas emissions through 2010. There remains a substantial reservoir of proven technology for improving motor vehicle fuel economy, and technologies that are very nearly market-ready (such as the DISC engine with lean-NO_x catalytic converter) will almost certainly further expand the potential to increase MPG by 2010. New technologies and operational efficiency gains hold out similar potential for air passenger travel and for truck and rail freight. Ethanol derived from cellulosic feed stocks instead of grain could also make a significant contribution by 2010 as a blending component for conventional gasoline if cost reductions foreseen by energy researchers are achieved. Overall, the combined impact of such technologies could be to reduce greenhouse gas emissions by 10% in 2010 and by almost

20% in 2015, relative to the business-as-usual case. If important breakthroughs can be achieved in fuel cells and other key technologies, transportation's greenhouse gas emissions in 2015 could be held below current levels.

In the business-as-usual case, transportation energy use grows from 25.5 quads in 1997 to 32.3 in 2010 and 34.0 in 2015. Carbon dioxide emissions, in million tonnes of carbon, increase from 487 in 1997 to 616 in 2010, and to 646 in 2015. As mentioned earlier, the business-as-usual case anticipates rates of growth in transportation activity that are slow by historical standards. The actual outcome could easily be 10% higher. The efficiency case holds transportation energy use to 29.3 quads in 2010 and 28.7 in 2015. Accordingly, carbon emissions grow to only 543 MtC in 2010 and 532 in 2015. The fact that emissions are lower in 2015 than in 2010 reflects the fact that changing the technology of transportation energy use requires the orderly turnover of durable capital stock. The high-efficiency/low-carbon scenario holds 2010 carbon emissions from transport to 512 MtC, and reduces 2015 emissions to 484 MtC, just slightly below the 1997 level.

Changes in the mix of transportation fuels in the three 2010 scenarios are summarized in Table 5.10. Although petroleum fuels are still the predominant source of energy for transportation, use of alternative fuels expands in all three scenarios. Natural gas consumption for transport grows from 0.75 TCF in 1997 (about 98% of which is used in natural gas pipelines) to roughly 1.2 TCF in 2010. In 2010 pipelines still account for 70-75% of natural gas use, but CNG vehicles consume about 0.25 TCF, and natural gas used to produce methanol for motor fuel accounts for nearly all of the rest. Biofuels in the form of cellulosic ethanol come on strong in the efficiency and high-efficiency/low-carbon scenarios, providing from one-fourth to one-third of an MMBD oil equivalent. In accord with the AEO97 reference case projections, all scenarios foresee substantial increase in electricity use, essentially all going to electric vehicles. The lower levels of electricity use in the efficiency and high-efficiency/low-carbon scenarios, like those of natural gas use, are due to the general improvements in vehicle technology in those scenarios.

Table 5.10 Transportation Energy Use by Fuel Type

Fuel	1997	2010		
		BAU	Efficiency	High-Efficiency
Petroleum Fuels (MMBD)	11.77	14.59	12.91	12.18
Natural Gas (TCF)	0.75	1.22	1.19	1.16
Biofuels (MMBD OE)	0.001	0.04	0.25	0.34
Electricity (MMBD OE)	0.04	0.23	0.22	0.20

Note: Petroleum fuels converted to million barrels per day oil equivalent using a heat content of 5.738 MMBtu/barrel. Natural gas includes pipeline fuel and natural gas used to produce methanol for use as a neat fuel, but does not include natural gas used to produce methanol for use in Methyl Tertiary Butyl Ether. It is assumed that, to produce one quad of methanol, 1.44 quads of natural gas are required. For electricity generation, 3.38 quads of primary energy are assumed to be required for each quad of electrical energy consumed.

Carbon emissions by mode are summarized in Table 5.11. Light-duty vehicles account for the vast majority of carbon emissions reductions versus the business-as-usual case, with significant contributions also being made by trucks and commercial aircraft. Rail freight shows the greatest relative reduction, while emissions from shipping, military and "other" are essentially constant across the three scenarios.

Table 5.11 Carbon Emissions in 2010 (MtC)

	1997	2010		
		BAU	Efficiency	High-Efficiency
Light-Duty Vehicles	278.7	346.3	297.3	273.0
Freight Trucks	73.3	95.0	83.4	80.9
Freight Rail	8.9	9.6	8.1	7.1
Shipping	30.8	42.7	42.3	41.6
Air Transport	60.0	83.5	72.9	69.6
Military, Transit, Other	35.3	39.0	39.3	39.3
TOTAL	486.9	615.9	543.3	511.5

Note: Breakdown into modal carbon emissions based on emissions factors taken from EIA (1996d) and DOE (1996)

Most of the reduction in energy use and carbon emissions comes from light-duty highway vehicles. There are four reasons for this. First, light-duty vehicle technology has been far more intensively studied, so that a great deal more is known about the technological potential for this mode. Second, the level of expenditure on technology R&D is greatest for this mode, with the possible exception of aerospace R&D, including defense aerospace. Third, the commercial modes are believed to be more sensitive to fuel costs and more aggressive in the adoption of energy-efficient technology. Therefore, the rates of energy-efficiency improvement in the business-as-usual case are higher for these modes. Finally, light-duty vehicles simply use more energy than any other mode: 60% in the business-as-usual case. The other modes cannot be ignored, however, and should probably be given much greater attention with respect to R&D investment.

Although technological improvements have the potential to cost-effectively restrain greenhouse gas emissions from transportation, it is not likely that the changes will come about without a major public policy initiative. There are two reasons for this. First, the problems posed by greenhouse gas emissions are what economists term a classical public good externality. This means that the market economy will not provide the right price signals either for the development or the adoption of low-carbon technologies. Second, the AEO97 projections foresee a world where fossil fuels are abundant, available and inexpensive. In particular, none of the oil market upheavals of the past quarter century are present in the forecast. As a result, there are no other economic incentives to encourage either energy-efficiency or alternative fuels. In such an environment, it is not reasonable to expect either that appropriate technology will be developed or that success in the marketplace will result.

As a result, the efficiency case is based on the assumption that policies are implemented to promote the development of cost-effective low-carbon technologies and to spur the adoption of these technologies. In our view, this would include at a minimum a greatly increased public sector investment in R&D addressing energy-efficient and low greenhouse gas technologies, perhaps two to ten times the current level of effort. There are other public interests in developing such technologies (e.g., energy security and environmental sustainability) that, we believe, could easily justify such a level of investment. But policies to insure the adoption of low-carbon technologies in the market would also be necessary. It is not the purpose of this study to recommend what those policies should be; nonetheless, we are obliged to point out that meaningful policies will be necessary.

Indeed, technology has enormous potential to reduce transportation's greenhouse gas emissions. Cost-effective technological change will take time however, and its full effects will not be felt for two decades or more. Because the problems that may result from increased carbon emissions affect

the global environment, significant reductions will demand meaningful public policy initiatives. These must include a greater effort to develop low-carbon technologies and a commitment to implement policies that will insure their adoption in the market.

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ENDNOTES

¹ This rate applies to the period 1973 (18.605 trillion Btus) to 1985 (20.067 trillion Btus). Source is Table 2.2, Monthly Energy Review, April 1997, DOE/EIA-0035(97/04), U.S. Department of Energy, Energy Information Administration, Washington, DC.

² This is a summary report. The full report, which presents this material, was not published due to OTA's closure, but it is now available as part of a three-CD set that contains all of OTA's reports since its inception. U.S. Congress, Office of Technology Assessment, *OTA Legacy: 1972 through 1995*, U.S. Government Printing Office, Washington, DC, Stock no. 052-003-01457-2, \$23 U.S.

³ The Toyota AXV5, with a C_d of 0.20, appears to avoid sacrifices in interior and cargo space. Removing its wheel skirts, which might inhibit maintenance and restrict the vehicle's turning circle, would likely raise its C_d to about 0.22. Because the vehicle's underbody cover adds weight, the net positive effect on fuel economy will be reduced somewhat (U.S. Congress, OTA, 1995).

⁴ In particular, requirements for 0-60 mph acceleration and sustained gradeability.

⁵ Also referred to as compression ignition direct injection (CIDI) engines and turbocharged direct injection (TDI) diesel engines.

⁶ An accurate cost comparison would have to account for the transmission needed by the engine versus the electric motor needed to convert the fuel cell's output electricity into shaft power. Also, the fuel cell drivetrain may need a powerful battery to drive the vehicle until the cell can warm up.

⁷ At about 3700 psi storage pressure, storage volume for hydrogen is about 5 times that needed for gasoline (Oei, 1997).

⁸ An additional cost may be the loss in system efficiency associated with onboard reforming as well as the original refining of the gasoline. However, onboard hydrogen storage has energy costs in the form of hydrogen production (probably at a large scale, and more efficient than the onboard reformer) and pressurization if stored in high pressure tanks.

⁹ Despite what is implied in the NEMS Transportation Model documentation, we were informed by Mr. David Chien, principal in charge of the Transportation Model, that the model's calculations were in 1987\$. Thus, \$8 in 1995 dollars equates to approximately \$6 in 1987 dollars.

¹⁰ For carbon only; or \$.08-\$.16 per gallon if the tax applies to all greenhouse gases, on a carbon equivalent basis.

¹¹ Communication from Margaret Singh of Argonne National Laboratory, April 3, 1997. Her calculations were made using the August, 1993 version of M. A. Delucchi's greenhouse gas emissions model and exclude any vehicle efficiency gains which might occur with the use of an ethanol vehicle.

¹² An alternative approach would have been to introduce these technologies using the Transportation Model's alternative fuel vehicle capabilities. This approach was not taken on the grounds that diesel is more conventional than an alternative fuel. Consumers are familiar with it, it is widely available and, especially for the advanced, clean, TDI technology considered here, its performance would be essentially identical to that of a gasoline vehicle.

¹³ Actually, for an accurate comparison, an ICE plus a transmission and inexpensive fuel tank should be compared with a fuel cell, hydrogen storage or liquid fuel storage/reformer system, battery for warmup power and power buffer, and electric traction motor, making the task of commercializing fuel cells all the more onerous.

¹⁴ The Class 8 truck is very efficient already. Considering an energy per ton-mile measure of performance, an equivalent passenger car needs to travel about 140 miles on a gallon of gas to be as efficient as a 7 MPG Class 8 truck.

¹⁵ This technology is required for direct-injection gasoline engines as well.

Chapter 6

THE ELECTRICITY SECTOR'S RESPONSE TO END-USE EFFICIENCY CHANGES

6.1 INTRODUCTION

Electricity consumption accounts for about 36% of both total primary energy consumption and carbon emissions in the United States (EIA 1996a). As a consequence, converting efficiency-induced electricity savings in the residential, commercial, and industrial sectors into carbon reductions is a critical part of this study.

This task is complicated by several factors. First, the U.S. electricity industry is in the midst of a major restructuring, from a highly regulated, vertically integrated industry to a largely competitive, deintegrated industry. Because this transformation is far from complete, it is difficult to predict the structure and operation characteristics of electricity markets for the year 2010. Second, electricity production in the year 2010 will depend on the generating units that are retired, repowered, and constructed between now and then, as well as on how those units are operated in 2010. The decisions made by the profit-maximizing owners of individual generating units are likely to be different than the cost-minimizing decisions made in the past by utility owners of large generation and transmission systems. As a result of these changing dynamics of capacity expansion and system operation, one cannot assume that the average and marginal carbon intensities of electricity use (tonnes of carbon/GWh) will be the same in 2010 as they are today. Indeed, they are likely to be quite different. Third, electricity prices in the year 2010 are likely to vary from hour to hour based on current spot-market prices; consumer response to such time-varying prices is likely to be substantial but is largely unknown.

The next section describes some of the key changes in the structure of the U.S. bulk-power system that are likely to occur over the next decade. Section 6.3 describes the Oak Ridge Competitive Electricity Dispatch (ORCED) model that is used here to project the characteristics of the electricity sector in the year 2010. Section 6.4 compares ORCED's projections for the electricity sector with those developed by EIA in its *Annual Energy Outlook 1997* (AEO97). We then develop a competitive-electricity market case for 2010, which is used as the base case against which the efficiency and high-efficiency/low-carbon cases are compared.

6.2 BACKGROUND

In response to the 1992 Energy Policy Act, the Federal Energy Regulatory Commission (FERC) issued a major order (Order 888) in April 1996, which it slightly revised in March 1997. This order requires utilities to unbundle their generation and transmission services. A utility cannot offer preferential transmission pricing for electricity generated by its own power plants. A key purpose of this order is to eliminate problems associated with vertical market power in bulk-power markets and thereby assure open access to the nation's transmission facilities.

Other factors are also forcing the U.S. electricity industry to change. These factors include low natural gas prices (both today and over the next 10 to 15 years), substantial improvements in the efficiency of gas-fired combustion turbines, and broad public sentiment to deregulate economic sectors wherever possible.

We see a future in which the generation sector will be driven primarily by competitive forces rather than by regulatory mandates. Decisions on whether, when, and where to build, repower, or retire generating units will be made by investors, not by regulators.¹ Historically, vertically integrated utilities have planned, built, and operated power plants to minimize the life-cycle costs of the entire electric-power system over a long time (e.g., 20- to 30-year horizon). In tomorrow's competitive environment, this decision rule will be replaced by one that emphasizes the profitability of individual generating units over a much shorter time horizon, using a higher discount rate to reflect the increased riskiness of power-plant ownership.

Our view of the future calls for most of today's utility-operated control centers to be replaced by *independent* system operators (ISOs) that cover larger areas. As a consequence, the number of control areas will decline from about 140 to perhaps only 20 to 50. Because these ISOs perform a monopoly function, they will be regulated by FERC.

Similarly, transmission will remain a monopoly function, also regulated by FERC. Increasingly, transmission will be separated from generation. Today, FERC requires utilities to "functionally" unbundle generation from transmission. In the future, utilities will increasingly divest themselves of their generation assets and will become "pure" transmission or transmission-plus-distribution utilities. In this environment, transmission will become a common carrier.

6.3 MODEL DESCRIPTION

ORCED is an expanded version of part of a previously developed model called ORFIN (Oak Ridge Financial Model) (Hadley 1996). Whereas ORFIN is a comprehensive electric-utility planning model, ORCED deals only with generation. We developed ORCED to aid in the analysis of the operation of competitive (as opposed to the traditional regulated) bulk-power markets. The model allows the following issues to be examined:

- Horizontal market power: concentration of generation assets among a few owners;
- Generator profitability: which units will be retired because their expected revenues will not cover the sum of their fuel costs, variable operations and maintenance (O&M) costs, and (avoidable) fixed O&M costs, as well as repowering and new construction decisions;
- Carbon emissions and other environmental effects of changes in the U.S. bulk-power sector; and
- Optimal mix of new and existing generators, including new generating technologies.

The model is structured to allow simulation of different bulk-power market structures. In particular, the user can specify various generation pricing schemes:

- An energy-only spot price as proposed by the three California investor-owned electric utilities. When unconstrained demand exceeds available supply, what would otherwise be unserved energy is "curtailed" because spot prices rise sufficiently to suppress demand to match the level of available generating capacity. The user simulates this situation by specifying a value for the price elasticity of demand during these time periods. ORCED uses the amount of demand to be curtailed and the price elasticity to calculate the value of unserved energy in ¢/kWh .²
- An energy-only spot price plus the loss-of-load probability (capacity) component used in the United Kingdom. Here, the user specifies a value for unserved energy (e.g., 200¢/kWh), which

the model multiplies by the hourly value of the loss-of-load probability to produce a time-varying increment to the energy-only spot price.

- An energy-only spot price plus a capacity reservation price (in \$/kW-year), as proposed by the PJM Interconnection and the New England Power Pool. In this case, the user specifies an amount of generating capacity needed for planning reserve, which determines the annual capacity payments (in \$/kW-year) required.

We are using ORCED to examine the issues listed above as functions of the following factors (in addition to the pricing schemes noted above):

- Characteristics of individual generators: type of unit, differences in capital and other fixed costs (\$/kW-year) vs. fuel and variable O&M costs (¢/kWh), dispatchability (e.g., fully dispatchable coal plant vs. must-run nuclear unit vs. stochastic wind plant), forced and planned outage rates (%).
- Customer and load characteristics: shape of load curve, price elasticities of demand, value of unserved energy.
- Generating-resource portfolio: mix of generating units and relationship between available generating capacity and unconstrained peak demand.

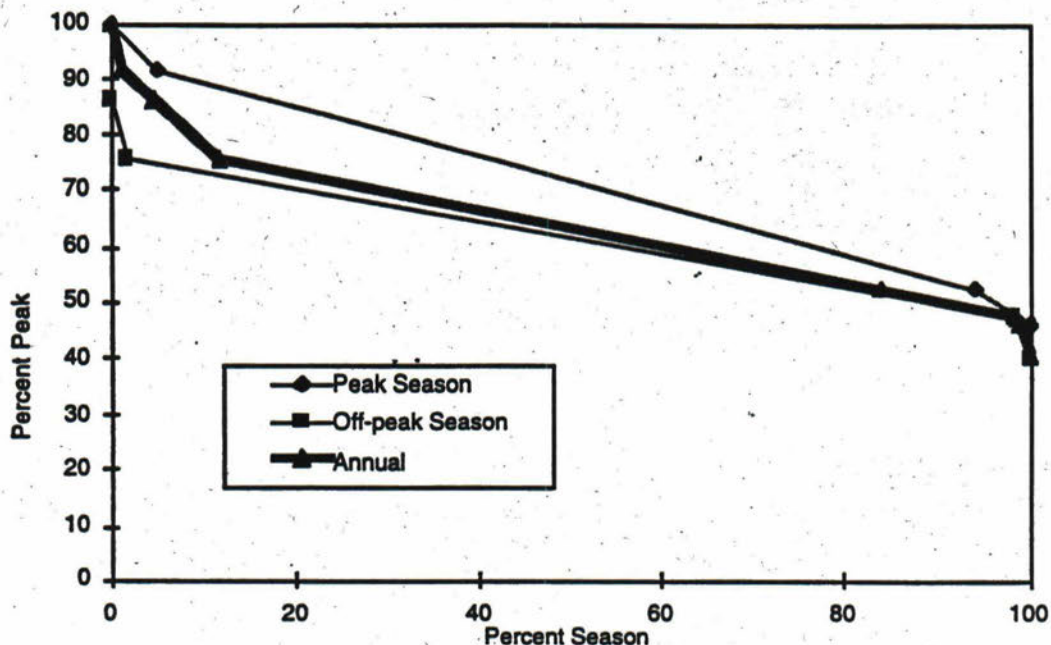
ORCED includes a production-costing model that uses load-duration curves rather than chronological loads as inputs. The model is run twice for each year of simulation, once for an on-peak season and a second time for an off-peak season (Figure 6.1). We define the on-peak season as June through August, and the off-peak season as the remaining nine months (September through May), although the model can accept alternative definitions of the two seasons. The model can incorporate disaggregate inputs on loads and load shapes for the residential, commercial, and industrial customer classes. Data on these class loads are aggregated for use within ORCED, which builds and dispatches generating units to meet aggregate load.

A load-duration curve is created by ordering demand (in MW) in terms of magnitude from highest to lowest. The resultant curve shows the percentage of time that demand exceeds a particular value, ranging from the one-hour peak demand down to the minimum demand.

Use of a load-duration curve to calculate production costs is much simpler and computationally much less burdensome than use of chronological loads (i.e., hour by hour loads). This simplification, however, has a price: because it obscures the timing of loads, one cannot accurately calculate production costs on the basis of generating-unit details, such as minimum and maximum loading points, startup times and costs, and minimum shutdown times. To partially remedy these problems, ORCED analyzes production costs using the two load-duration curves, one for the three-month summer peak period and the other for the nine-month off-peak period. ORCED also simulates the effects of startup costs for those units with capacity factors of less than 10%.

For each season, the model has available to it 26 generating units. The first 25 units are characterized in terms of capacity, forced and planned outage rates, fuel type, heat rate, variable O&M costs, fixed O&M costs, and annual capital costs (based on initial construction cost, year of completion, and capitalization structure). The 26th unit is an energy-limited hydro unit, for which the inputs include, in addition to those noted above, the plant's capacity factor (equivalent to its maximum energy output for the year). This treatment of hydro as energy-limited ensures that hydro displaces the most expensive energy (i.e., at the top of the load-duration curves).

Figure 6.1 Example Load-Duration Curves for Peak and Off-Peak Seasons



The model dispatches these 26 generating units separately for the two seasons. Although the calculation process is the same for the two seasons, the results differ because of differences in the load-duration curves and because all the planned maintenance is assumed to occur in the off-peak season.

The plants are first dispatched against the load-duration curve on the basis of bid price, the default for which is variable (fuel plus variable O&M) costs. (If the user bids a zero price for a unit, the generator is treated as a must-run unit and is dispatched first by the model.) Because plants are not available 100% of the time, we also model forced outages on a probabilistic basis.³ Thus, the higher-cost plants will see demands not only from customers, but "equivalent demands" based on the probability that plants lower in the dispatch order (i.e., less expensive) will be undergoing a forced outage. The model creates an equivalent load-duration curve for each plant, which extends the amount of time the plant runs based on the forced-outage rates of the plants lower in the dispatch order.

Model results include spot prices for each point on the two load-duration curves. These prices are based on the bid prices for each generator. The prices also reflect any externally imposed uplift charge, capacity charge, or emissions taxes. Finally, the prices during high-demand hours reflect generating-unit startup costs and the costs of unserved energy for those hours that unconstrained demand exceeds supply. See Appendix F for more details on the inputs and results from ORCED.

ORCED can be run iteratively to estimate the response of customers to changes in overall and time-of-use electricity prices. User inputs include an overall price elasticity of demand and a time-of-use elasticity. The overall price elasticity adjusts the entire load-duration curve up or down in response to decreases or increases in the average price of electricity. The time-of-use elasticity adjusts each point on the load-duration curve up or down based on price decreases or increases during that time period.

In addition, the model can use the time-of-use elasticity to compute the value of unserved energy (in ¢/kWh) that equilibrates supply and demand when unconstrained demand would otherwise exceed online supply. Alternatively, the user can input an estimate of the value of unserved energy, which is then used to calculate the costs associated with those times when unconstrained demand would exceed supply. A third approach involves user specification of a minimum reserve margin and associated annual capacity payment (in \$/kW-year) to pay for this "extra" capacity.

In addition to dispatching power plants and computing production costs, the model can also "optimize" the mix of generating units available for the year of analysis. (That is, the model includes a capacity-expansion module as well as a production-costing module.) We put optimize in quotes because the factor on which to optimize is almost certain to be different for a competitive electricity industry than it was for the regulated electric utility industry. For example, the model could choose from among the following optimization functions:

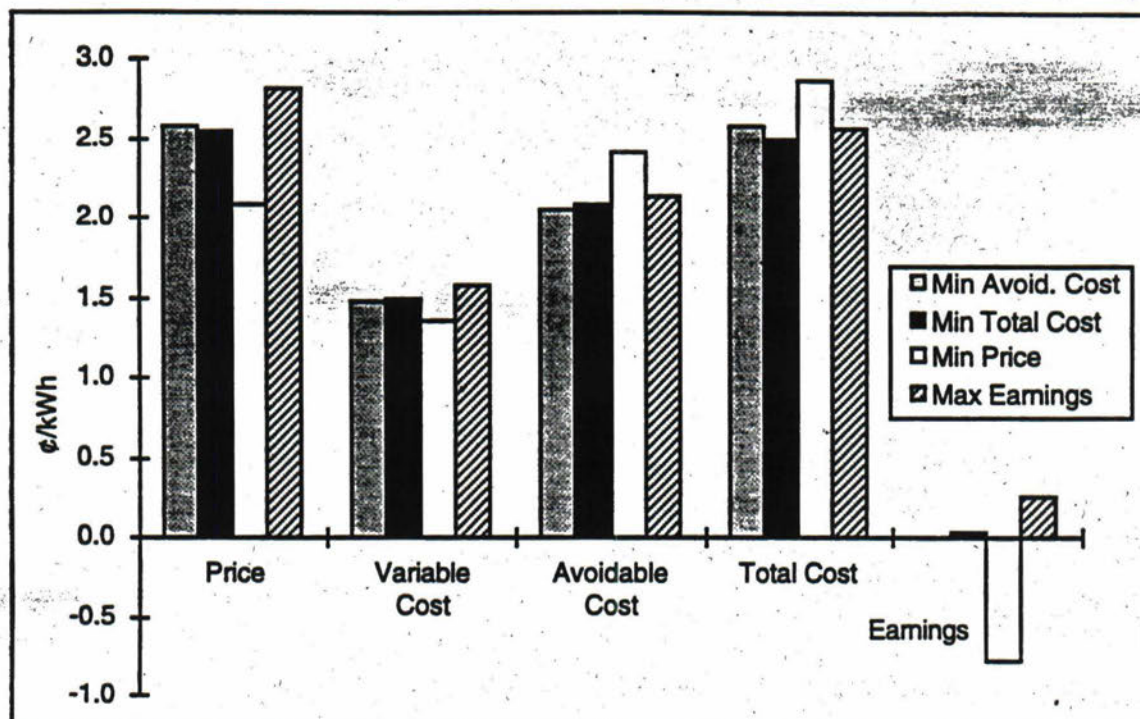
- Minimize total costs;
- Minimize avoidable costs (fuel, variable and fixed O&M);
- Minimize electricity prices; or
- Maximize generator earnings.

In Figure 6.2 we show the impact of different objective functions for optimization. Minimizing price does not necessarily minimize cost, because prices are based on the variable costs only and ignore fixed costs. Given choices of technology, ORCED would select low variable cost but high total cost technologies. Conversely, maximizing earnings does not raise total cost. Instead, the model selects high variable/low fixed cost technologies. For our analysis we chose to optimize on minimizing avoidable costs; we made this choice because it was conceptually the most appealing and the results were the most reasonable for a system-wide optimization. For plants not yet built, their capital costs as well as all operating costs are avoidable. Since no costs have been expended to build them, their construction costs are not "sunk" and can be avoided by not building them.

In addition to specifying the optimization function, the user can also specify constraints on individual generating units or the mix as a whole. For example, the user could set minimum and/or maximum capacity levels for each generator. Maximum levels could be specified for those units that were built earlier. Minimum levels could be specified for those units that must be available for policy reasons (e.g., renewable resources that might not be fully cost-effective but are deemed desirable from a broad societal perspective). Also, minimum levels for new plants may be specified to represent plants built between the current year and the study year. Otherwise, the model may choose not to build these intermediate plants, selecting only those with the most advanced technologies. Constraints could be specified for a minimum capacity reserve margin, for a maximum carbon emission allowance, or to ensure that each generating unit recovers at least its variable plus avoidable fixed costs, and so on.

Since ORCED is written in Microsoft Excel, there are several methods that can be used for optimization. The easiest is to use the built-in Solver tool. A single cell can be identified as the objective function to be minimized, and other cells can be identified as variables, with constraints placed on their values and/or other parameters within the spreadsheet. Since the problem is non-linear, Solver uses a Generalized Reduced Gradient method, running the model thousands of times searching for a solution. Another method, which is generally slower but avoids problems of local optima, is the use of genetic algorithms.

Figure 6.2 Generation Price and Costs Using Different Optimizations (10% Fixed Reserve Margin)



6.4 SCENARIOS FOR 2010

6.4.1 Calibration to EIA AEO97

Before analyzing the two end-use efficiency scenarios, we first calibrated ORCED results to those produced by EIA's NEMS model for 1995 and 2010. Unfortunately, reconciling the two sets of results to each other is difficult because of differences in the ways that the two modeling systems classify various costs (e.g., fuel, variable O&M, fixed O&M, and capital costs associated with generation) as well as EIA's inclusion of administrative and general (A&G) and customer service costs in the basic categories of generation, transmission, and distribution costs.⁴ Because of these difficulties, our numbers do not always match the EIA numbers exactly.

This calibration ensures that the assumptions concerning the mix of generating units, fuel prices, customer demand, environmental regulations, and so on are consistent between ORCED and those developed by EIA. For example, both sets of results assume the continuation of current economic and environmental policies affecting the U.S. electricity industry. However, EPA's proposed regulations to tighten standards for emissions of nitrogen oxides and small particulate matter are reflected in neither the EIA nor the ORCED results.

We first developed a base case for the year 2010 that includes the same mix of generating units (in both capacity and energy) as that produced by EIA, with the same reserve margin (11%), as shown in Table 6.1. In addition to data from the AEO97, we used other data from EIA (EIA 1996b, EIA 1996c, EIA 1995), as well as data from the North American Electric Reliability Council (NERC 1996), the Electric Power Research Institute (EPRI 1993), and a compilation of various official databases by Resource Data International, Inc. (RDI 1996).

Table 6.1 Comparison of Year 2010 AEO97 and ORCED Estimates of U.S. Generating Capacity and Generation

	Percent of generating capacity		Percent of generation	
	EIA	ORCED	EIA	ORCED
Hydro+other renewables	13.4	11.3	9.6	9.2
Coal	35.0	36.9	50.1	50.8
Nuclear	10.2	11.1	15.8	15.5
Oil	3.2	3.1	1.5	0.1
Gas	38.3	37.6	23.0	24.4

ORCED analyzes the generation sector only; the model is silent with respect to the costs of transmission, distribution, and customer service. ORCED produces the following cost estimates for 2010, all expressed in 1995 dollars and adjusted upward by 1/0.93 to reflect the 7% T&D losses between the generator busbar and the customer meter:⁵

Fuel	1.35
Variable O&M	0.18
Fixed O&M	0.51
Capital	1.00
Total	3.04¢/kWh

We developed an estimate of the EIA capital cost of generation by subtracting estimates of the capital costs associated with transmission, distribution, and administrative and general (A&G) services from EIA's total capital cost:

$$[2.32 - (0.52 + 1.46) * 0.63 - 0.08] = 1.00¢/kWh.^6$$

Total (Trans + Dist) A&G

Our estimate of the EIA fuel cost is based on the sum of EIA's fuel cost plus 88% of its wholesale purchase cost:

$$(0.98 + 0.67 * 0.88) = 1.57¢/kWh.^7$$

Fuel Wholesale

We used the ORCED estimates of fixed and variable O&M costs to impute a comparable (i.e., equal) value for EIA.

The net result is very close agreement between the ORCED and EIA scenarios for 2010 (Table 6.2). EIA's estimate of the total cost of generation (3.26¢/kWh) is 7% higher than the ORCED result (3.04¢/kWh). The ORCED cost is lower because ORCED dispatches fewer expensive oil-fired resources than does the EIA model (Table 6.1). These differences in dispatch and variable costs occur because ORCED dispatches generation nationwide and ignores transmission constraints. The close agreement between EIA and ORCED results, in spite of all the adjustments required to produce a set of internally consistent and comparably defined terms, is reassuring. It lends confidence to our

development of alternative cases in which we intended to reflect more fully than EIA did the effects of competition in bulk-power markets.

Table 6.2 Comparison of EIA and ORCED Estimates of Generation Costs (1995¢/kWh)

Generation costs	EIA AEO97	ORCED
Capital	1.00	0.99
Fuel	1.57	1.36
O&M	0.69	0.69
Total	3.26	3.04

6.4.2 The Base Case for a Competitive Market

Beginning with the AEO97 case, we developed a case intended to reflect the workings of a fully competitive bulk-power market in the year 2010. (The AEO assumes a continuation of current economic regulation, as indicated above, and therefore does not account for the possible effects of a restructured and largely competitive U.S. electricity industry.) To reflect these changes, we let the model select the amounts of each of the generating units that minimize the sum of variable plus avoidable costs. Instead of specifying the amount of generating capacity that must be online in 2010 (to yield a 10.7% reserve margin in the AEO97 case), we allowed the model to select the amount of capacity that minimized the cost of the power-supply system plus the cost of unserved energy. We used a demand elasticity of -0.05 for those time periods when capacity is insufficient to meet unconstrained demand. The resultant optimization yielded a reserve margin of 6.8%.

In general, we set prices equal to their real-time (hourly) values based on the variable (fuel plus variable O&M) cost of the unit on the margin each hour of the year, adjusted overall electricity demand to reflect lower prices using an assumed overall elasticity of -0.5, and adjusted the load shape to reflect the response to real-time pricing using a value of -0.1 for the price elasticity within each time period.

Beginning with the ORCED run that matches the AEO97 values for 2010, we first reran the model allowing it to select the "optimal" amounts of generating capacity from among all the plants that, according to EIA, are scheduled to come online after the year 1998. (The optimization was based on a minimization of avoidable costs.) We also allowed the model to select plants for retirement. For each of the new plants, we use the levelized fixed charges rate to calculate the annual capital cost of the plant and treat all fixed costs (both capital and O&M) as avoidable.

Next, we adjusted the load-duration curves for the two seasons simulated by the model (peak and off-peak). The new system load has a peak demand that is 3.4% below the AEO97 case and a total demand that is 1.2% higher. We then reran ORCED using the new load shapes. Table 6.3 compares the two sets of results. Although demand is higher in the restructuring case than in the AEO97 base case, carbon emissions are lower. The lower carbon emissions are the result of reduced coal use and increased natural gas use in the restructuring case.

Notice that, under restructuring, the total generating cost goes down 0.3¢/kWh and yet the system average price increases slightly. In a deregulated market, prices will be based on the variable cost (or bid price) of the most expensive plant at that time. This is known as the "market clearing price." Consequently, the link between total costs and prices is broken. Whereas current electric utility

regulation sets prices to recover total costs, future prices may, or may not, be sufficient to recover all costs.

Overall, ORCED prices under restructuring did not differ greatly from the AEO97 price forecast. Part of the reason for this similarity of results is that EIA did assume some cost decreases in their model; we did not assume further O&M cost decreases on a plant-by-plant basis due to the pressure of competition. Also, the objective function used in our cases was to minimize avoidable costs on a system-wide basis. This did not necessarily create the lowest-priced scenario, as discussed in section 6.3. Because prices were similar to those in the AEO97 (less than 5% difference when factoring in transmission and distribution prices), we simply used the AEO97 price forecasts for analysis of energy-efficiency savings in the other chapters of this report.

Table 6.3 Comparison of Year 2010-Forecasts: AEO97 and the ORCED Base Case for a Competitive Electricity Industry

	AEO97	Competitive Industry Restructuring
Peak demand, GW	734	709
Total end-use electricity sales, TWh	3,784	3,828
System load factor, %	62.8	65.7
Reserve margin, %	10.7	6.8
Generation shares, %		
Coal	50.8	47.4
Gas	24.4	29.2
Other	24.8	23.4
Generation prices and costs, ¢/kWh		
Retail price	3.04	3.02
Variable cost	1.43	1.45
Total cost	2.81	2.51
Carbon emissions, MtC	631	625

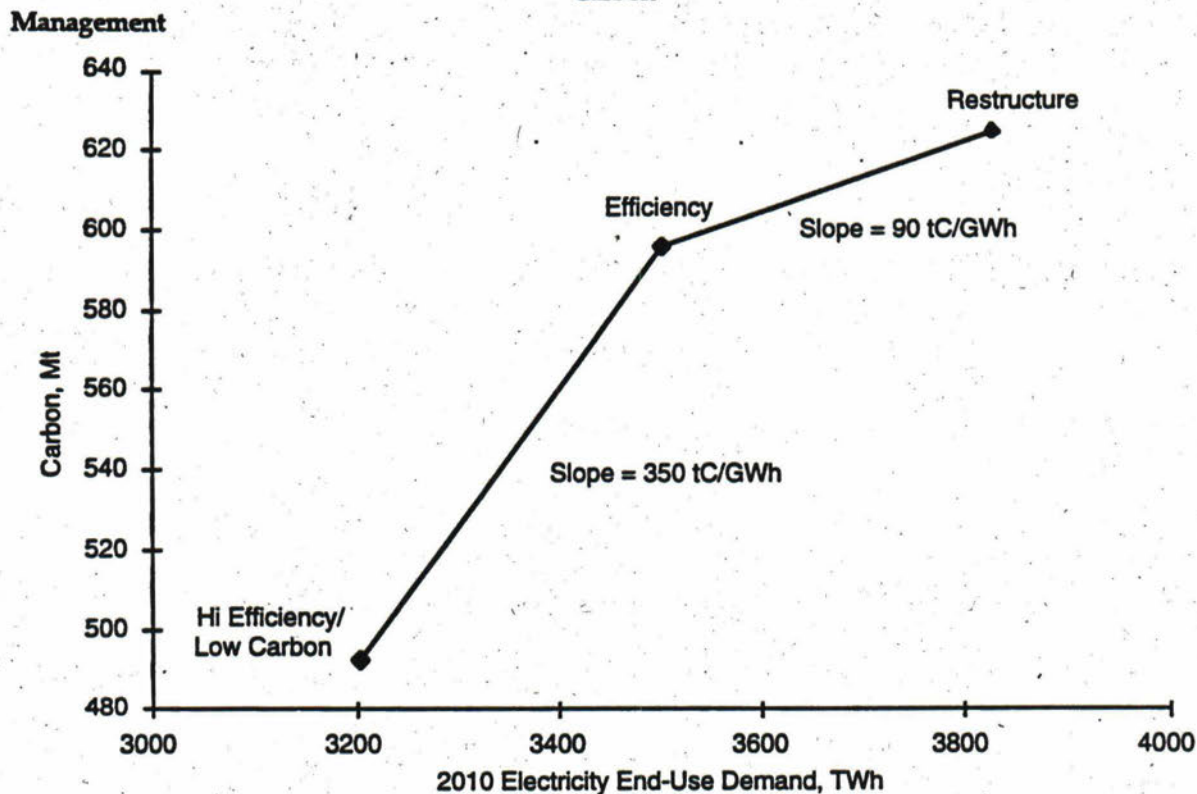
6.4.3 Efficiency and High-Efficiency/Low-Carbon Cases

We next applied the electricity-savings estimates, described in Chapter 3 for the residential and commercial sectors and in Chapter 4 for the industrial sector, to adjust the aggregate load shape for the United States as a whole. We then reran ORCED using the new, lower load shapes. As in the reference case, capacity was optimized to minimize avoided costs, and dispatched on the basis of lowest variable costs. Avoided costs for existing plants only included their variable, start-up, and fixed O&M costs, while plants to be built between 1997 and 2010 also included the annualized capital cost of their construction. As part of the high-efficiency/low-carbon case, we included an additional cost of \$50 per tonne of carbon, to be consistent with the rationale used in the demand-side efficiency scenarios.

Once power plant production levels were determined, carbon production and primary energy use could be calculated. We calculated marginal carbon savings, the carbon saved by the reduction in energy, by taking the difference in carbon production and dividing by the reduction in energy demand. This is in contrast to using the average carbon intensity as an approximation of the carbon saved per unit of energy saved. The marginal carbon and energy savings take into account the change in production mix that occurs with energy-efficiency and carbon-reduction measures. A plot of the carbon savings and primary energy used in each scenario shows the changes as a function of the end-use energy saved (Figures 6.3 and 6.4). The slopes of the lines represent the marginal carbon and primary energy saved.

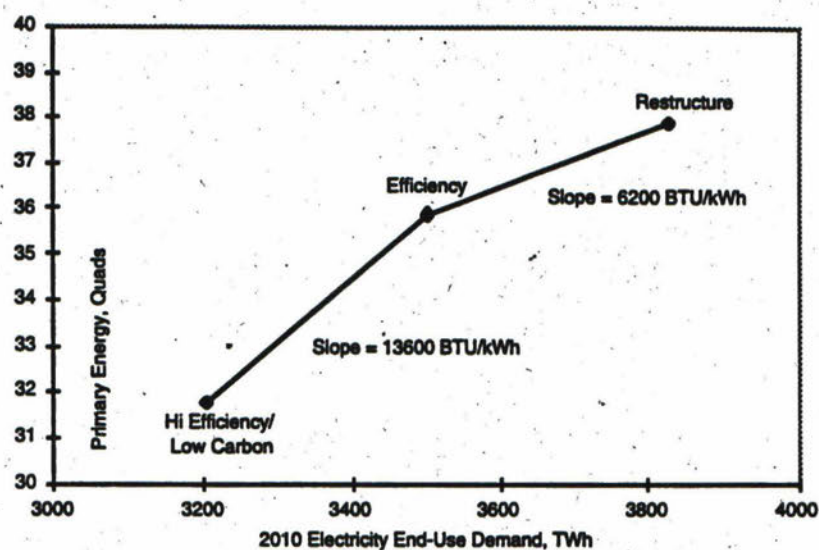
Table 6.4 summarizes the results for the three scenarios. Table 6.5 describes these results in terms of percent change relative to the base case for a competitive utility industry. The efficiency case yielded a 8.5% reduction in electricity end-use energy and the high-efficiency/low-carbon case reduced end-use energy by 16.3% relative to the restructuring case summarized in Table 6.3.

Figure 6.3 Carbon Production Versus End-Use Demand: Reductions Due to Energy Efficiency and Carbon



Note: Slope is equal to marginal carbon savings in tonnes of carbon per gigawatt-hour.

Figure 6.4 Primary Energy Production Versus End-Use Demand: Reductions Due to Energy Efficiency and Carbon Management



Note: Slope is equal to marginal energy savings in Btu per kilowatt-hour.

Table 6.4 Comparison of Year 2010 Forecasts: Results of Efficiency and High-Efficiency/Low-Carbon Scenarios

	Competitive Industry Optimization	Efficiency	High-Efficiency/ Low-Carbon
Peak demand, GW	709	651	596
Total Primary Energy used, quads	37.9	35.9	31.8
Total electricity generated, TWh	4,090	3,740	3,420
Total end-use electricity demand, TWh	3,830	3,500	3,200
System load factor, %	65.7	65.5	65.5
Reserve margin, %	6.8	7.9	12.9
Generation shares, %			
Coal	47.4	52.1	46.2
Gas	29.2	22.2	26.0
Other	23.4	25.7	27.8
Generation prices and costs, ¢/kWh			
Retail price	3.02	3.03	3.66
Variable cost	1.45	1.43	2.07
Total cost	2.51	2.46	3.21
Carbon emissions, MtC	625	596	492
Average carbon emissions, kg/MWh	163	170	154
Marginal carbon saved, kg/MWh	—	89	350

Table 6.5 Comparison of Year 2010 Forecasts: Effects of Efficiency and High-Efficiency/Low-Carbon Scenarios

	Change relative to the competitive utility industry base case	
	Efficiency	High Efficiency/Low Carbon
Peak demand	-8.2%	-16.0%
Total energy	-8.5%	-16.3%
System load factor	-0.2% points	-0.2% points
Reserve margin	+1.1% points	+6.1% points
Generation shares		
Coal	+4.7% points	-1.2% points
Gas	-7.0% points	-3.2% points
Other	+2.3% points	+4.4% points
Generation prices and costs		
Retail price	+1%	+21%
Variable cost	-1%	+43%
Total cost	-2%	+28%
Carbon emissions	-4.6%	-21.2%

The efficiency scenario forecasts a lower percentage reduction in carbon (4.6%) than in end-use energy (8.5%) (Figure 6.5). The difference occurs because lower end-use demands translate into less construction and operation of high-efficiency gas-fired combustion turbines and combined-cycle units (Figure 6.6). (Because of their high capital costs, ORCED selects only the minimum amounts of advanced coal and renewable technologies in the base restructuring case.) In the efficiency case, relative to the restructuring case, capacity and generation for combined-cycle units declines by about 27%; capacity for combustion turbines drops 28% (generation drops by 68%); and coal and gas-powered steam plants actually increase their production slightly.

Identification of high-efficiency gas-fired combustion turbines and combined-cycle units as the marginal plants under consideration has the effect of substantially lowering the avoided carbon from electric efficiency improvements. The forecasts contained in AEO97 are consistent with this assumption through the year 2010. For example, page 49 of the AEO97 states that, "of the new capacity [required through 2015], 81 percent is projected to be combined-cycle or combustion turbine technology fueled by natural gas or both oil and gas."

In contrast, the HE/LC case forecasts a higher percentage reduction in carbon (21.2%) than in end-use energy (16.3%). This is because the inclusion of the charge of \$50 per tonne of carbon changes the mix of technologies used to produce electricity so that low-carbon supply options are favored. Over 16% of the coal capacity is retired in this scenario, and the remaining, more-efficient coal plants operate at a lower capacity factor. Overall, generation from coal declines 18% compared to the reference case. Capacity from combined cycle plants actually increases over the amount in the efficiency case, but still has a 14% decline from the reference case. Combustion turbine generation declines 84% from the reference case while combined cycle generation declines only 13%.

Figure 6.5 Energy and Carbon Changes from Restructure Case

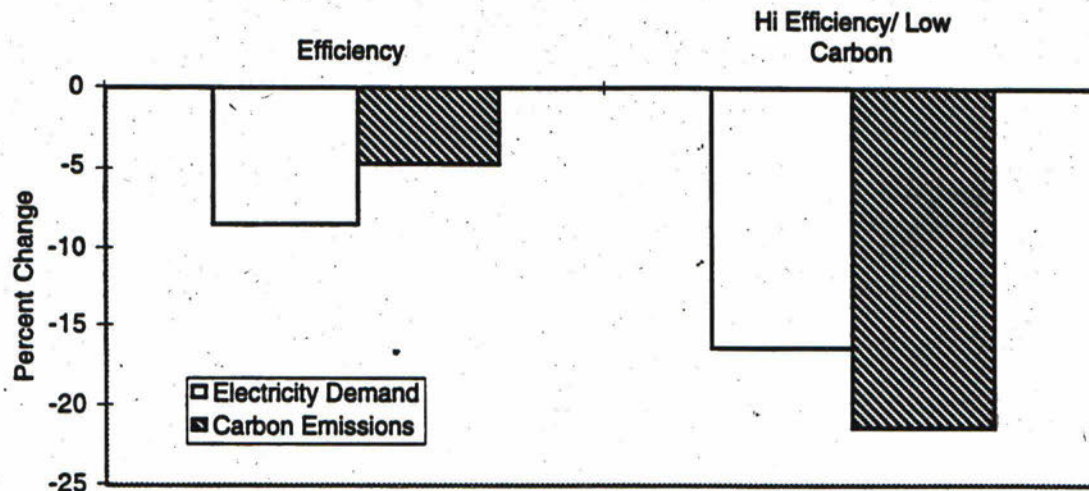
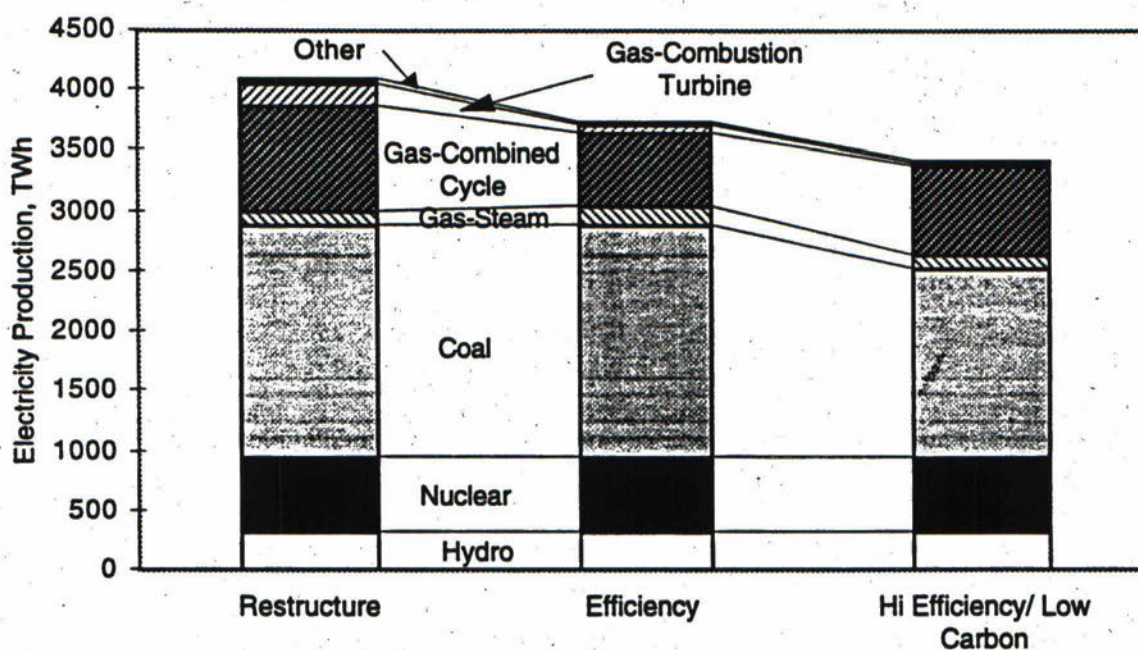


Figure 6.6 Generation by Technology Under Each Scenario



Compared to the reference case, generating prices and costs remain about the same under the efficiency scenario. In the HE/LC scenario, prices and costs increase about two-thirds of a cent because of the additional charge of \$50/tonne of carbon. This carbon charge represents a 1.4¢/kWh increase to the more expensive coal plants, but only a 0.5¢/kWh increase to the better gas-fired combined cycle plants. ORCED redispatched and changed capacities so that the cost increase would be minimized. Note that, although the generation price increases by 21%, the price of generation

represents only about half of the total price of electricity. Keeping transmission, distribution, and customer service prices the same, the total price increase would be only 10%.

Because electricity prices are essentially unchanged under the efficiency scenario (changing from only 6.20¢/kWh to 6.22¢/kWh including other components), total electricity costs to consumers decrease by an amount that is proportionate to the reduced electricity demand (i.e., 330 TWh). Thus, the cost reduction is approximately \$20 billion. This value takes into account the savings in transmission, distribution, and customer service costs included in the full retail price of electricity. The high-efficiency/low-carbon case yields slightly lower savings of around \$18 billion. Total energy savings almost double to 630 TWh, but the price increase of 0.65¢/kWh due to the carbon charge cuts into the overall savings.

One way to measure the cost impact of the \$50/tonne of carbon cost is to evaluate the extra cost due to plant operation changes (redispatch, retirements, and new construction). In the high-efficiency/low-carbon case, we construct and operate the plants as optimized with the carbon charge. If we remove the charge, but construct and dispatch plants as in the high-efficiency/low-carbon case, we are no longer operating at minimum cost. The excess above the minimum cost is about \$2.2 billion. Dividing this amount by the tons of carbon saved from the minimum-cost case yields an average cost of \$30 per tonne of carbon saved.

Allocating the carbon savings in the efficiency case between the buildings and industrial sectors, we find that the buildings sector (residential and commercial) saved 19.4 Mt of carbon while the industrial sector saved 9.6 Mt (Table 6.6). The carbon savings for each were proportional to their savings in electricity, since electric generation is determined by the system load.

Table 6.6 Carbon Reductions from Electricity Savings by Sector under the Efficiency and High-Efficiency/Low-Carbon Cases (MtC)

Sector	Efficiency Case	High-Efficiency/Low-Carbon Case
Buildings (Residential)	10.9	49.2
Buildings (Commercial)	8.5	38.3
Industry	9.6	45.0
Total	29.0	132.5

Note: Transport is not included since electricity use in that sector is negligible.

Some of the 133 Mt of carbon that is forecast to be displaced by the high-efficiency/low-carbon case can be attributed to the end-use efficiency improvements in the buildings and industrial sectors. The remaining savings are attributed to the change in electricity generation mix that resulted from the charge of \$50/tonne of carbon. Two methods of allocating the carbon savings between the end-use and supply sectors were examined.

- In the first method, ORCED modeled the high-efficiency/low-carbon case without the \$50/tonne charge in the supply sector. The result was a savings of 56 MtC, attributed to energy efficiency alone. The rest of the carbon savings (77 MtC) is then attributed to the electricity sector.
- In the second method, ORCED modeled the restructure case with the \$50/tonne charge in the supply sector, but without the demand reduction due to efficiency improvements. The result was a savings of 33 MtC, which is attributed to the electricity sector. The rest of the carbon savings (100 MtC) is attributed to the end-use sectors based on their energy savings.

The results of these alternative allocations (including the distribution of carbon savings across the buildings and industrial sectors) are shown in Table 6.7 and Figure 6.7. The total carbon that is displaced by the lower electricity demand is the same (133 MtC), but the allocation between the end-use and supply sectors varies widely depending on the method used to allocate the savings.

Because the savings involve a synergy between increased energy efficiency and changes to supply dispatching, it is difficult to identify the appropriate allocation of savings for the end-use vs. electricity supply sectors. To simplify matters, we used the average between the two methods described above. Specifically, the following averaging was used:

- The minimum carbon reduction attributed to electricity end-use efficiencies is 56 MtC (Method 1) and the maximum is 100 MtC (Method 2). The average of 78 MtC is therefore assumed for the end-use sector.
- The minimum carbon reduction attributed to the electricity sector is 33 MtC (Method 2) and the maximum is 77 MtC (Method 1). The average of 55 MtC is therefore assumed for the electricity supply sector.

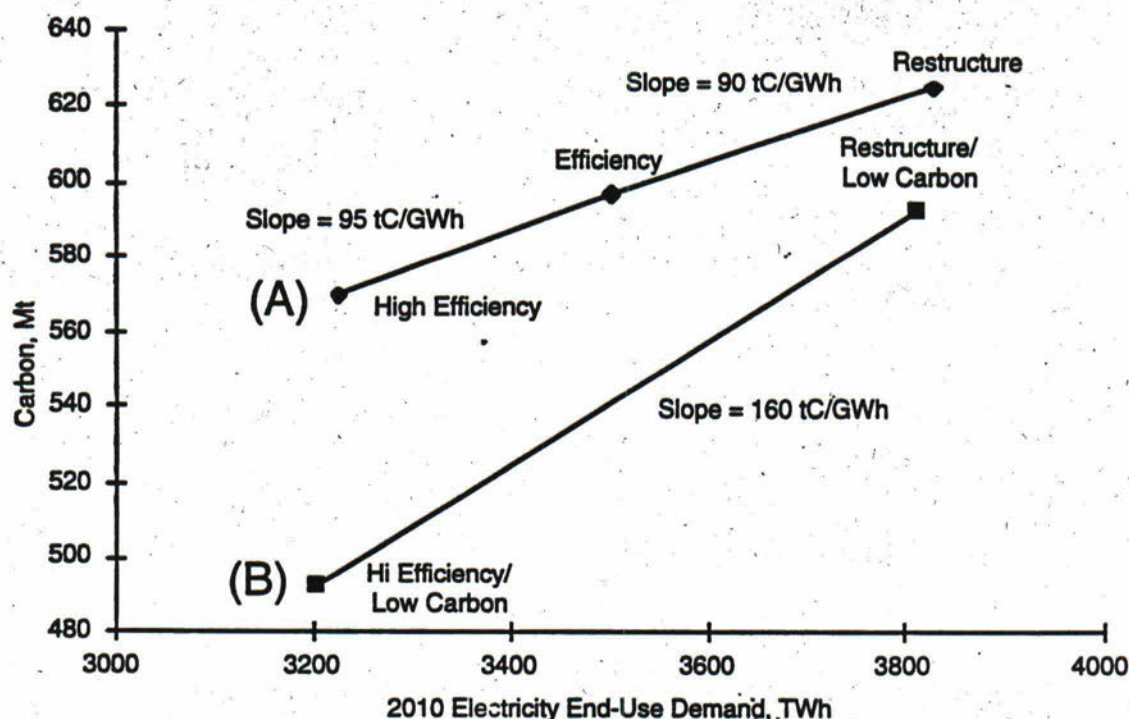
Table 6.7 summarizes this allocation process.

Table 6.7 Allocation of Carbon Reductions from the Electricity Saved by the High-Efficiency/Low-Carbon Case (MtC)

Sector	Method 1: Carbon Reduced by Energy Efficiency First	Method 2: Carbon Reduced by \$50/tC Charge First	Final Allocation by Averaging
Buildings (Residential)	21	37	29
Buildings (Commercial)	16	29	22
Industry	19	34	27
<i>Subtotal</i>	56	100	78
Electricity Sector	77	33	55
Total	133	133	133

Based on the results shown in Figure 6.7, 160 tonnes of carbon are displaced for each GWh of electricity saved in the high-efficiency/low-carbon case with carbon permit price of \$50/tonne, reflecting the introduction of new low-carbon technologies. This is the marginal carbon-to-energy ratio that is therefore used for analyzing the impacts of other carbon management strategies in the electricity sector in Chapter 7. This value is significantly higher than the marginal carbon-to-energy ratio used in the efficiency case (90 tonnes of carbon per GWh of electricity, as also shown in Figure 6.3), for the reasons noted earlier.

Figure 6.7 Carbon Reductions Due to Energy Efficiency and Carbon Management: (A) Without a Carbon Charge and (B) With a Carbon Charge of \$50/Tonne



Note: Slope is equal to marginal carbon savings in tonnes of carbon per gigawatt-hour. In (A), the high-efficiency option represents all the assumptions of the high-efficiency/low-carbon scenario except that there is no charge for carbon.

6.5 SUMMARY

The U.S. electricity industry is undergoing massive change. Because the process is far from complete, it is even more difficult to make estimates about electricity production and use for the year 2010 than it would otherwise be. However, we developed a reasonable and internally consistent picture of electricity demand and supply for the year 2010 on the basis of EIA's AEO97 projection and additional simulations with the Oak Ridge Competitive Electricity Dispatch (ORCED) model.

ORCED was used to simulate the operation of the U.S. electric power supply system in 2010. We first calibrated our input data so that our results closely matched those produced by EIA for its *Annual Energy Outlook 1997*. We then developed a case for 2010 that is intended to reflect the ways in which a fully competitive industry might operate. Compared to the AEO97, these results suggest greater electricity use, lower peak demand, and a generation mix that includes more natural gas and less coal. Thus, although consumption is higher, carbon emissions are lower.

We then simulated the operation of this competitive electricity industry given the efficiency-induced reductions in electricity use in the residential, commercial, and industrial sectors as described in Chapters 3 and 4. The efficiency case reduced electricity demand by 9%, which led to a 5% reduction in carbon emissions. The high-efficiency/low-carbon case reduced electricity use by 16%, which led to a 21% reduction in carbon emissions.

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ENDNOTES

- ¹ States will continue to oversee power-plant siting and environmental emissions.
- ² The value of unserved energy is the price that customers would be willing to pay for electricity that is unavailable as a result of demand exceeding supply.
- ³ The amount of computer time required for a full simulation depends strongly on the number of generators treated probabilistically. We found a reasonable tradeoff between computing time and accuracy when about 10 plants are modeled probabilistically and the other 16 are derated.
- ⁴ Inclusion or exclusion of the data for cogenerators (which account for about 4% of electricity in the year 2010) is another source of confusion.
- ⁵ According to AEO97, total generation in 1995 was 3246 billion kWh and sales totaled 3008 billion kWh, implying a loss of 7.3%.
- ⁶ The 63% multiplier for T&D represents the percentage of T&D costs attributable to capital as opposed to O&M.
- ⁷ This 88% multiplier is derived from ORCED's estimates of fuel and O&M costs of 1.35¢/kWh for fuel and 0.18 ¢/kWh for O&M. The 88% then is $[=1.35/(1.35+0.18)]$.

Chapter 7

ELECTRICITY SUPPLY TECHNOLOGIES

7.1 INTRODUCTION

The electricity industry has many supply-side options at its disposal to reduce or offset carbon dioxide emissions from electricity production by the year 2010. One of these options, reconfiguring the generation mix to reflect a \$50/tonne charge for carbon, was discussed in Chapter 6. We labeled this option "carbon-ordered dispatching" because it involves the same technologies that were considered in the AEO97 reference case. Electricity was redispatched from the existing generation mix, and the construction and retirement of power plants also changed, but no new technologies were introduced. Chapter 7 considers other electricity supply technology options, including:

- Repowering coal-based power plants with natural gas;
- Implementing renewable electricity technologies;
- Improving efficiency in generation and transmission and distribution (T&D) systems;
- Extending the life of existing nuclear plants; and
- Constructing new power plants using advanced coal technologies.

Each of these options is assessed independently. Because interactions among the options are not taken into account, there is a likely possibility of double-counting with respect to the actual emissions reduction potential.

The viability and costs of these supply options in 2010 are based on the assumption that the electricity grid is transformed by the carbon-ordered dispatching that occurs under the "high-efficiency/low-carbon" (HE/LC) scenario, as described in Chapter 6. Thus, since we assume that considerable decarbonization has already taken place, this chapter addresses the question: What additional supply technology options now make sense in a scenario in which carbon has acquired a value of \$50/tonne? We conclude by discussing the significant contribution that renewable energy technologies can make by the year 2020.

7.2 REPOWERING COAL-BASED POWER PLANTS WITH NATURAL GAS

The conversion of existing coal-fired power plants to operate on natural gas (via repowering) is one option to significantly increase the efficiency of power generation and reduce carbon emissions in the U.S. electric power sector.¹ Natural gas is a less carbon-intensive fuel and its use also reduces emissions of the following criteria air pollutants: sulfur dioxide (SO₂), nitrogen oxide (NO_x), total suspended particulates (TSP), and hazardous air pollutants (HAPs). Our analysis shows that natural gas combined cycle (NGCC) is a cost-effective power generation technology and carbon emission reduction option. Depending upon assumptions regarding the differential in the delivered price between natural gas and coal, the price of carbon permits, and environmental externality values for criteria air pollutants, we found that carbon emissions of up to 238 MtC could be reduced annually through repowering.

7.2.1 Repowering Approaches

The simplest repowering approach is *site repowering*, where the existing power plant site is reused with an entirely new NGCC system. Cost and performance data for the General Electric "H" frame turbine was used; this class of turbine will be the most efficient in the post-2000 period, with the lowest cost per kilowatt of capacity. While site repowering provides the highest cycle efficiency (since none of the existing boiler island equipment is reused), it also requires a greater capital investment (see Appendix G-1).

The more conventional approach is referred to as *steam turbine repowering*. In this case, a new gas turbine and heat recovery steam generator (HRSG) are integrated with the existing steam turbine and auxiliary equipment from the coal plant. Due to age of equipment and the fact that the steam turbine was designed for linkage with a coal-fired boiler, the efficiency of a *repowered* steam turbine plant would be lower than at a *site repowered* plant. The steam turbine repowering option has a higher operating cost (due to the lower efficiency) but a lower capital cost (see Appendix G-1).

The cost-effectiveness (\$/tC) of both repowering options was examined for all coal-fired power plants greater than 50 megawatts (MW).² Included in the cost calculation were the cost of repowering, hook-up, and transmission. We analyzed the site repowering results for the two alternative gas/coal price differentials: \$0.72 and \$1.18 per million Btu (MBtu)³, three price ranges for carbon permits (<\$50/tonne, \$50-100/tonne, and \$101-150/tonne), and three environmental externality values for SO₂ and NO_x (none, low, and high). In addition, a sensitivity analysis was performed to examine the impact on cost-effectiveness if additional natural gas pipeline infrastructure (hook-up and transmission) were not needed to ensure gas deliverability to repowered plants. This sensitivity analysis (referred to as the "no additional transmission cost" case) was conducted only for those power plants that are currently connected to the natural gas pipeline network (i.e., dual-fuel). Appendix G-3 contains a complete description of the methodological steps and key data parameters.

The analytical approach was static in that the cost of repowering was computed for each candidate power plant but the analysis did not optimize unit/plant production cost, dispatch, or system load. Moreover, for the steam repowering case, the largest steam turbine (not each individual steam turbine) at the plant was repowered to generate the equivalent of 1995 plant output (kilowatt-hours, kWh), since this is both more economic and consistent with industry practice than repowering each turbine. Lastly, the gas delivery infrastructure costs (hook-up and transmission) were derived assuming (1) no excess capacity in the current delivery system, and (2) that if such a fuel-switching strategy were implemented, the natural gas pipeline industry would build capacity (even if done incrementally) to meet the total estimated gas requirements of repowering all candidate plants and allocate appropriate delivery costs to each repowered plant. Assumptions regarding gas deliverability are described below in Section 7.2.2.2.

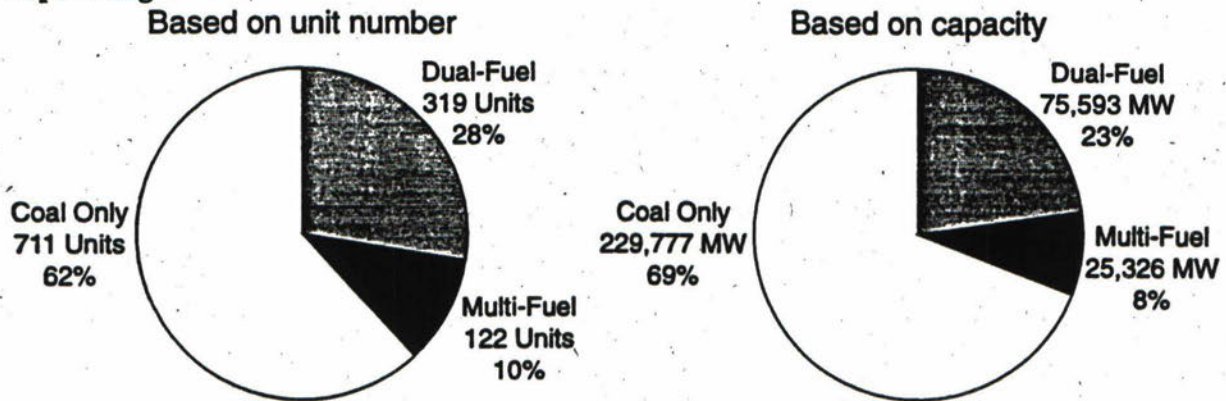
7.2.2 Repowering Issues

In 1995, there was 335 GW of coal-fired capacity at 404 power plants in the United States. Figure 7.1 indicates that this capacity was comprised of:

- 319 dual-fuel units (units that can burn both coal and natural gas),
- 122 multi-fuel units (coal-fired units at sites with natural gas or petroleum units), and
- 711 coal-fired units (units at coal-only plant sites).

Figure 7.1 Candidate Coal-Fired Power Plants for NGCC

Repowering



These categories reflect differences in the investment cost of conversion and deliverability of natural gas (i.e., those plant sites consuming gas in 1995 would have a natural gas pipeline connection, thereby resulting in a lower hookup cost.)

7.2.2.1 Increase in Natural Gas Demand

Utility gas consumption in 1995 was 3.5 trillion cubic feet (TCF). Figures 7.2 and 7.3 show the increases in natural gas demand from this base that would result from either site or steam turbine repowering for each of three cost-effectiveness values: less than \$50/tC, \$50-100/tC, and greater than \$150/tC. The increase in gas demand ranges from 1.0 TCF (<\$50/tC) to 4.9 TCF (\$50-100/tC) in the low gas/coal price differential case without externalities. This quantity of gas for repowered plants represents 29% and 140% increases in 1995 utility gas consumption, respectively.

If all the candidate coal-fired power plants were repowered with NGCC, natural gas demand in the utility sector would increase by 9.0 TCF/yr (site repowering) or 9.4 TCF/yr (steam turbine repowering) to either 12.5 TCF/yr or 12.9 TCF/yr, respectively, an increase of over 250% compared to current consumption levels.

The potential gas price increase resulting from NGCC repowered plants was not analyzed in this study. Only the current and projected gas/coal price differentials expected under AEO97 were included in the cost analysis. However, EIA has prepared a preliminary estimate; they found that an 11 TCF increase in demand would increase natural gas prices by \$3.09/MBtu over 20 years (1995-2015), if coal-fired power plants were converted to natural gas when scheduled for life extension/refurbishment and there was considerable demand-side energy-efficiency investment.

Figure 7.2 Incremental Increase in Gas Consumption Resulting from Coal to Gas Conversion with Constant 1995 Gas/Coal Price Differential (\$0.72/MBtu)

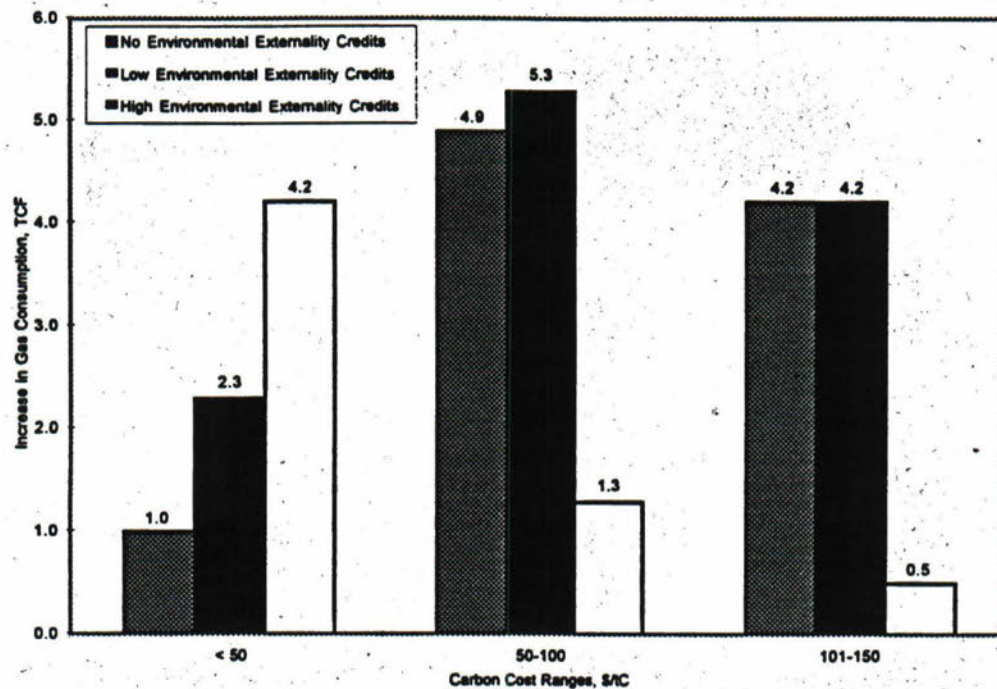
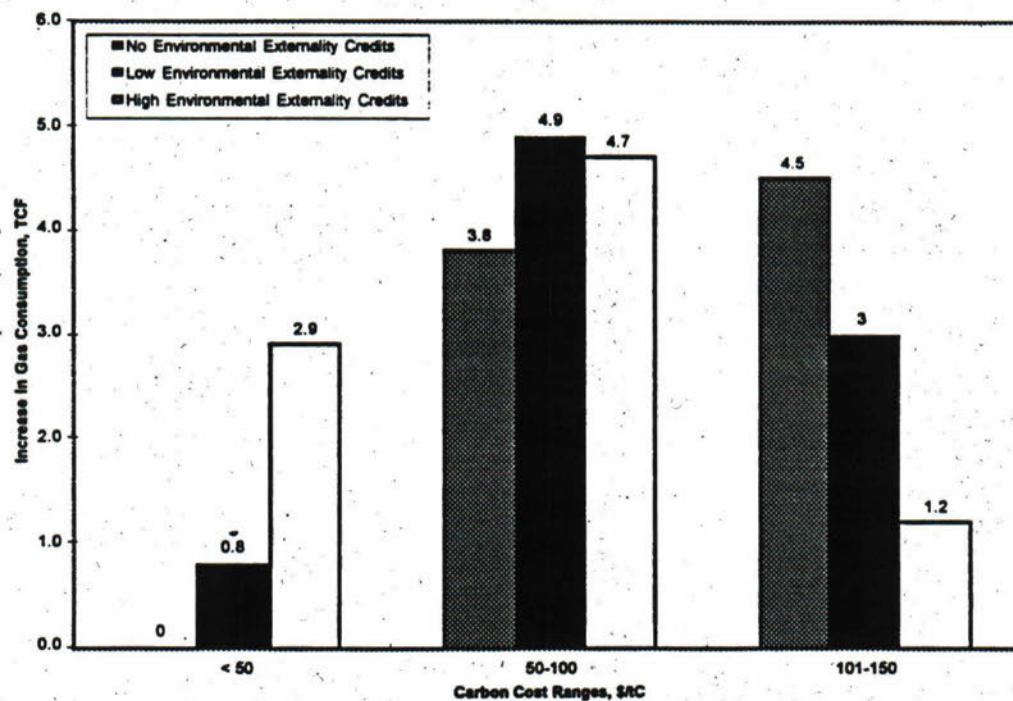


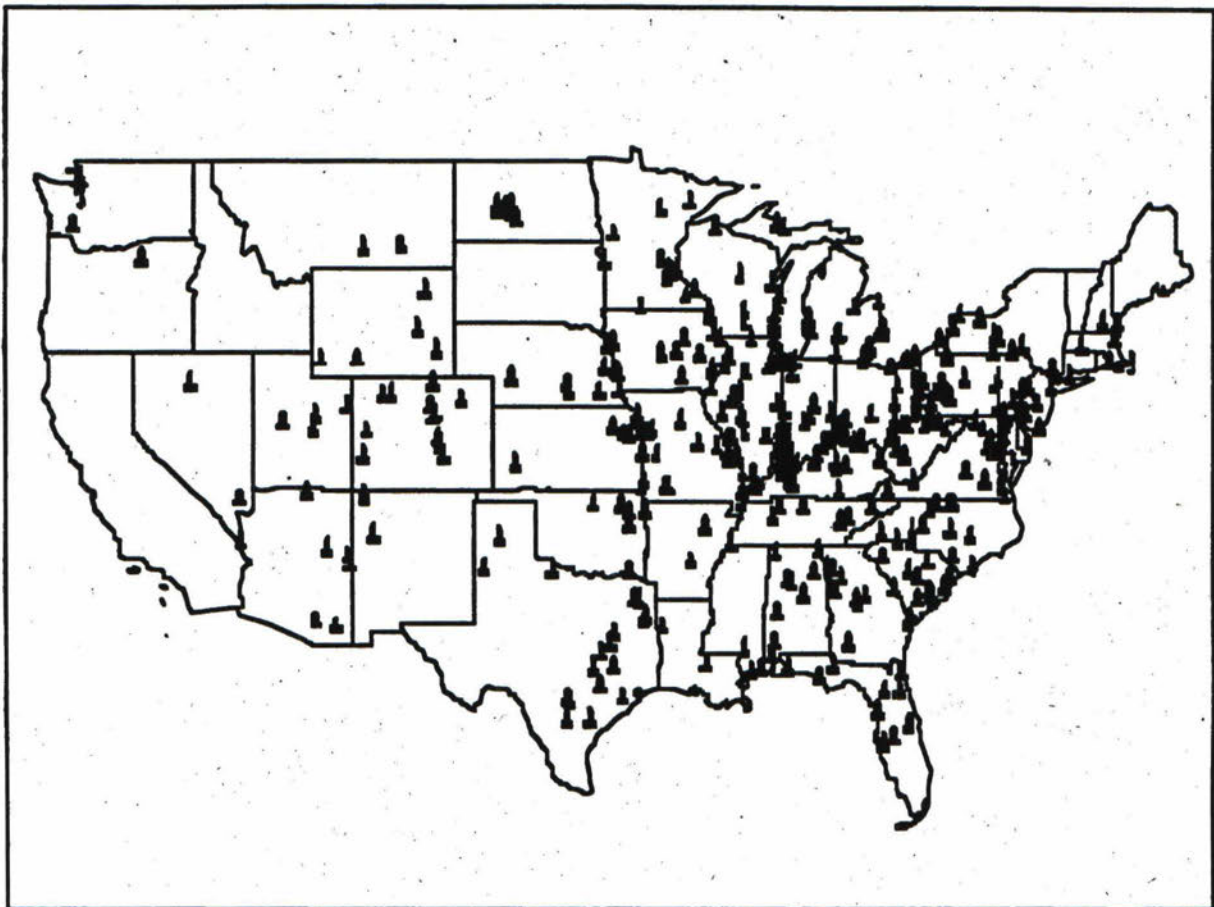
Figure 7.3 Incremental Increase in Gas Consumption Resulting from Coal to Gas Conversion with Constant 2010 Gas/Coal Price Differential (\$1.18/MBtu)



7.2.2.2 Gas Deliverability

The spatial distribution of the initial 404 candidate plants is depicted in Figure 7.4. Some of the candidate plants were not considered for repowering since they were (1) not considered economic by EIA, or (2) determined to be unnecessary due to reductions in demand arising from end-use efficiency improvements.² Most of the plants are located in the Mid-Atlantic, South Atlantic, Midwest, and Plains regions. While these are also primary gas-consuming regions served by major trunk lines, many industry experts believe there is limited unused or underutilized capacity in the current 1.2 million mile pipeline system (transmission - 264,900 miles; distribution - 935,000 miles; field - 62,200 miles). Since this capacity is necessary to accommodate peak winter demand and non-utility growth, it is of little value to power plants considering conversion, since these power plants require firm pipeline commitments.

Figure 7.4 Location of Candidate Plants for Coal/Gas Repowering in the U.S.



Due to the potentially significant increase in utility gas demand that could result from repowering (either site or steam turbine) coal-fired power plants, and the uncertainties regarding when repowering would take place, new pipeline capacity sufficient to serve all candidate plants was developed to ensure deliverability. A detailed assessment was performed (using a geographical information system, GIS) to compute the distance of each candidate power plant to its nearest trunk line. Cost estimates were derived for the cost of upgrading the lines to meet the increased gas demands (see Appendix G-4).⁴ Table 7.1 summarizes the distance of the candidate plants to their closest production zone.

The requirement to add new pipeline capacity could affect the attractiveness of repowering as a carbon mitigation strategy. During 1994 and 1995, 1,200 to 1,500 miles of new pipeline were added to the system. According to Federal Energy Regulatory Commission (FERC) filings of pipeline projects, there are a considerable number of new pipelines and pipeline expansions that have been proposed, some of which are still pending approval. While mileage is not included with each filing, in the regions of concern (Central, Midwest, Northeast, and Southeast), more than 8,200 miles of pipe is projected to be added; this level of expansion is greater than the 1994-95 rate of addition. However, it is not known how long it will take to complete these proposed pipelines. Consequently, an accurate assessment of the ability to increase the rate of pipeline expansion/construction could not be estimated as a part of this study.

Table 7.1 Plant Distance from Production Zone

Range (Miles)	Dual-Fuel		Multi-Fuel		Coal Only		Total	
	# Units	%	# Units	%	# Units	%	# Units	%
60 - 440	48	37	5	12	55	22	108	26
440 - 620	33	25	8	19	64	26	105	25
620 - 890	30	23	15	35	59	24	104	25
890-1,480	19	15	15	35	67	27	101	24
Total	130	100	43	100	245	100	418	100

7.2.3 Emissions Reductions

Based on our analysis, repowering of coal-fired power plants with NGCC is a cost-effective carbon reduction strategy. Tables 7.2-7.4 summarize the site repowering results for the two alternative gas/coal price differentials: \$0.72 and \$1.18 per million Btu (MBtu), three price ranges for carbon permits (<\$50/tonne, \$50-100/tonne, and \$101-150/tonne), and three environmental externality values for SO₂ and NO_x (none, low, and high). The price differential of \$0.72/MBtu represents the 1995 gas/coal price differential held constant, while \$1.18/MBtu is EIA's forecasted price differential for the year 2010.⁵⁶ In addition to the "no externalities" case, two alternative market values were used for SO₂ and NO_x: low externalities represent \$0 per ton of SO₂ and \$700 per ton of NO_x; high externalities represent \$100 per ton of SO₂ and \$1400 per ton of NO_x.

As can be seen in Table 7.2, given a carbon permit price of less than \$50/tC and a gas/coal price differential of \$0.72/MBtu, 30 to 119 MtC could be removed via NGCC site repowering, depending upon externality assumptions. When the price differential increases to \$1.18/MBtu, 0 to 83 MtC could be removed from utility emissions. Consequently, we see that a increase of \$0.46/MBtu in the price differential decreases carbon reductions from NGCC repowering by approximately 30 MtC. Although the disaggregated data are not presented, most of the carbon reduction in the <\$50/tC range actually occurs in the \$25-50/tC range.

An ancillary benefit of switching from coal to gas and improving conversion efficiency is reduction in SO₂ and NO_x, two criteria pollutants. At the <\$50/tC level, approximately 50% of the SO₂ and NO_x would be removed (depending on the externality value); at \$50-100/tC and higher almost all the remaining coal-fired SO₂ and NO_x emissions would be eliminated. If all the candidate plants were repowered, almost all of the SO₂ and most of the NO_x would be removed.

The economic value of the SO₂ and NO_x emissions reductions that would result from repowering of the plants was also assessed in this study. Using the methodology described in Appendix G-2, SO₂

was valued from \$0-100/ton; NO_x was valued at from \$700-1400/ton. These values were used as the basis for the environmental externality credits to offset the investment cost of repowering.

Table 7.2 Summary Statistics: Coal to Gas Repowering with a Carbon Permit Price of <\$50/tonne

<i>Constant 1995 Gas/Coal Price Differential (\$0.72/MBtu)</i>					
Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO ₂ Removed (Mt)	Incremental NO _x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
None	30.3	0.5	0.7	26.8	1.0
Low	66.0	1.2	1.4	63.3	2.3
High	118.6	4.0	2.6	122.6	4.2
<i>Gas/Coal Price Differential in 2010 (\$1.18/MBtu)</i>					
Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO ₂ Removed (Mt)	Incremental NO _x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
None	0	0	0	0	0
Low	23.6	0.3	0.6	20.2	0.8
High	83.4	2.5	1.9	83.3	2.9

* Two alternative market values were used for SO₂ and NO_x: low externalities represent \$0 per ton of SO₂ and \$700 per ton of NO_x; high externalities represent \$100 per ton of SO₂ and \$1400 per ton of NO_x.

**TCF = trillion cubic feet

Table 7.3 Summary Statistics: Coal to Gas Repowering with a Carbon Permit Price of \$50-100/tonne

<i>Constant 1995 Gas/Coal Price Differential (\$0.72/MBtu)</i>					
Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO ₂ Removed (Mt)	Incremental NO _x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
None	134.6	4.9	2.7	147.3	4.9
Low	140.4	6.7	2.8	165.6	5.3
High	106.7	5.0	1.8	130.8	4.2
<i>Gas/Coal Price Differential in 2010 (\$1.18/MBtu)</i>					
Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO ₂ Removed (Mt)	Incremental NO _x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
None	109.6	2.5	2.2	108.9	3.8
Low	134.1	5.0	2.7	146.4	4.9
High	123.9	5.5	2.3	147.6	4.7

* Two alternative market values were used for SO₂ and NO_x: low externalities represent \$0 per ton of SO₂ and \$700 per ton of NO_x; high externalities represent \$100 per ton of SO₂ and \$1400 per ton of NO_x.

**TCF = trillion cubic feet

Table 7.4 Summary Statistics: Coal to Gas Repowering with a Carbon Permit Price of \$101-150/tonne

<i>Constant 1995 Gas/Coal Price Differential (\$0.72/MBtu)</i>					
Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO ₂ Removed (Mt)	Incremental NO _x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
None	69.4	4.0	1.2	93.9	2.8
Low	31.0	1.6	0.5	43.8	1.3
High	13.1	0.6	0.2	20.9	0.5
<i>Gas/Coal Price Differential in 2010 (\$1.18/MBtu)</i>					
Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO ₂ Removed (Mt)	Incremental NO _x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
None	117.2	6.6	2.3	148.4	4.5
Low	75.1	4.0	1.2	98.6	3.0
High	29.8	1.5	0.4	41.4	1.2

* Two alternative market values were used for SO₂ and NO_x: low externalities represent \$0 per ton of SO₂ and \$700 per ton of NO_x; high externalities represent \$100 per ton of SO₂ and \$1400 per ton of NO_x.

**TCF = trillion cubic feet

7.2.4 Cost-Effectiveness

Figure 7.5 portrays the cost-effectiveness of site repowering with NGCC and the corresponding cumulative carbon removed for the two alternative gas/coal price differentials when no environmental externalities are considered. With a price differential of \$0.72/MBtu, approximately 30 MtC can be removed for <\$50/tC, an additional 135 MtC can be removed for \$51-100/tC, and an additional 77 MtC can be removed for >\$100/tC. When the price differential increases to \$1.18/MBtu, 0 MtC of carbon are removed at <\$50/tC, 110 MtC are removed at \$51-100/tC, and an additional 132 MtC are removed at >\$100/tC.

Figures 7.6 and 7.7 depict the effect of environmental externality credits for SO₂ and NO_x on carbon cost-effectiveness. As mentioned above, in addition to the "no externalities" case, two alternative market values were used for SO₂ and NO_x: low externalities represent \$0 per ton of SO₂ and \$700 per ton of NO_x; high externalities represent \$100 per ton of SO₂ and \$1400 per ton of NO_x. The rationale for these values is explained in Appendix G-3. Both Figures 7.6 and 7.7 (together with Tables 7.2 - 7.4) illustrate that the effect of the environmental externality credit is to shift the carbon cost curve downward and to the right causing more capacity (GW) and carbon removal (MtC) to occur at lower carbon permit price levels.

Because dual-fuel plants are already receiving natural gas (although at lower volumes than a repowered plant), a sensitivity analysis was conducted wherein no hook-up or transmission costs were incurred to deliver an increased quantity of natural gas to these repowered plant sites. This "no additional transmission cost case" is illustrated in Figures 7.8 and 7.9, which depict the two alternative gas/coal price differentials and include externality credits for site and steam turbine repowering. Since transportation costs comprise approximately 30% of the total investment cost, the carbon cost curves shift downward considerably when these costs are removed. In Figure 7.8, approximately 45 GW of coal-fired capacity can be repowered at <\$50/tC, removing 42 MtC of carbon, 1.2 Mt of SO₂ and 0.9 Mt of NO_x. The amount of natural gas required by these repowered plants is 1.5 thousand cubic feet; approximately 50% of 1995 utility consumption.

The cost-effectiveness numbers derived in this study are optimistic. These numbers should be used with caution because they do not (or do not adequately) consider the following factors that will determine the ultimate cost-effectiveness of the coal-to-gas repowering:

- Potential increase in gas prices from NGCC repowering,
- Actual cost of repowering the candidate coal-fired power plants,
- Excess transmission capacity, and/or economies of scale in delivering the required gas,
- Capacity utilization of the converted plants,
- Costs associated with breaking long-term coal contracts, and
- Other socioeconomic factors (e.g., differential state/federal tax effects, displaced coal miners).

In addition, the effectiveness of repowering as a carbon control strategy will depend on whether and to what extent the converted plants are dispatched. If, because of the costs associated with conversion, the repowered plants are not dispatched or their utilization is minimized, the associated carbon reductions will depend on the fuels and technologies used at the plants dispatched ahead of the repowered plants.

Figure 7.5 Carbon Curve for Coal/Gas Site Repowering: No Environmental Externality Credits

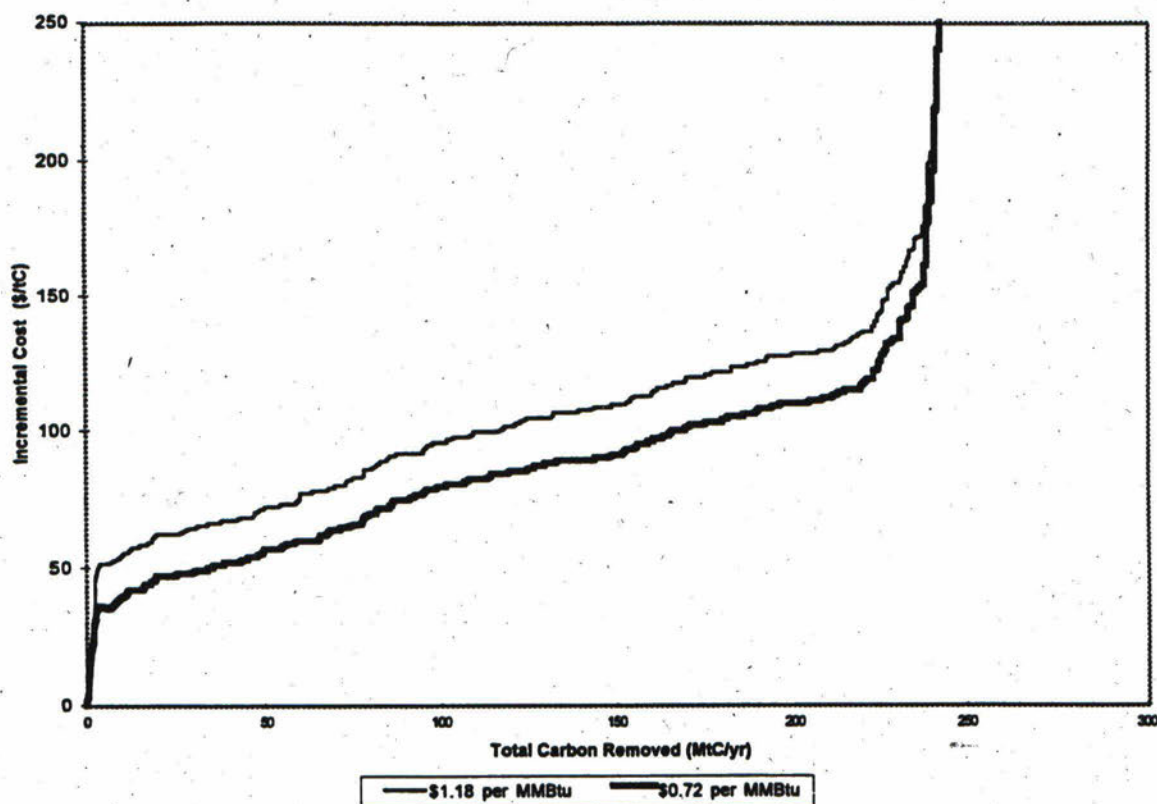


Figure 7.6 Carbon Curve for Coal to Gas Site Repowering: Effect of Environmental Externality Credits on Cost of Carbon Removal with Constant 1995 Gas/Coal Price Differential (\$0.72/MBtu)

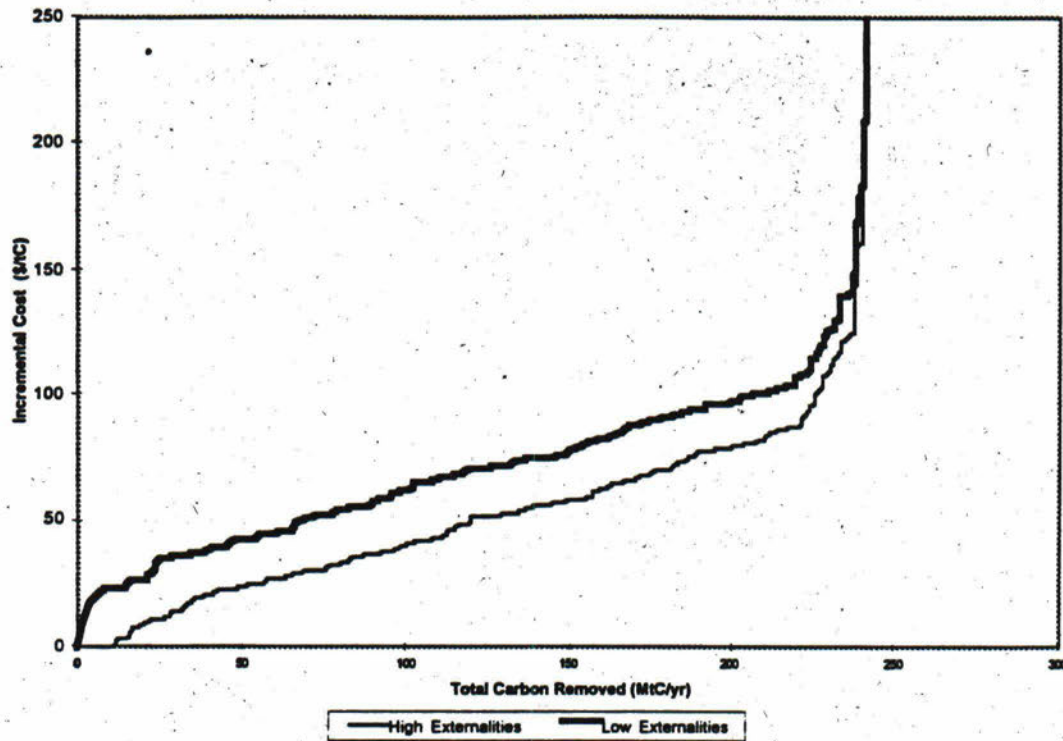


Figure 7.7 Carbon Curve for Coal to Gas Site Repowering: Effect of Environmental Externality Credits on Cost of Carbon Removal with Gas/Coal Price Differential in 2010 (\$1.18 MBtu)

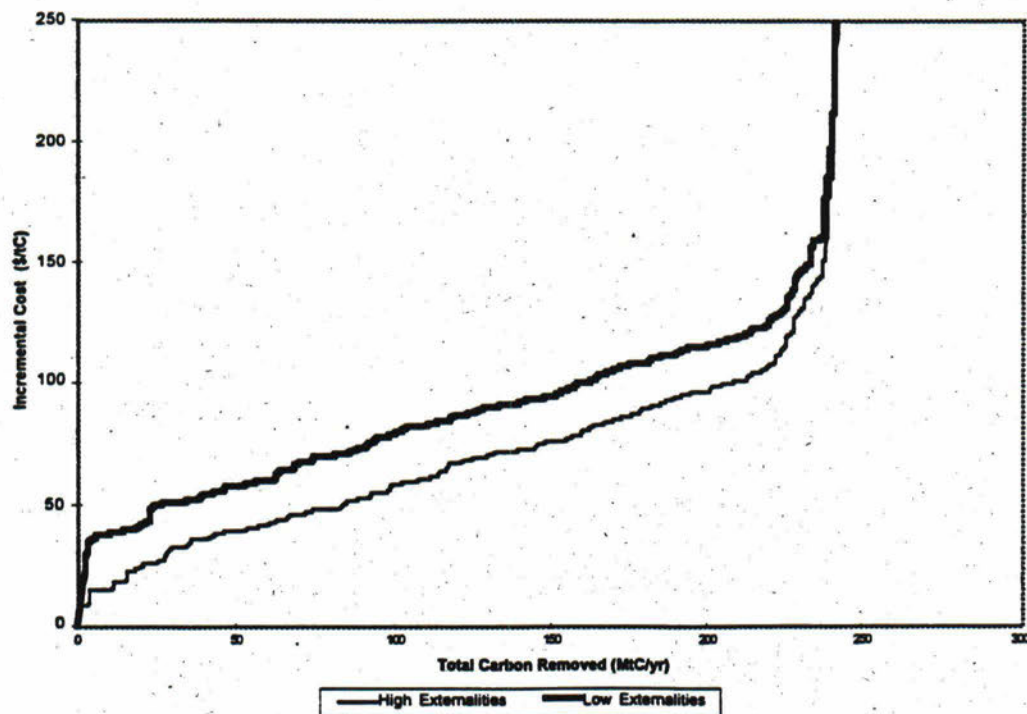


Figure 7.8 Carbon Curve for Partial Repowering⁷: Constant 1995 Gas/Coal Price Differential (\$0.72 MBtu) Low Environmental Externality Credits

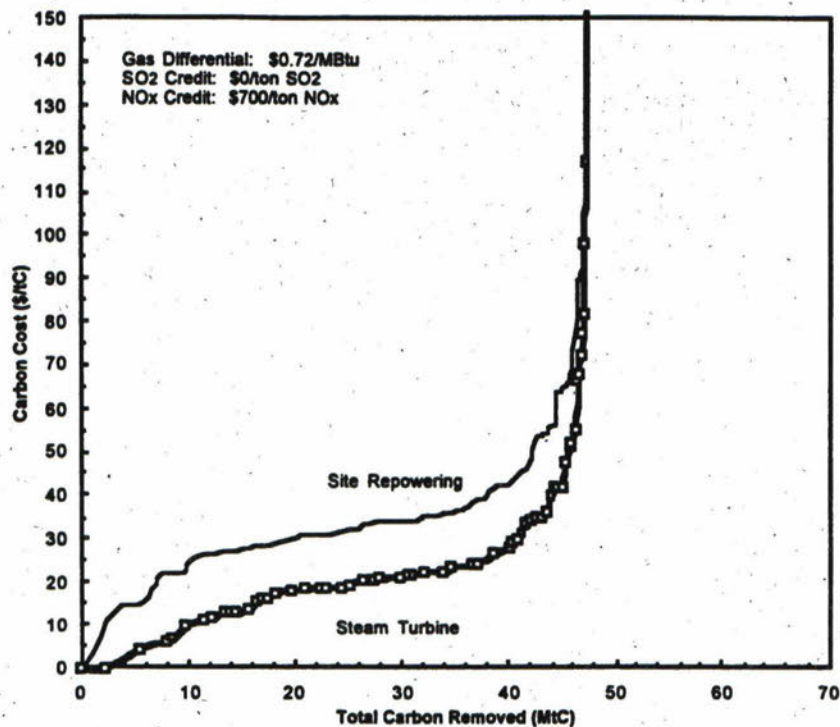
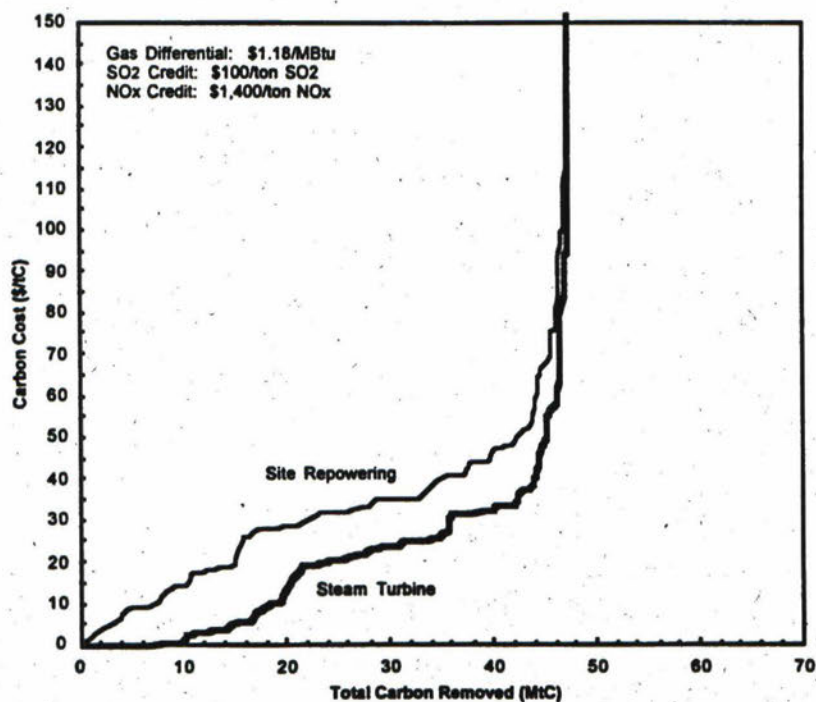


Figure 7.9 Carbon Curve for Partial Repowering⁷: Constant 2010 Gas/Coal Price Differential (\$1.18 MBtu) High Environmental Externality Credits



7.3 RENEWABLE ELECTRICITY TECHNOLOGIES

Over the long term, renewable energy technologies are likely to play a crucial role in limiting carbon emissions and global warming. While aggressive energy efficiency and fuel switching can reduce domestic carbon emissions to approximately 1990 levels by 2010, controlling or reducing carbon emissions beyond that date will require greater energy contributions from low-carbon technologies such as renewables. In other words, renewables will play an essential role in helping the United States to cut carbon emissions in the years beyond 2010.

Renewables will also make important contributions to both domestic and international carbon emission controls by 2010. Renewable technology contributions to domestic electricity and carbon savings in 2010 under the HE/LC scenario are summarized in Table 7.5.

Table 7.5 Additions to Generating Capacity Electricity and Carbon Emission Reductions from Renewables for the HE/LC Case in 2010

Renewable Technology	Capacity Additions (GW)	Electricity (TWh)	Carbon Emission Reduction (MtC) ^a
Included in Scenario:			
Biomass Cofiring	8-12	58-88	16-24
Wind	8-23	28-81	6-20
Hydropower	10-16	23-35	3-5
Subtotal			25-49
Excluded from Scenario:			
Landfill Gas ^b	3-7	20-50	25-53
PV	3-5	6-10	1-2
Geothermal	6-14	47-110	6-16
Solar Thermal	0-2	0-6	0-1
Subtotal			32-72
Total	38-79	182-380	57-121

^a These carbon emissions reductions represent the difference between the high-efficiency/low-carbon case and the business-as-usual forecast for 2010.

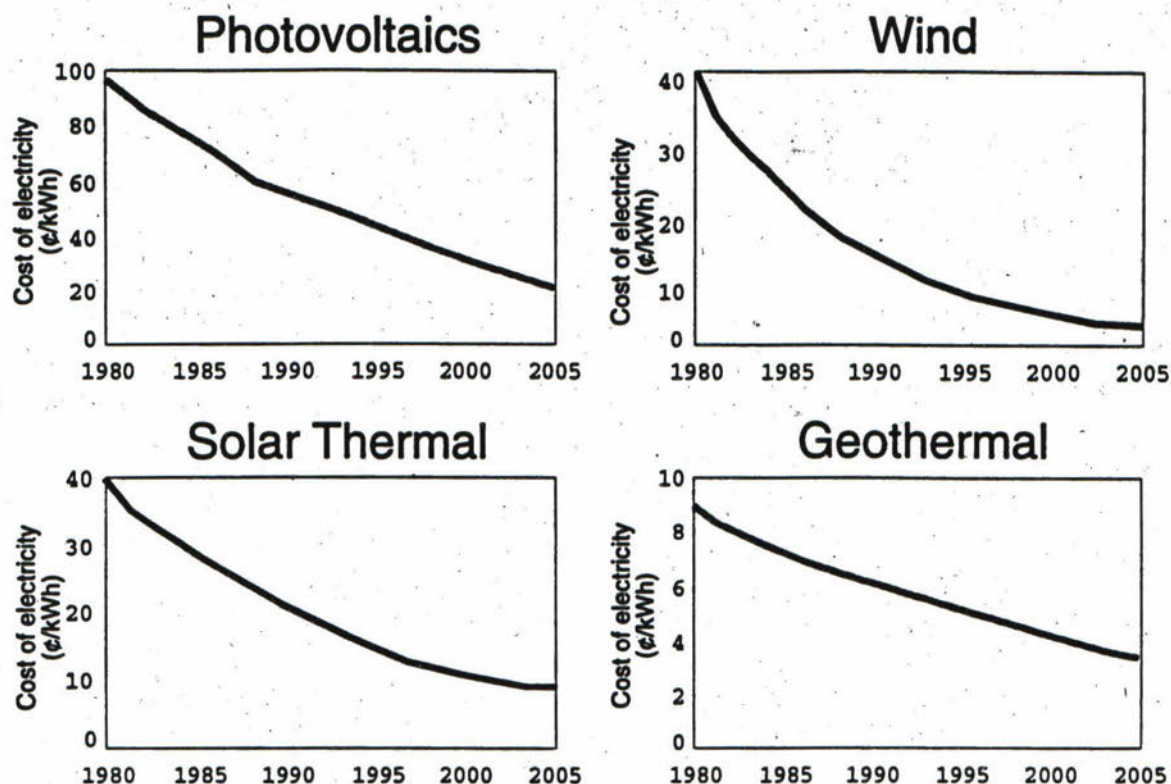
^b The carbon emission reduction in this case represents the equivalent derived from the prevention of the methane release coupled with its radiation-trapping properties.

This section examines the potential for renewable electricity technologies to reduce U.S. carbon emissions. The contributions of renewables in various end-use sectors, such as transportation, are discussed in other chapters in this report.

Renewables are in the midst of a major, long-term transition, from being "advanced technologies" with only a peripheral market role to becoming mainstream "technologies of choice" in the energy marketplace early in the next century. One clear marker of this transition is the changing cost of electricity from renewable power technologies. Figure 7.10 displays these costs for the period from

1980 to 2005, based on both historical data and recent projections (Office of Utility Technologies, 1997).

Figure 7.10 Historical and Projected Costs of Electricity from Four Renewable Power Technologies



The pace and timing of this transition is difficult to project, however, because it is strongly dependent on such variables as the progress made through research and development, the evolution of energy economy policies, and the magnitude and impact of consumer interest in "green" energy. For example, under the \$50/MtC cost-of-carbon scenario assumed in this study, the adoption of wind power in the United States is likely to increase rapidly on an economic basis. In addition, increasing attention is being focused on consumer interest in green energy. As the electric utility sector moves toward competitive markets, consumers probably will have the option of purchasing power that is environmentally cleaner.

The rate of change will impact the role of renewables in 2010 at least as much as the specific energy contribution of renewables in that year. Therefore, this section discusses the trends as well as the predicted contributions of renewables to the energy supply and to carbon emission reductions in 2010.

A thorough analysis of the role of renewables in 2010, which captures the complexity of their transition, has not been conducted as a part of this study. Instead, this section presents analyses of a few renewable technologies whose role is likely to be quite significant by 2010, and includes a general discussion of the other renewable technologies. A more thorough analysis of the relationship between renewables and reductions in carbon emissions over a longer time frame is the subject of a future study.

Thus, this section discusses the role of renewables in two time frames: (1) developments and contributions by 2010, and (2) the long-term outlook.

7.3.1 Renewable Electricity in 2010

As stated earlier, renewable electric technologies will make important contributions to carbon emission reductions in 2010 in the context of a policy that imposes a \$50/tonne cost on carbon emissions. Estimates of those contributions are presented here. While the scope of this study did not include a thorough and systematic analysis of this issue, the estimates given are based on a number of directly relevant studies. These include, in particular, carefully developed performance and cost projections for renewable electric technologies (Office of Utility Technologies, 1997) and projections of future market penetrations of these technologies (Office of Energy Efficiency and Renewable Energy, 1997).

The potential of biomass cofiring was assessed because that technology provides an opportunity for reasonably straightforward displacement of a significant amount of coal. This assessment, which draws upon another recent analysis, is presented first.

An analysis of the impact of a \$50/tonne cost of carbon on wind power was also conducted, and those results are discussed second. Wind was selected because cost projections for wind power indicate that this technology will be competitive with other electricity generation sources according to the electricity costs modeled in the HE/LC scenario of this study. In addition, wind power is already successfully penetrating electricity markets in the United States and abroad.

This analysis is followed by estimates of carbon emission reductions that would be likely to result from hydropower upgrades and landfill gas capture and use. These estimates are derived from DOE and EPA studies relevant to market projections for those two technologies, respectively (Rinehart et al., 1997; EPA, 1993).

Finally, other key renewable power technologies are discussed briefly. We present estimates of the likely contribution of these technologies in 2010, developed through comparisons and extrapolations from earlier projections (Office of Energy Efficiency and Renewable Energy, 1997).

7.3.1.1 Cofiring Coal with Biomass

Cofiring biomass with coal has the technical and economic potential to replace at least 8 GW of the nation's coal-based generating capacity by 2010, and as much as 26 GW by 2020. Though the current substitution rate is negligible, a rapid expansion is possible with the use of wood residues (urban wood, pallets, and secondary manufacturing products) and dedicated feedstock supply systems (DFSS) such as willow, poplar, and switchgrass.

The current coal-fired power-generating system represents a direct opportunity for carbon mitigation by substituting biomass-based renewable carbon for fossil carbon. Extensive demonstrations and trials have shown that biomass can replace up to about 15% of the total energy input with little more than burner and feed-intake system modifications to existing stations (CONEG, 1996). Since large-scale power boilers in today's 310-GW-capacity fleet range from 100 MW to 1.3 GW, the biomass potential in a single boiler ranges from 15-150 MW.

Preparation of biomass to an appropriate size of less than one-quarter inch, with a moisture content of less than 25%, can be achieved using existing commercial technologies. "Tuning" the combustion output of the boilers causes little loss in total efficiency, implying that the biomass-to-electricity

combustion efficiency is close to the 33-37% range of an unmodified coal plant, an efficiency that stand-alone biomass generating capacity has yet to demonstrate.

Economics

The cost of implementing biomass cofiring varies from site to site. It is influenced by the space available for yarding and storing the biomass, the installation of size-reduction and drying facilities, and the nature of the boiler burner modifications required. The cost is expected to be in the range of \$100-\$700/kW of biomass capacity. Early trials indicate that a median value of about \$180/kW is likely. A 100-MW coal plant with 10% biomass substitution would then require an investment of \$1.8 million. There is an O&M cost increase of \$70,000/year over coal, as a result of the need for an additional yard worker to handle the biomass. Assuming a GENCO recovers its investment cost in three years, the annual fuel offset then has to be \$670,000 to cover capital recovery (\$1.8 million) and increased O&M costs (\$210,000 for three years). If the average price of coal is about \$1.40/MBtu (million Btu), the annual fuel cost of coal is \$1.081 million (10 MW of biomass capacity at 85% capacity factor and 32.9% thermal efficiency, 10,337 Btu/kWh). The allowable cost of biomass then is \$411,000, or about \$9/tonne. Above this cost, the biomass would have to be subsidized to encourage a GENCO to use biomass cofiring.

Fuel Costs

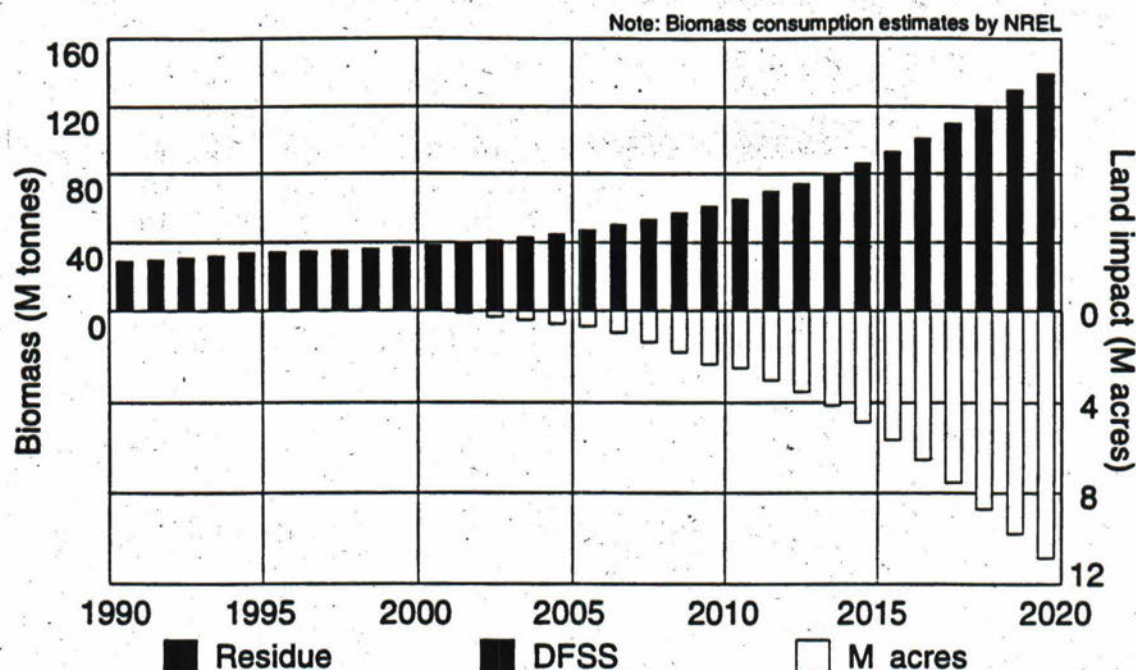
Near-term potential biomass feedstocks are those residues available within a radius of about 50 miles around a plant. Data from existing biomass power plants in the Northeast and California indicate that there are extensive sources of biomass residues available for about \$0.50/MBtu (less than \$9/tonne). Transportation costs limit the range over which such biomass feedstocks can be acquired and, in the long term, there are likely to be dedicated feedstock systems much closer to the power plants. By definition, residues (e.g., urban wood residues, rights-of-way clearance, construction and demolition wood, pallets, and sawdust shavings from secondary wood processing) are finite and will respond to the prices offered for them.

Dedicated feedstocks would not be bound by this constraint. However, such feedstocks are much more expensive than residues. With current technology the price is about \$2/MBtu, although the current development goal is in the range of \$1-\$1.50/MBtu. It is assumed that an estimated 10.4 million acres will be needed to reach a nominal production of 86 Mt by 2020. Because DFSS is in an early stage of development, the model assumes that the initial planting will yield only about 6 tonnes/acre by 2002 (today's state-of-the-art), and that by 2010 the yield will be closer to 8 tonnes/acre. Today's costs are high; \$45/tonne is feasible, but a combination of learning-curve improvements and economies of scale should bring the cost down to about \$32/tonne by 2010. The competing coal price is assumed to be \$1.40/MBtu (\$1.33/GJ) throughout.

Biomass Substitution Potential

The cofiring estimates in this section were derived from a 30 GW scenario for all biomass technologies, developed by NREL for the current Biomass Power Program Strategic Plan. This scenario is for a mix of steam, cofiring, and integrated gasification/combined cycle (IGCC) biomass generation. However, the resource plan that was developed, which included residues and DFSS, is independent of the end use and involves the development of 11-12 million acres of land for DFSS by 2020, or just under 3 million acres by 2010. The resource development shown in Figure 7.11 is used as the basis for this carbon assessment. This indicates that DFSS would come on rapidly after the year 2001 and assumes that residues would be capable of only a small increase in quantity, since much is already being utilized. The average cost of residues is expected to increase gradually, while the cost of DFSS crops is expected to demonstrate a strong learning curve and large economies of scale.

Figure 7.11 30 GW Strategic Plan Scenario



Timing

While a coal-fired station could be modified for cofiring in less than one year (including environmental permitting), a biomass resource assessment, contractual arrangements, and logistics for biomass residues could take the better part of 18 months, based on actual project experience. Although the availability of residues is assumed to be significant and would ultimately supply about 50 Mt, price and availability are likely to be variable. The price will no doubt increase with the level of demand; therefore, the biomass feedstock supply is expected to be a blend of DFSS and residues.

The DFSS component is predicated on making a start on land accumulation (whether purchases, leases, or cooperatives), with land preparation and planting in 1999. A significant effort will be required to initiate development of the 11-12 million acres proposed for 2020; today, discussions are about DFSS demonstrations at the 1000-acre level. Adequate clonal material and management systems for planting, tending, and harvesting will also need to be developed. The crops of choice in much of the Northeast and Southeast are probably woody species, which would require extensive nursery activity to put the needed clonal material in place for planting out. With willow, the first harvest cycle would be four years after planting and a rotation of three years thereafter. For poplar, the cycle is likely to be in the range of six to eight years.

Environmental Issues

Because biomass generally contains significantly less sulfur than coal, cofiring with biomass could reduce SO_x emissions. Early results suggest that there is also a NO_x reduction potential using woody biomass. However, most coal-fired power stations have efficient precipitators and some have sulfur-capture technologies, so the net environmental effect of 10% biomass substitution (on an energy basis) appears to be negligible. The solid wastes (ash) would be little changed in either composition or mass (most biomass has considerably less ash than coal). But some stations sell fly ash to Portland

cement manufacturers, so there may be a need to negotiate the acceptance of mixed biomass and coal ash in such applications with respect to ASTM standards.

The DFSS environmental impact is dependent on the choice of lands for plantations. Replacing annual cropland with perennial DFSS appears to result in a net environmental gain. Results for pasture land are probably negligible and replacement of forest may result in some increased impacts.

The use of residue has the potential to offset landfilling as well as potential methane emissions from landfilling clean biomass materials. Experiences in California indicate that the issue will be one of rationalizing the cost distribution between the waste generator, the hauling contractor, and the generating station receiving the residue rather than it going to a landfill. If such negotiations were successful, and the generating station could guarantee reception of the residues at all times (many urban wood residue generators do not have storage facilities), both residue costs and their availability could improve significantly.

Impact on Carbon Emissions

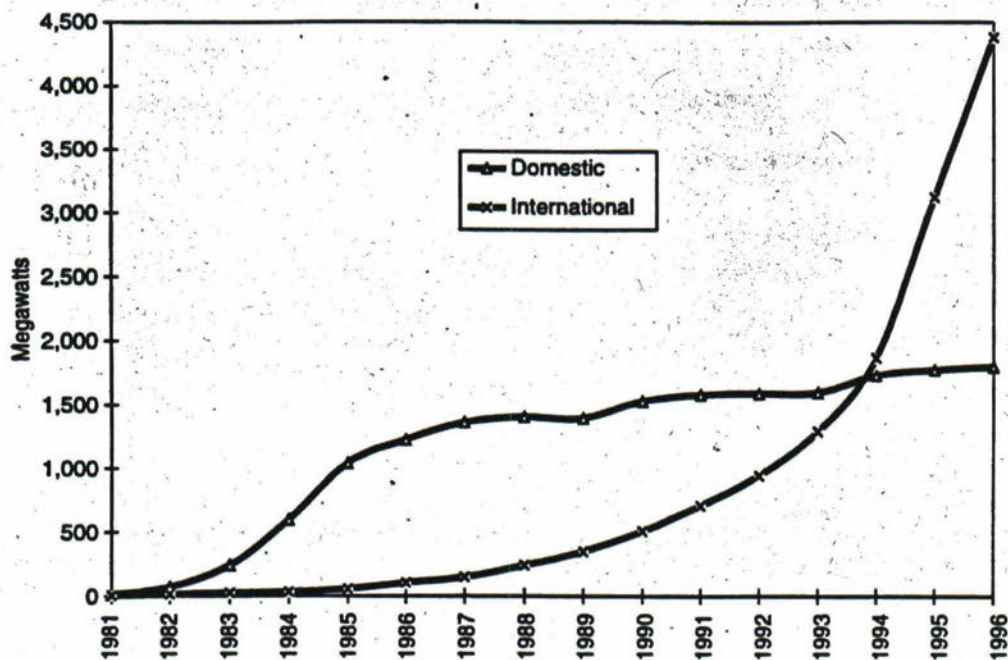
Given the technical and economic potential described above, it is probably reasonable to assume additional biomass-cofired capacity of 8-12 GW by 2010, which should reduce carbon emissions by 16-24 MtC.

7.3.1.2 Wind Power

The development of wind power systems has progressed quite rapidly since 1980. There are approximately 1800 MW of wind capacity operating in the United States today, and another 4300 MW of capacity overseas (Figure 7.12). This capacity growth is almost certain to continue because of continuing decreases in the cost of wind-generated electricity as well as growing interest in emission-free power derived from local, renewable resources. Figure 7.13 shows the projected cost of wind-generated electricity for wind farms located in Class 4 and Class 6 resource sites (as presented in DOE's 1997 Technology Characterizations). Class 4 sites have average wind speeds of 5.6-6.0 m/s, Class 6 sites have average wind speeds of 6.4-7.0 m/s, both measured at a height of 10 meters. Figure 7.13 also displays the median, 10th percentile, and 90th percentile of electricity generation prices in 2010 based on the HE/LC case described in Chapter 6. As these projections indicate, wind power prices are projected to drop below the median 2010 price for that scenario before 2005. Thus, strictly on a price-of-energy basis, in this scenario wind power will be able to compete favorably with other power sources for several years prior to 2010.

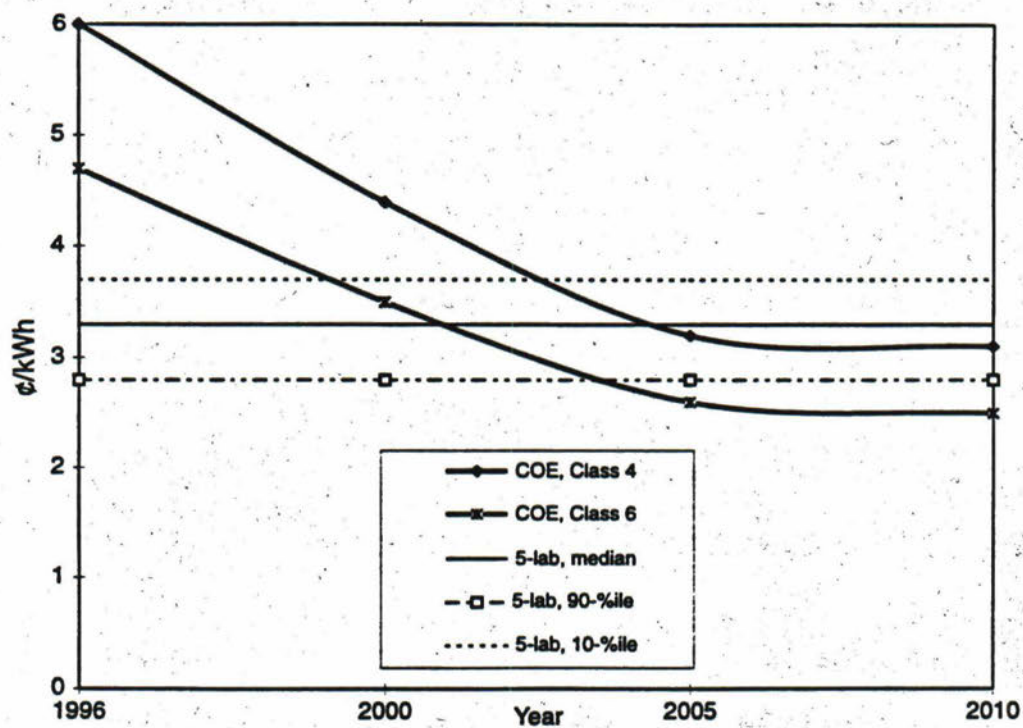
In addition to the price of energy, a number of other factors will affect the extent to which wind power systems will be adopted between now and 2010. These include, for example, the overall market for new power systems, the price penalty that wind power will encounter for providing intermittent power, and the price advantages that wind power will realize because it is a "green" power source and because it is not subject to the risk of future fuel price increases. Because the level of influence of each of these factors has not been analyzed, it is difficult to project their combined impact.

Figure 7.12 Domestic and International Wind Power Capacity, Grid-Connected



Source: Department of Energy, Office of Utility Technologies Wind Division

Figure 7.13 Projections of Wind Power Costs



In the AEO97 reference case forecast, EIA projects electricity generation to increase by about 800 TWh by 2010, from 3083 TWh in 1995 to 3874 TWh in 2010 (EIA, 1996). In this context, EIA projects a total of only 3800 MW of wind generating capacity. The Quality Metrics analysis by the Office of Energy Efficiency and Renewable Energy (EERE) of the impacts of its R&D program estimates that additional installed wind power generating capacity will reach 8 GW and contribute approximately 29 TWh to the electricity market by 2010 if wind program goals are met. This will result in a carbon emission reduction of 6 MtC. Neither of these projections, however, assumes a major new market policy to promote wind power.

In the HE/LC case of this study, electricity generation will increase by significantly less than in the business-as-usual case. Thus, the HE/LC scenario presents a much smaller target market for new power-generation sources. However, under the transition of the utility sector to a competitive market, it is very likely that newer technologies with lower generating costs will displace some existing generation capacity with higher generating costs. Moreover, in the HE/LC scenario, generation costs are projected to be more than 25% higher than in the base case. Thus, as illustrated in Figure 7.13, wind power generation costs will be highly competitive in this marketplace, so displacement of higher-cost existing generation by wind is likely. In an attempt to model the penetration of wind under these conditions, the ORCED model was run using the wind technology characteristics developed by the Office of Utility Technologies (Office of Utility Technologies, 1997). As might be expected, the results indicated that the level of wind penetration in this case is quite sensitive to the actual input parameters. According to the model, for example, using the cost and performance characteristics projected by DOE for the year 2005 could lead to the adoption of as much as 50,000 MW of wind power by 2010. Using 160 kg/MWh, the average carbon intensity of the generation displaced (see Chapter 6), this would result in a carbon emission reduction of 28 MtC. Because the ORCED model indicated that this new wind capacity would displace coal-fired generation, a higher conversion ratio (275 kg/MMh) is used to estimate carbon emission reductions, resulting in an estimated reduction of 48 MtC.

This level of penetration would require wind-turbine manufacturing capacity to expand at a rate of approximately 25% per year. As Figure 7.12 indicates, this level of wind capacity expansion has been reached in the past. Europe's experience with wind power also indicates that this technology can expand quite rapidly. It is possible for the manufacturing industry to respond quickly to market demands, since most of the components of wind systems (generators and gearboxes) are readily available, and not specific to wind technology. In 1991, the European Wind Energy Association set a goal of 4 GW of wind by 2000. This goal has been realized already in 1997, and the new targets are 8 GW by 2000 and 40 GW by 2010. Given that Europe is a much more land-constrained continent with generally lower wind resources than the United States, this comparison suggests that 50 GW of wind power capacity can be realized in the United States by 2010 in the context of a strong policy environment.

The HE/LC context of this analysis assumes a policy environment that acknowledges the need to address global warming. In such an environment, renewable energy, including wind power, will be able to demand somewhat higher prices because of consumers' preferences for green power. The value of that premium is not yet known.

It is well-documented that wind resources in the United States are quite extensive. For example, an assessment of wind resources and access to transmission indicates that more than 115 GW of Class 5 and Class 6 sites are within 5 miles of existing lines, and more than 1,000 GW Class 4 sites are within that same range (Parsons et al., 1995). This assessment excludes sites that are not suitable for wind farm development, such as cities and wilderness areas. Thus, 50 GW could probably be developed primarily in Class 5 and Class 6 areas, which means that they will operate with

relatively high capacity factors and low costs of energy. (The Draft Technology Characterizations indicate that capacity factors will be 45% in Class 6 regions and 35% in Class 4 regions by 2005.)

This analysis does not take into account the fact that wind-generated electricity will probably face at least a partial price discounting because wind power is not fully predictable. At this time, the level of this discounting is simply not known. To date, with low levels of penetration into grid-connected generation, intermittency has not been an issue. There are some indications that the range of electricity prices in a competitive market will be fairly narrow. For example, prices for electricity transactions on the Continental Power Exchange during peak hours generally vary only by about 2 cents/kWh (Continental Power Exchange, 1997). This implies that price variations between different generation sources cannot vary by more than that, and it is likely that the difference will be much smaller under full competition.

In summary, analyses indicate that total wind power capacity in 2010 could range from as low as 5 GW, based on a simple extrapolation of today's energy economy, to as high as 50 GW in an environment that includes competitive pricing and policies emphasizing control of carbon emissions. Given these results, it is probably reasonable to estimate that additional wind capacity will be 8-23 GW in 2010. This translates into electricity contributions of 28-81 TWh, resulting in reductions of carbon emissions of 6-20 MtC relative to the BAU forecast for 2010.

7.3.1.3 Increasing Generation and Capacity at Existing Hydropower Plants

Hydroelectric power currently supplies about 10% (78 GW) of the nation's electricity and constitutes 84% of the nation's generation from renewables (EIA, 1996). Hydroelectric power plants produce no greenhouse gas emissions during operation (DOE, 1994). In the 1940s, 40% of the country's electricity came from hydropower plants (Williams and Bateman, 1995). The adverse environmental affects of some hydropower projects are now relatively well known (e.g., Mattice, 1991), but significant progress is also being made in mitigating these problems (Sale et al., 1991).

Hydroelectric power uses the energy of falling water to generate electricity. Hydroelectric generation technologies for utility-scale applications are generally considered to be mature, with turbine efficiencies typically in the 75%-85% range (OTA, 1995). There are three types of hydropower facility:

1. Most hydropower plants use dams to raise the water level, which increases the water's potential energy, and allows for regulation of the water availability. Conventional hydropower (with reservoir storage) can provide baseload, intermediate, or peaking power, depending on the availability of water and project design (OTA, 1995).
2. Run-of-river systems do not use large dams or storage reservoirs. Instead, smaller diversion structures are used to channel some of the water through a canal or penstock to a powerhouse, after which the water is returned to the river. Run-of-river systems avoid some of the costs and environmental impacts associated with large hydro facilities.
3. Pumped storage projects use off-peak electricity (usually from a baseload power plant) to pump water to an upper reservoir; this water is later released to flow through a generator during periods of peak demand. Such plants are net consumers of energy. Although pumped storage is not a renewable energy technology, it can result in a net reduction in greenhouse gas emissions when the fuel providing electricity for pumping has a lower carbon content than the fuel being displaced by the pumped storage generation (DOE, 1994).

The main challenge for hydropower in recent years has been the growing concern over its local environmental impact. By damming rivers to create storage reservoirs, hydro facilities can have an adverse effect on terrestrial and aquatic ecosystems. Wildlife habitats can become inundated. Fish migration routes can be cut off, and fish can die in the generating turbines or because the downstream water quality and habitat are changed. Plants that grow along the riverbanks can be disrupted by changes in the natural water level, both above and below the dam, and large or rapid variations in the amount of water being discharged can disrupt aquatic habitats and accelerate erosion downstream.

Regulatory measures — such as the licensing of non-federal hydropower projects and the Endangered Species Act — are reducing the environmental impact of hydropower projects, but they are also reducing total electricity production from this energy source. Between 1995 and 2010, 19 GW of hydropower at non-federal projects will be subject to relicensing. Recent trends indicate that relicensing results in an average 8% loss in generation due to the imposition of new environmental constraints on operation.

Under the HE/LC scenario, and assuming a sustained regulatory reinvention effort between now and the year 2010, incentives could be in place to increase hydroelectric power generation in either of two ways. Neither of these opportunities involves the construction of hydropower plants at new sites. However, both will require continued R&D to improve the design of turbine systems and to minimize adverse environmental effects:

- Increasing generation at existing hydropower plants. This option consists of modernizing and upgrading existing turbines and generators to increase their efficiency and/or electrical output. With enabling incentives, upgrading hydropower plants can result in energy production gains of 5%-10%. Hydropower upgrades would also have significant environmental benefits, because new generating technologies offer improved fish passage, better water quality, and new opportunities for improving downstream aquatic habitats.
- Adding generating capacity at existing dams. A recent resource assessment identified 20 GW of undeveloped hydropower capacity at existing dams (Rinehart et al., 1997). About 36,000 GWh of new hydropower generation could be added by developing these sites between 1995 and 2010 (Office of Conservation and Renewable Energy, 1990).

Further expansion of hydropower capacity is possible, but unlikely until after 2010. The national hydropower resource assessment (Rinehart et al., 1997) has identified an additional 11 GW of environmentally acceptable hydropower at undeveloped sites (those requiring the construction of new dams or diversions). These resources may eventually be developed, given more advantageous economics, regulatory reinvention, and/or technology improvements. Further development of efficient low-head generating technologies would encourage deployment at the many low-head sites that are currently unsuitable for hydropower additions.

Considering only the near-term options, and the fact that there may be some loss of hydropower capacity due to relicensing issues and environmental mitigation regulations, net capacity additions by 2010 could be 10-16 GW, reducing emissions by 3-5 MtC. Additional carbon savings can be achieved after 2010 with continuing advancements in generating technologies and environmental mitigation techniques.

7.3.1.4 Landfill Gas

When food scraps and other organic wastes in landfills decompose, they produce methane. Methane is a potent greenhouse gas that is also the main ingredient of natural gas. According to the

Intergovernmental Panel on Climate Change, each kilogram of methane is about 21 times more effective at trapping radiation in the atmosphere than a kilogram of carbon dioxide. Landfills are the largest source of anthropogenic methane emissions in the United States; they are responsible for almost 40% of these emissions each year (EPA, 1997).

New EPA regulations require operators to seal larger, closed landfills with a special cap, collect the gas, and burn it to prevent atmospheric releases of methane. But wells sunk into landfills can capture the gas before it escapes the surface. It can then be used for a variety of applications, including generating electricity.

Today, about 165 landfills recover and utilize methane as a fuel. Various estimates (Governmental Advisory Associates, 1994; EPA, 1997) indicate that between 300 and 750 of the country's 3500 landfills could economically recover methane using currently available technologies. The development of more efficient, less expensive technologies for gas recovery, clean-up, and utilization could accelerate the adoption of landfill gas-to-energy systems. For example, highly efficient, experimental fuel cells have operated on landfill gas processed using new clean-up technology.

By 2010, 0.2-0.5 quads of energy per year could be recovered from the methane in landfills and converted to electricity. Taking into account the difference in the radiative effects of methane and CO₂, this represents the equivalent of 25-53 MtC in reduced emissions (DOE, 1994).

7.3.1.5 Other Renewable Power Technologies

This section examines three more renewable electric technologies: photovoltaics (PV), geothermal power, and solar thermal power. Figure 7.10 illustrates that the costs for these three technologies have also decreased sharply over the past 15 years. It is very likely that this trend will continue. While none of these technologies are expected to contribute as much electricity as biomass cofiring or wind power by 2010, their role in 2010 electricity markets may be significant and growing.

Photovoltaics

Photovoltaics (PV) uses solar cells to generate electricity from sunlight without any emissions or moving parts. This technology has made substantial progress since its first successful application in space. While PV power costs are still significantly higher than the costs of other renewable technologies, sales of PV power systems have been growing steadily, probably because of the many unique advantages of PV. These include modularity (applications can range from solar calculators to power stations), widespread applicability (since adequate solar resources are widely available), and ease of integration into the built environment (through incorporation into building facades, roofing materials, highway sound barriers, parking-lot structures, etc.). The most important application of PV today is in stand-alone systems that provide power to remote water pumps or off-grid residences, for example. Because approximately two billion people live in villages without grid electricity, remote power represents a very large and important market for PV in developing countries.

For grid-connected applications, one of the most promising trends in the past few years is "building-integrated" PV. Numerous buildings have been constructed — primarily in Europe, Japan, and the United States — that incorporate PV panels in windows, awnings, or roofing materials. Thus, the PV panels serve a dual function, which effectively lowers the cost of their role as power generators. In these applications, the PV power directly displaces grid electricity at the end point of the delivery system, where it has the greatest value. Another advantage of PV is that its peak power output generally coincides with peak electricity demand, which further enhances its market value.

Worldwide sales of PV power systems have grown to nearly 100 MW per year, up from 10 MW in 1982, an average annual growth rate of about 20%. This rate of growth is likely to increase as a result of numerous programs promoting PV for village power in developing countries as well as programs promoting greater use of PV in several developed nations. One example is the U.S. Million Solar Roofs program, announced by President Clinton at the United Nations on June 26, 1997. Others include Japan's Sunshine Project, Germany's subsidy of up to 70% of PV system costs, and Switzerland's PV Schools Program.

EIA estimates that total installed PV capacity in the United States will be only 0.2 GW in 2010 (EIA, 1996). However, an independent assessment of the impact of DOE's R&D programs indicates that, by 2010, installed U.S. PV capacity will be approximately 1.3 GW under a BAU scenario (Office of Energy Efficiency and Renewable Energy, 1997). Using this as a starting point, and considering the many advantages of PV, an estimate of installed capacity of 4-7 GW in 2010 is probably reasonable for the HE/LC scenario. This would provide 6-13 TWh of electricity and reduce carbon emissions by 1-2 MtC. One important addition to PV capacity will come from the recently announced Million Roofs Initiative, which will result in 1-2 GW of new capacity.

The market trends for PV in 2010 are probably more significant than its energy and carbon contributions. By 2010, PV energy prices will be substantially lower than they are today, and we will have had considerably more experience with the development and use of building-integrated PV products. In this context, the United States will be moving into a situation in which a significant and increasing fraction of construction includes PV generation capabilities.

Geothermal Electricity

Geothermal power technologies use the thermal energy from underground reservoirs of hot water or steam to produce electricity. With higher temperature resources, the steam is used to drive a turbine directly; with lower temperature resources, a binary technology is used in which the hot water vaporizes another working fluid, which then drives a turbine. These geothermal power-generation technologies are considered fairly mature. The major challenge lies in locating and characterizing the size and longevity of specific geothermal reservoirs.

Approximately 3 GW of geothermal capacity is installed in the United States today. While EIA estimates that geothermal capacity will increase by only 0.2 GW by 2010 (EIA, 1996), DOE's recent Quality Metrics Study indicates that geothermal power capacity will increase by 5.8 GW, and electricity production will increase about 45 TWh, in a BAU scenario (Office of Energy Efficiency and Renewable Energy, 1997). While a \$50/tonne cost of carbon would improve the economics for geothermal, it is not expected to provide as much of a boost as it does for wind or biomass. It is probably reasonable to use the DOE estimate as the lower boundary, and project that total installed geothermal power capacity in 2010 under the HE/LC case will be 8-16 GW. The 6-14 GW increase in geothermal capacity over today's level would reduce carbon emissions by 6-16 MtC.

Solar Thermal Electric Technology

Solar thermal power technologies use mirrors to concentrate direct sunlight onto a thermal receiver, thus creating a high-temperature energy source that can be used with a heat engine to generate electricity. There are three types of solar thermal power systems: parabolic troughs, power towers, and dish/engine systems. Parabolic trough systems use large fields of linear parabolic reflectors, each of which heats a fluid flowing through a receiver pipe located along the focal line of the reflector. About 350 MW of these systems are operating in California. A 10-MW demonstration of a solar thermal power-tower system, which uses large mirrors to direct solar rays to a thermal receiver atop a tower, is also operating in California. The third technology uses individual

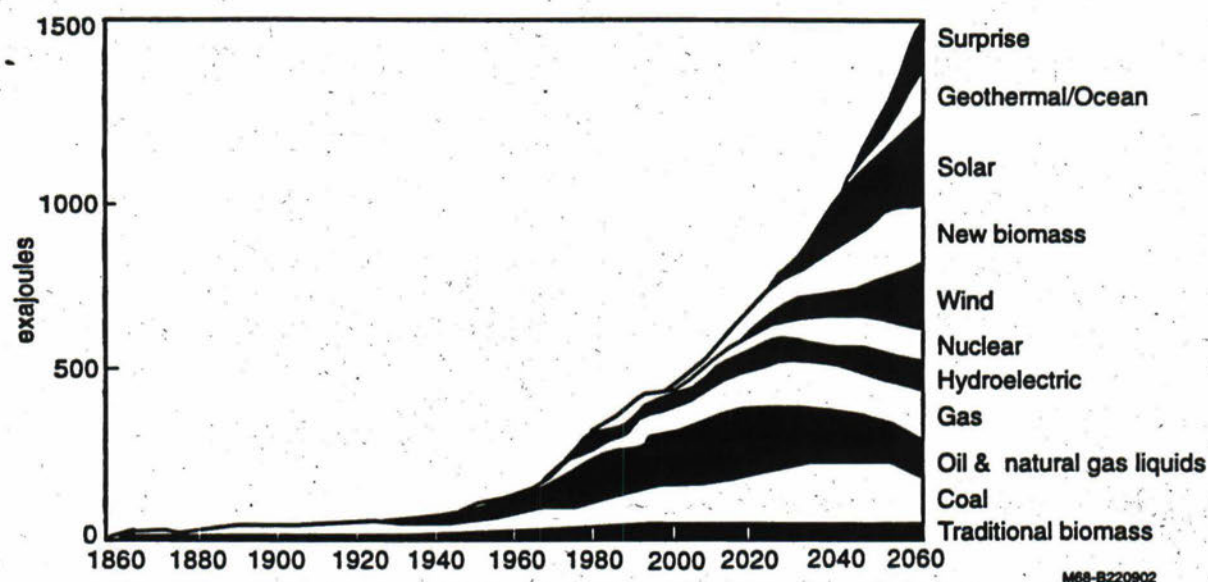
parabolic dish reflectors to provide thermal energy to a Stirling engine mounted at the focal point of the dish. A few individual prototype units, which have power outputs of about 10-25 kW each, are being tested in the United States.

While EIA projects negligible gains for solar thermal generating capacity by 2010 (EIA, 1996), DOE's recent Quality Metrics Study suggests that solar thermal systems will provide approximately 2 TWh of electricity in 2010 in a BAU scenario (Office of Energy Efficiency and Renewable Energy, 1997). Under the HE/LC scenario of this study, an estimate of 0-2 GW capacity and 0-6 TWh electricity generation in 2010 is probably reasonable. This would reduce carbon emissions about 0-1 MtC.

7.3.2 The Long-Term Role of Renewables

As indicated at the beginning of this section, it is quite likely that renewable energy technologies will play a crucial role in limiting carbon emissions and global warming in the long term. Continued domestic and international economic development that does not foster further global warming will require greater energy consumption coupled with lower carbon emissions. The only options are thus low-carbon energy supplies, such as nuclear power or renewables, or the sequestration of carbon emissions from the use of fossil fuels. With the continuing technological development and cost reductions of renewables, renewables may become preferred energy resources some time within the next one to three decades. Moreover, they will probably expand to become the world's primary energy resource in the latter half of the next century. In fact, just such a transition was suggested recently by Shell International (Figure 7.14) (Royal Dutch/Shell Group of Companies, 1996).

Figure 7.14 Sustained Growth Scenario from Shell International (Reproduced courtesy of Shell International Petroleum Company)



This subsection describes the future direction and likely accomplishments of continuing R&D in renewables. This discussion should lend credence to the prediction that non-hydro renewables will make the transition from a minor to a major contributor to the world's electricity supplies.

Biomass Power

The most important R&D areas for biomass power are in gasification/conversion systems and in feedstock production. Gasification involves converting the solid biomass feedstock material to a gas that is cleaned and then burned in a combustion turbine or used in a combined-cycle plant. This technology is currently in the initial demonstration stage of development.

The importance of this technology is that it can take advantage of advanced turbine designs and heat-recovery steam generators to achieve almost twice the efficiency of currently installed biomass technologies (NREL estimates, 1997). High-pressure gasification technologies yield the highest efficiencies, but they also require the development of efficient, cost-effective methods for cleaning the hot gases before they enter the turbine.

On the biomass production side, genetic research is likely to produce energy crop species that provide consistently higher biomass yields on an energy-content basis, thus providing a proportional reduction in biomass feedstock costs. Related research into new species designed for better fuel production also looks promising in terms of significantly decreasing biofuels costs over time. Research into advanced agricultural methods will also lower feedstock production costs over time. Finally, the development of simpler feedstock handling and processing methods will also lead to lower costs. Whole-tree processing methods, for example, which avoid the cost of chipping the wood before processing or use, could reduce the cost of harvesting and delivering the biomass to the power plant by about one-third (OTA, 1995).

Taken together, improvements in biomass power conversion as well as feedstock production and processing could reduce the cost of electricity from biomass to about 3-4 cents/kWh. This would make biomass power very economical in comparison to other mainstream electricity sources. As biomass power expands, most of it will employ dedicated feedstocks. In this context, biomass use will entail low net carbon emissions. These net emissions primarily result from the combustion of fossil fuels in production and delivery, because the carbon emitted during conversion will be reabsorbed as new feedstock grows. Thus, biomass power can become a major contributor to reducing overall carbon emissions from electricity generation in the coming decades.

Wind Power

The technological and economic feasibility of wind power — both in the United States and abroad — has already been well established, as the wind generation capacity curves in Figure 7.12 indicate. Nonetheless, major advances for wind power technology in both the short-term and long-term are likely. These are predicted for the short-term by DOE's cost and performance projections (Office of Utility Technologies, 1997), as illustrated in Figure 7.13.

Wind turbine design is the most critical R&D area. In general terms, the research goals are to produce turbine designs that have half of the material content of today's turbines, at perhaps three-quarters of the material cost (to account for more expensive materials), but with higher efficiencies and longer lifetimes. Such design improvements will not only lower the cost of wind-generated electricity, they will also make it economically practical to utilize the widespread, somewhat lower quality wind resources found in Class 4 wind regimes. Some of the critical research needed to achieve these goals includes continued empirical research into the air-turbine blade interface, computational fluid dynamics modeling of that interaction, and fatigue testing and structural modeling coupled with materials research. This is all aimed at producing more efficient turbine blades that minimize material utilization while extending blade operating lifetimes.

Another important area of R&D concerns the development of direct-drive generators and improved power electronics. This will yield higher conversion efficiencies and more durable power-conversion components, eliminating the need for a gearbox in the drive train. A major challenge will be the integration of advanced components and controls into large-scale, utility-class hardware.

There is also considerable room for improvement in turbine manufacturing processes through process development and automation, since today's turbine blades are still largely built by hand.

A fourth critical research area is that of wind prospecting and prediction. Wind regimes are extremely site-specific, so even though wind resources have been broadly categorized for the nation and the world as a whole, the siting of individual wind farms requires detailed information in order to select the best site. Wind speeds can vary dramatically over the course of seconds (due to turbulence), hours (diurnal variations), days (weather fronts), and months (seasonal variations). The best locations are those with strong, sustained winds having little turbulence. Finding such locations requires extensive prospecting and monitoring (OTA, 1995). The development of better tools for resource characterization and prediction will both improve the economics of wind power and enhance its value by enabling utilities to more reliably predict the power output from specific wind power plants.

Another important thrust for research is to address siting issues. For example, the tops of ridges are often good wind sites, but such a visible location for a wind farm can be a cause for concern when the site is either close to a population center or in an area of particularly great scenic value. To date, there have been virtually no studies to understand the local values associated with the visual impact of wind systems relative to other energy technologies in the United States. Yet such analysis could play a key role in decisions about the adoption of wind power in specific regions. Another environmental consideration affecting site selection is the potential risk to birds, particularly raptors, which sometimes fly into the rapidly turning rotor blades. This, too, seems like an issue that may well be resolved through research to understand the scope of the problem relative to other threats to bird species as well as the development of ways to keep birds a safe distance from moving turbine blades.

In summary, the research front for wind power technology is very broad. Achievements are likely to lead to widespread adoption and application of this electric power technology throughout the world, wherever resources are adequate, over the next few decades.

Geothermal Electricity

Both current geothermal power systems and advanced geothermal power technology concepts will benefit from continuing R&D.

Today's geothermal power plants use the thermal energy from hot water and steam in hydrothermal reservoirs to generate electricity. While the power conversion and drilling technologies related to these power plants are considered relatively mature, they will also benefit from R&D in heat exchangers, hot fluid management systems, and new thermal conversion cycles. These activities alone could result in energy cost reductions of at least 20% in the next few years (NREL estimates, 1997).

The most important R&D area for conventional geothermal technology is resource exploration and characterization. The cost of geothermal electricity is highly dependent on resource characteristics such as temperature, depth, sustainable extraction rate, fluid chemistry, and ease of drilling. By 2020, improvements in drilling technology, advanced seismic data gathering, and better computer

modeling and interpretation of the data could lower the average cost of locating and assessing geothermal resources by 50% (NREL estimates, 1997).

In the long term, geothermal power plants could make use of hot dry rock resources — areas of exceptionally hot rock (above 150°C) that have little or no water in them. Energy can be extracted from these zones by injecting water from the surface underground, where it is heated. Although the engineering feasibility of extracting energy from hot dry rock has already been demonstrated (Secretary of Energy Advisory Board, 1995), further R&D is necessary to make the technology commercially viable. With success in that endeavor, the potential for geothermal power would be vastly expanded because hot dry rock resources are widely available.

Photovoltaic Power Systems

Although PV power technology has already experienced major gains in both performance and economics as a result of R&D conducted over the past 30-40 years, there is still considerable potential for further improvements. This is true for essentially all aspects of PV power systems, including research on basic photovoltaic materials, development of high-efficiency PV cells and modules, development of better PV power products, lower cost manufacturing processes, and improvements in the various components of PV systems.

A good example of the potential of PV R&D is found by comparing the module efficiencies of current commercial PV modules with the efficiencies of individual solar cells. For crystalline silicon PV technology, the technology representing about 90% of current sales, commercial module efficiencies are generally between 10% and 15%, while the best laboratory cell efficiencies are well above 20%. For thin-film PV technology, which includes amorphous silicon, copper indium diselenide, and cadmium telluride modules, current module efficiencies are generally well under 10%, but cell efficiencies are above 15%. Thus, in all cases, progress in commercial products would be virtually assured through the replication of established laboratory results. There is also clearly the potential for greater increases in cell efficiencies over today's laboratory results. Some of the research tools that are being applied include computer modeling of various semiconductor materials and atomic-level engineering of new devices to better understand their photovoltaic and electronic properties.

Looking ahead, we find that significantly greater efficiencies are possible. For example, multi-junction cells have been tested with efficiencies above 30%. At this time, these are small, laboratory-scale devices whose initial application is expected to be with concentrators, in which the cost of the cell is significantly offset by the increased solar energy captured by the optical concentrator. However, in a decade or two, it is certainly conceivable that low-cost processes for making similar high-efficiency multi-junction devices will have been developed, which will make it possible to use them in conventional, flat-plate PV modules.

In the area of manufacturing processes, considerable effort is being made to perfect processes that provide uniform, high-quality materials for the thin-film technologies. The fruits of these efforts are likely to be realized in the next few years as a number of firms construct fairly large (5-20 MW per year) manufacturing plants based on the results of process research and development.

There is still considerable progress to be made in the development of PV power products. For example, many PV power systems today are still being individually designed for specific applications. Off-the-shelf PV power systems and consumer products (such as PV walk-lights, lanterns, and battery chargers) are becoming more available, but the commercial PV industry is still a long way from making it as easy to purchase a residential PV system as it is to buy a refrigerator. The development of products that are readily applied to such individual needs will have an

important effect on PV electricity costs because it will increase the volume of sales. A particularly important set of PV products is likely to be PV components for building shells. These include windows, wall materials, awnings, and roofing materials that incorporate PV and are as readily installed as the components they replace in today's building industry. A reasonable long-term target is to have a large fraction of new construction incorporate such building-integrated PV products.

Finally, we will continue to see improvements in the balance-of-system components of PV systems. Examples include power conditioners and controllers, which serve as the electrical operating and interface system for integrating PV power modules with the load and/or the power grid. These components will continue to improve as well as benefit from developments in power electronics. Greater system integration is also likely, simplifying overall system design. A good example is the development of PV modules that incorporate dc-to-ac inverters, an activity that is currently under way.

In summary, PV technology will benefit from major R&D advances for many years to come, and these advances will significantly improve the economics of PV power. Among the implications of these advances, it is likely that PV power systems will reach prices of \$3000/kW by 2010, which is less than half the current average price. Further price reductions will no doubt occur beyond that.

Solar Thermal Electricity

Solar thermal technologies will benefit from R&D in a broad range of areas. For example, successful development of durable silver/polymer reflectors will reduce reflector costs by 25% to 50% for all three technologies, reducing system costs by 10% to 20%. Improved reflectors and receivers will also allow higher operating temperatures and thus higher solar-to-electric conversion efficiencies. Technology advances for Stirling engines will directly benefit dish/engine systems; one of the most important areas is the extension of operating lifetimes between overhauls. The development and application of hybrid solar/natural gas systems will be particularly important for power tower and parabolic trough technologies. These will make it possible to provide dispatchable power and to use combined-cycle technology, as well as smaller solar fields without being penalized by smaller steam turbines, which tend to be less efficient.

By 2020, we are likely to see power-tower conversion efficiencies around 30%, compared with about 15% today, and dish/engine conversion efficiencies of about 35%, up from about 25% in current prototypes. At the same time, these technologies will cost less and be more durable. At this stage, they are likely to be fully competitive with other mainstream power technologies in areas with good solar resources throughout the United States and the rest of the world.

7.4 EFFICIENCY IMPROVEMENTS IN GENERATION AND TRANSMISSION & DISTRIBUTION

Lowering the heat rates of fossil-fueled generation results in greater efficiency (i.e., less fuel burned per electricity generated) and lower carbon emissions. OTA (1991, p. 320), for instance, suggests that improved maintenance could reduce heat rates by 5%, resulting in a reduction of 22 million tonnes of carbon emissions by the year 2000. OTA includes this measure in their "moderate" scenario, viewing it as either a low-cost or a no-cost measure. The rate of improvement assumed by OTA is consistent with a power plant performance monitoring and improvement project conducted by the Electric Power Research Institute (1986; 1989). Hirst and Baxter (1997) also note the value of cutting heat rates for fossil-fuel power plants, as a carbon reduction option. No efficiency improvements to existing fossil plants are assumed in the 1997 *Annual Energy Outlook's* reference case (Schouberlein, 1997).

The Southern Company has had extensive experience with improving the efficiency of their electric utility system. Over a thirteen-year period, the Southern Company was able to reduce its heat rate by 5.8%, lowering it from approximately 10,300 Btu/kWh (in 1982) to less than 9,700 Btu/kWh (in 1994) (Southern Company, 1993; Siegel, 1997). This represents an improvement in fossil system efficiency from approximately 33.2% (in 1982) to 34.8% (in 1994). The current level of efficiency in U.S. fossil-fired power plants is approximately 33%. In addition to improving the company's system-wide heat rate, the Southern Company was able to increase its reliability from 88% (in 1982) to 96% (in 1994) (Southern Electric International, 1996), and was able to increase its availability to approximately 86%. The current availability of U.S. fossil-fired power plants is approximately 81%.

These heat rate and availability improvements to the Southern Company's electric system have provided benefits valued at \$1.1 billion/year. One of the largest benefits to the Southern Company has been from the deferral of 6,000 MW of new capacity. The cost of these heat rate and reliability improvements to the Southern Company is estimated at approximately \$325 million/year. The operation and maintenance activities that comprise these costs include: establishing a heat rate improvement training program, creation of a plant heat rate review board and a system heat rate technical network, assignment of an efficiency engineer at each plant, instituting a program of heat rate monitoring, and investing in design upgrades (Siegel, 1997).

The Southern Company's experience is consistent with the OTA and EPRI estimate that a 5% heat rate improvement is technically feasible at a low cost or at no cost. Such an improvement would result in a concomitant reduction of 5% in the carbon emissions of the utility sector. Based on Chapter 6's HE/LC case (Table 6.4), the electricity sector's carbon emissions in 2010 would be 492 MtC. Although coal generation accounts for only 46.2% of the electricity generation forecasted for 2010, coal plants account for 81% (or 400 MtC) of the carbon produced by the electricity sector. A 5% reduction would represent 20 Mt of carbon emissions. Assuming that 35-65% of this total is feasible, a realistic estimate of the potential reduction is 7-13 MtC.

Improving the efficiency of transmission and distribution (T&D) systems is another supply-side option available to utilities. As with generation, T&D improvements can include both capital investments (for example, new transformers and conductors) and improved operations. Because T&D losses account for only about 7% of total generation, the opportunities to reduce CO₂ emissions through such mechanisms are limited. However, they could nonetheless be cost-effective. Improving T&D efficiency by 10% would cut emissions by almost 1% (Hirst and Baxter, 1997).

7.5 NUCLEAR PLANT LIFE EXTENSION

In both the AEO97 reference case and the restructured case described in Chapter 6, nuclear plants are projected to lose market share in the national mix of electricity generation. Similar trends are forecast worldwide, with the forecasted decline in nuclear power in Europe being particularly large (South, et al., 1997).

In the U.S., the nuclear power capacity of 99.2 gigawatts that existed in 1995 is projected to drop to 88.9 gigawatts in both the AEO97 reference case and the restructured case in 2010. This drop is primarily the result of the retirement of 17 plants whose licenses expire between 1999 and 2010. The combined capacity of these 17 plants is 11.5 gigawatts. The average capacity factor of the remaining plants ranges from 76-79% throughout the forecast, deviating little from the current capacity factor of 77%.

No additional nuclear units are actively under construction in the U.S. Therefore, no new planned units are assumed to come into service during the 2010 forecast. One nuclear unit, Watts Bar 1 owned by the Tennessee Valley Authority, received its license in 1996, but a few plants have also recently closed.

Nuclear power is a carbon-free source of electricity. Retaining as much as possible of its current power generation would therefore be an important carbon mitigation strategy in an economy where carbon emissions bear a charge of \$50 per tonne, as in the HE/LC scenario.

AEO97 defines a "high nuclear case" which assumes that every nuclear plant operating in 1996 has an additional 10 years of operation, as long as their operating costs do not exceed 4 cents/kWh. This 2010 forecast results in the closure of only three nuclear plants (totaling 1.3 gigawatts of capacity) due to license expirations and the addition of 10.2 gigawatts of new capacity from 14 plant lifetime extensions (EIA, 1996; Nuclear Regulatory Commission, 1996). Thus, nuclear capacity in EIA's forecast for 2010 grows from 88.9 gigawatts (in the reference case) to 99.1 gigawatts (in the "high nuclear case"). Based on a capacity factor of 77%, this 10.2 gigawatts of capacity expansion from nuclear plant life extensions results in 69,000 GWh of additional nuclear energy in 2010, compared to the reference case.

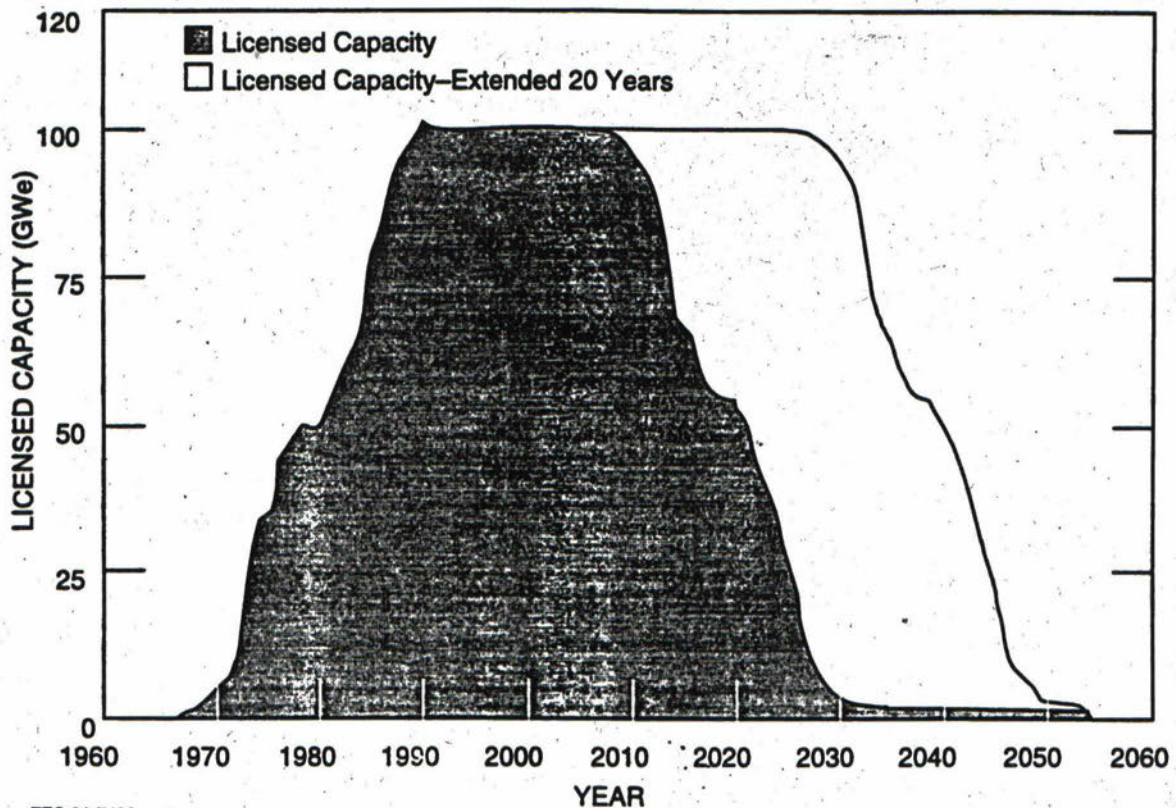
According to EIA's "high nuclear case," 12 Mt of carbon would be offset by this additional carbon-free source of electricity. Using the capacity on the margin in the HE/LC case (with carbon emissions averaging 160 tonnes/GWh), we estimate that the carbon reductions from this additional nuclear resource drop to 11 MtC. A range of 4-7 MtC (from 35-65% of this potential) would appear to be a more realistic forecast for the HE/LC scenario. This range recognizes that it will not be economical or politically feasible to extend the operation of nuclear power plants with licenses that expire by the year 2010.

The AEO97 reference case forecasts that nuclear capacity in the U.S. will decline at an increasing pace after 2010, decreasing from 88.9 gigawatts in 2010 to 62.7 gigawatts in 2015. Thus, with the demand for energy continuing to grow, the impact of nuclear power as a carbon offset declines precipitously over this slightly longer planning horizon. Under the "high nuclear case," the assumed 10-year nuclear plant licensing extensions (subject to the 4 cents/kWh maximum cost) increases nuclear capacity in 2015 from 62.7 gigawatts (in the reference case) to 94.7 gigawatts (in the "high nuclear case"). Thus, the magnitude of carbon offsets offered by this strategy becomes quite significant after 2010.

Figure 7.15 illustrates the accelerated role that nuclear power life extension could have in offsetting carbon emissions after 2010. Only 45 of the nation's 105 nuclear plants have licenses that extend beyond 2020 (Nuclear Regulatory Commission, 1996). An effort to maintain the viability of this capacity could result in a very large contribution to carbon reductions over the next quarter century.

AEO97 does not estimate the cost of its "high nuclear case," although it acknowledges that the physical degradation of some units would have to be reversed. OTA (1991) also notes the potential carbon savings of extending the useful life of all nuclear plants to 45 years, but assumes that this option involves either low costs or saves money. Understanding the effects of aging in order to better manage the aging nuclear infrastructure is an important R&D topic. Pressure vessel embrittlement and the degradation of cables, pumps, and valves can be better managed by advances in materials science and by developing and implementing advanced monitoring technologies. Such technologies are the result of R&D and help maintain the current licensing basis of the nation's nuclear power plants, thereby enabling their operation to extend beyond the initial 40-year licensing period.

Figure 7.15 U.S. Commercial Nuclear Power Reactor Generating Capacity



7.6 ADVANCED COAL TECHNOLOGIES

To test the possible effects on carbon emissions of other advanced fossil-fired electricity generation technologies, we replaced the advanced technologies used by EIA with estimates from DOE's Office of Fossil Energy (see Table 7.6). These estimates changed the construction costs and heat rates for advanced combustion turbines, combined-cycle units, and coal units. ORCED did not select the advanced coal unit with either the EIA or the Fossil Energy estimates of this unit's costs and operating characteristics; in both cases, its initial cost was too high to warrant inclusion in the generation mix. The only significant change to occur was the replacement of the most advanced combustion turbine as specified by EIA with an older combined cycle unit. The net effect of this change on carbon emissions was negligible.

This limited analysis suggests that between now and the year 2010, highly efficient (i.e., a heat rate of about 7000 Btu/kWh) but expensive (i.e., a cost of over \$1000/kW) advanced coal units cannot compete economically with either the generation mix that remains from the 1990s or with gas-fired combined-cycle units.

Table 7.6 Base Case Technologies Compared to Advanced Technologies (costs in 1995\$)

	Original	Alternative	Original	Alternative
Advanced Gas Combined Cycle				
Year of construction	2005	2005	2009	2010
Capital Cost, \$/kW	410	525	410	500
Heat Rate	6284	5688	5817	5538
Fixed O&M, \$/kW-yr	27	16	27	16
Variable O&M, ¢/kWh	0.05	0.015	0.05	0.015
Advanced Gas Combustion Turbine				
Year of construction	2002	2005	2008	2010
Capital Cost, \$/kW	339	400	374	364
Heat Rate	10873	8699	7793	8533
Fixed O&M, \$/kW-yr	11.9	17.6	16.9	17.6
Variable O&M, ¢/kWh	0.010	0.012	0.05	0.012
Advanced Coal				
Year of construction	2006	2005		
Capital Cost, \$/kW	1340	1050		
Heat Rate	9600	7064		
Fixed O&M, \$/kW-yr	34	26		
Variable O&M, ¢/kWh	0.25	0.2		

7.7 SUMMARY

Table 7.7 summarizes the potential reductions in carbon emissions that could occur as the result of the technology options discussed in this chapter. Each option is intended to reflect roughly the amount that could be achieved under aggressive policies combined with a carbon incentive of approximately \$50/tonne. The total carbon reductions from the options shown in Table 7.7 range from 80 to 117 MtC by the year 2010. Additional carbon reductions may result from landfill gas recovery, photovoltaics, geothermal, and solar thermal resources.

The analysis of renewable energy potential over the next quarter century indicates that with a vigorous and sustained program of research, development, and deployment, renewable energy technologies could be providing a greater and rapidly growing contribution to electricity generation by the year 2020. The potential contributions of carbon sequestration, advanced coal technology, and nuclear power were not explored in this report.

Table 7.7 Carbon Reduction Potential of Selected Electricity Supply Technology Options in the HE/LC Scenario with Carbon Permit Price of \$50/tonne

	High-Efficiency/Low-Carbon Case (MtC)
Converting coal-based power plants to natural gas	44
Cofiring coal with biomass	16-24
Wind	6-20
Hydropower	3-9
Efficiency Improvements	7-13
Extending the life of existing nuclear plants	4-7
Total	80-117

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ENDNOTES

¹ Other approaches include (1) repowering with an advanced coal technology (integrated coal gasification combined cycle (IGCC), or pressurized fluidized bed combustion (PFBC)) or (2) plant performance (efficiency) improvements through various management and technical adjustments. With both of these "other" repowering options, the carbon emissions reduction potential is not as great as with NGCC due to (1) the magnitude of efficiency improvement and (2) the carbon (together with sulfur and nitrogen) content of coal versus natural gas.

² All coal-fired power plants greater than 50 MW, and projected to remain in operation, were considered for NGCC repowering: 22.5 gigawatts (GW) of capacity identified by EIA in AEO97 to be uneconomic were deleted, as were 47.5 GW determined to be unneeded due to end-use energy efficiency improvements (see Section 6). Appendix G-2 discusses the deletion of this capacity from the coal/gas repowering analysis.

³ One million Btu (MBtu) is the equivalent of one thousand cubic feet (MCF) of natural gas. One trillion cubic feet of natural gas is abbreviated as TCF.

⁴ This estimate of gas transmission cost may be high, since it may overestimate the amount of interstate and intrastate pipeline that is needed to serve the repowered capacity. Alternatively, since the costs are averaged over all candidate plants based on gas volume delivered to the repowered site, it may approximate the diseconomies of scale that might arise in expanding compression or building new pipeline to serve only a limited amount of repowered capacity.

⁵ A constant 1995 gas/coal price differential assumes that (1) end-use energy efficiency has an offsetting effect on increased utility gas consumption and/or (2) extraction/production costs for natural gas decline at the same rate as the increase in demand.

⁶ The gas/coal price differential of \$0.72/MBtu represents the 1995 value as reported by EIA in its Annual Energy Outlook (AEO97). It represents a lower bound value, since the differential remains constant over time (and demand), reflecting no price response by the natural gas industry with increasing utility fuel demand. The \$1.18/MBtu reflects the 2010 gas/coal price differential within AEO97. This differential reflects a real natural gas price increase of \$0.40/MBtu (\$2.04/MBtu in 1995 to \$2.44/MBtu in 2010) and a 1.9 TCF increase in utility gas demand.

⁷ "Partial Repowering" is equivalent to the "no additional transmission cost" case.

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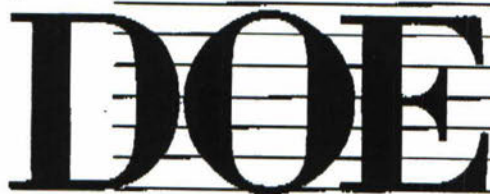
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CLEAN TECHNOLOGY CAN ACHIEVE SIGNIFICANT GREENHOUSE GAS REDUCTIONS

Peer-Reviewed Energy Study: What's Good for Environment is Good for Economy

National investment in energy-efficiency and clean energy technologies can reduce U.S. emissions of global warming gases and produce energy savings that roughly equal or exceed the costs to implement them, Energy Department experts predict. A study conducted by five Department of Energy laboratories and peer-reviewed by industry and academic experts demonstrates that the United States could hold down the costs of meeting climate change goals through technological solutions such as advanced natural gas turbines, biomass and biofuels, and energy-saving appliances. Overall, the study concludes that progress in reducing greenhouse gas emissions can be achieved without increasing the nation's energy bill. Many consumers and businesses could actually save money through reduced energy use and lower overall energy bills.

"This analysis shows that what's good for the environment also can be good for the economy," said Energy Secretary Federico Peña. "Technology can and must play an important role in addressing climate change. President Clinton's commitment to make technology a cornerstone for reducing greenhouse gas emissions is right on target. From the Partnership for a New Generation of Vehicles that's creating the super-efficient car of the future to expanded use of renewable energy sources, we are demonstrating that technology will save energy and protect the environment."

Current projections suggest that a carbon emissions reduction of 390 million metric tons (MMT) would be required to reduce U.S. emissions in 2010 to 1990 levels. The study models a scenario that combines a vigorous national technology program with a domestic system of carbon trading to achieve the reduction. The study concludes that such an approach could reduce emissions by up to 390 MMT. The analysis does not consider international emissions trading and joint implementation that would lower the cost of meeting any emissions reductions. Moreover, the study is not a full macroeconomic analysis.

This study estimated the potential costs of the reductions at \$50 to \$90 billion per year. Costs in the study include incremental investments to deploy clean energy or energy efficient technologies by consumers and industry as well as those associated with hypothetical increases in energy prices. In addition, Energy Department experts reviewed energy cost savings resulting from the use of these technologies; these estimated savings through 2010 total \$70 to \$90 billion per year. This indicates that the clean energy investments could produce energy cost savings roughly equal to or greater than the costs of implementation, on a life-cycle basis.

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The "bottoms-up" approach in the study examines 200 specific technologies in four major sectors of the economy -- buildings, industry, transportation and electric utilities -- and analyzes the possible advances in each sector. For the buildings, industry and transportation sectors, the study analyzes the impacts of end-use energy-efficiency improvements and low-carbon technologies on carbon emissions. The utility sector analysis estimates the impacts of clean energy activities, such as increased use of natural gas and renewable energy. While no one measure can address the entire problem, technologies already in development could contribute substantially to the reductions. For example:

- **Transportation:** The Partnership for a New Generation of Vehicles is developing advanced automobiles that will be three times more fuel-efficient than today's vehicles but still safe and affordable. In the biofuels area, cellulosic ethanol, a promising biofuel made from agricultural and forestry wastes, produces no net carbon emissions; the Energy Department projects cutting the cost of ethanol to under 70 cents/gallon by 2010.
- **Buildings:** The study projects promising carbon reductions from energy-efficient appliances supported by the Energy Department, including a 1 kilowatt-hour/day refrigerator and advanced lighting. Advanced fuel cells powered by natural gas will produce electricity and provide heating at 80-percent efficiency, while lowering the current cost of power.
- **Utilities:** Wind turbines are expected to produce power at less than 3 cents/kilowatt-hour by 2010. Biomass co-firing with coal at some plants could produce significant emissions reductions.
- **Industry:** Advanced turbines are expected to achieve 80 percent system efficiency, producing electricity and steam in industrial plants at less than today's costs. Advanced motor systems and clean industrial technologies can cut emissions and costs while increasing productivity.

The Department of Energy's Oak Ridge and Lawrence Berkeley National Laboratories led the comprehensive one-year analysis, with contributions by the National Renewable Energy Laboratory and Pacific Northwest and Argonne National Laboratories. The findings, which were reviewed extensively by representatives from industry and academia, are consistent with those of two previous studies. Those studies, released by the National Academy of Sciences and Office of Technology Assessment in 1991, also concluded that technology could play a prominent role in reducing U.S. greenhouse gas emissions.

To request a summary or full copy of the study, titled *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficiency and Low-Carbon Technologies by 2010 and Beyond*, media can call the Department of Energy Press Office at 202/586-5806; others can call Public Inquiries at 202/586-5575.

EXECUTIVE SUMMARY

This report presents the results of a study conducted by five U.S. Department of Energy national laboratories that quantifies the potential for energy-efficient and low-carbon technologies to reduce carbon emissions in the United States.¹ The study documents in detail how four key sectors of the economy – buildings, transportation, industry, and electric utilities – could respond to directed programs and policies to expand adoption of energy-efficiency and low-carbon technologies, an increase in the relative price of carbon-based fuels by \$25 or \$50/tonne (e.g., as a result of a cap on domestic carbon emissions and a market for carbon "permits"), and an aggressive program of targeted research and development. Current projections suggest that a carbon emissions reduction of 390 million metric tons per year (MtC/year) is required to stabilize U.S. emissions in 2010 at 1990 levels.

The study, which has been peer-reviewed by industry and academic experts, uses a technology-by-technology assessment as well as an engineering-economic modeling approach. It draws upon a wide variety of technology cost and performance information to assess potential impacts. Analysis of the buildings, industry, and transportation sectors quantifies the impacts of end-use energy-efficiency improvements on carbon emissions. The utility sector analysis estimates the impacts of those improvements on utility carbon emissions, and quantifies additional emissions reductions through conversion of a number of coal power plants to natural gas, dispatching of the utility grid with \$25 and \$50/tonne carbon permit prices, the accelerated use of biomass cofiring and wind energy, and other low-carbon electricity supply options. Finally, a number of other promising low-carbon technologies are examined to determine their potential for reducing emissions in the end-use sectors, including advanced gas turbines in industry, transportation biofuels, and fuel cells in buildings.

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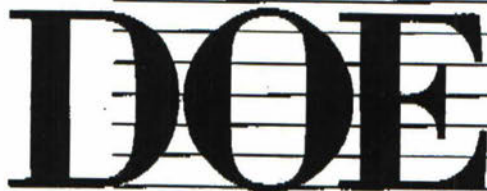
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September 25, 1997

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-DOE-

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REMARKS:

To: People Working on Climate Change Issues

Enclosed is a news release issued yesterday, September 25, by the Sustainable Energy Coalition commenting on the newly-published Department of Energy's five national laboratories' study on climate change.

Generally, the Sustainable Energy Coalition commends DOE for being on the right track in quantifying the significant contribution that can be made by renewable energy and energy efficiency in reducing greenhouse gas emissions.

However, the Coalition also believes that these technologies can take the U.S. faster and further in meeting climate change goals given the right mix of federal policies and private sector incentives.

Comments are welcomed.

SUSTAINABLE ENERGY COALITION

315 Circle Avenue, #2; Takoma Park, MD 20912-4836 (301-270-2258; fax: 301-891-2866

DOE LABS' CLIMATE CHANGE STUDY ON THE RIGHT TRACK BUT UNDERESTIMATES POTENTIAL TO REDUCE GREENHOUSE GAS EMISSIONS

**For Release: September 25, 1997
5:00 p.m. (EST)**

**Contact: Ken Bosson 301-270-2258
Howard Geller 202-429-8873**

Washington, DC -- A major study released today by five national U.S. Department of Energy (DOE) laboratories recognizes the prominent role to be played by renewable energy and energy efficient technologies in reducing greenhouse gas emissions. However, while acknowledging it to be the best federal government study yet released on the role these technologies could play in addressing climate change, the Sustainable Energy Coalition, a coalition of 40+ national business, environmental, consumer, and energy policy organizations, contends that its conclusions are still too conservative and underestimate the potential of renewables and energy efficiency.

The DOE study concludes that a "vigorous" national commitment to deploy cost-effective energy-efficient and low-carbon technologies, including renewable energy, could halt the growth in U.S. energy consumption and carbon emissions so that levels in 2010 are close to those in 1997 (for energy) and in 1990 (for carbon). It suggests that the near-term contribution of renewable energy technologies -- particularly biomass, hydropower, and wind -- would be at least modest although they, along with geothermal, and solar "could deliver significant quantities of electricity" by 2020. The DOE study finds that the reduction in energy use and carbon emissions can be realized without harming the U.S. economy; in fact, it might yield a net economic benefit -- an important conclusion consistent with the views of the Sustainable Energy Coalition.

However, noting that the United States accounts for only 4 percent of the world's population but is responsible for 22 percent of its greenhouse gas emissions, the Coalition believes the U.S. can -- and must -- move further and faster in deploying sustainable energy technologies than the DOE study envisions. In fact, the Coalition maintains that waiting until 2010 to stabilize greenhouse gas emissions at 1990 levels, a goal this country had earlier committed to reach by 2000, is both irresponsible and unnecessary. Instead, the

United States should assume a leadership role in negotiating an international agreement in Kyoto, Japan in December setting legally binding targets to achieve substantial reductions in the emissions of greenhouse gases from 1990 levels by 2010 at the latest as has been proposed by the European Union and other nations.

This goal can be achieved through policies that aggressively promote the expanded use of presently-available and cost-effective energy-efficient and renewable energy technologies. Widespread market penetration of energy-efficient technologies could insure that total energy consumption is no higher than today's levels by the year 2010 while, in combination with changes in the fuel mix, reducing greenhouse gas emissions by at least 10 percent below 1990 levels. Furthermore, by the year 2010, renewable energy could at least double its present contribution to meet 14 percent, or more, of the nation's energy consumption.

Achieving reductions beyond those in the new DOE study are possible through cuts in the growth in vehicle use, advanced building technologies, and expanded adoption of renewable energy sources -- measures that are excluded from, or only partially included, in the DOE report. Policies such as higher fuel efficiency standards for automobiles, appliances, motors, lighting, and buildings as well as requirements to include an increasing percentage of renewable energy in the electrical generation and transportation sectors are needed to remove the barriers inhibiting widespread adoption of these efficiency measures and renewable energy technologies.

Finally, the Sustainable Energy Coalition also questions DOE's suggestion that nuclear power plant life extension might play any role as a greenhouse gas control strategy. Although DOE sees nuclear power reducing greenhouse gas emissions by about only one-third of one percent, it is doubtful whether the nation's aging nuclear plants will survive in a deregulated utility market. In addition, safety and radioactive waste concerns coupled with the generation of carbon dioxide in the total nuclear fuel cycle make nuclear power a poor climate stabilization strategy.

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A copy of the DOE study's 16-page "Analysis Results" is available upon request from the Sustainable Energy Coalition. A list of the participating organizations that comprise the Sustainable Energy Coalition is also available upon request.

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Key findings and conclusions emerge from the analysis of alternative carbon scenarios. First, a vigorous commitment to develop and deploy energy-efficient and low-carbon technologies has the potential to restrain the growth in U.S. energy consumption and carbon emissions such that levels in 2010 are close to those in 1997 (for energy) and 1990 (for carbon). We analyze a case in which energy efficiency and low-carbon technologies reduce carbon emissions by 120 MtC/year by 2010. We analyze a second case, with policies that include the option of energy-efficient and low carbon technologies and a \$25/tonne carbon permit price, that achieves carbon reductions of 230 MtC/year in 2010. Under a \$50/tonne carbon permit price and aggressive research and development, carbon emissions could be cut by about 390 MtC/year. The analysis also suggests that substantial savings are available if permit prices were to begin to rise above the \$50/tonne level.

The overall conclusion is that, if feasible ways are found to implement the carbon reductions as described in the cases (with reductions varying between 120 and 390 MtC/year by 2010) can produce energy savings that are roughly equal to or exceed costs.² The analysis includes only technologies estimated to be cost-effective under 2010 energy prices (with a \$25/tonne and \$50/tonne carbon permit price for the cases); it has not, however, analyzed specific policies to achieve the cases, identified the feasibility of policies, or described a pathway to achieve the cases.

The overall conclusion is that a next generation of energy-efficient and low-carbon technologies promises to continue the continuation of an aggressive pace of carbon reductions over the next quarter century. This requires a wide array of advanced technology options that could be cost-competitive by the year 2010, and a vigorous and sustained program of energy R&D beginning now and extending beyond 2010.

National laboratories participating in the study were: Argonne National Laboratory (ANL), Lawrence Berkeley Laboratory (LBL), National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL). LBNL and ORNL were the co-leaders of the effort.

We report as benefits only the energy savings to the nation. We have not credited reduced CO₂ emissions or other benefits. Costs include the increased technology cost plus an approximate estimate of the costs of program and administration.

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FOR IMMEDIATE RELEASE

September xx, 1997

**Clean Technology Can Achieve
Significant Greenhouse Gas Reductions**

Peer-Reviewed Energy Study: What's Good for Environment is Good for Economy

Redoubled national investment in energy-efficiency and clean energy technologies can reduce U.S. emissions of global warming gases and produce energy savings that roughly equal or exceed the costs to implement them, Energy Department experts predict. A study conducted by five Department of Energy laboratories and peer-reviewed by industry and academic experts demonstrates that the United States could hold down the costs of meeting climate change goals through technological solutions such as advanced natural gas turbines, biomass and biofuels, and energy-saving appliances. Many consumers and businesses would actually save money through reduced energy use and lower overall energy bills.

"This analysis provides strong evidence that climate change goals can be achieved without increasing the nation's energy bill. What's good for the environment also can be good for the economy," said Energy Secretary Federico Peña. "President Clinton's plan to make technology a cornerstone for reducing greenhouse gas emissions can achieve these results. From the Partnership for a New Generation of Vehicles that's creating the super-efficient car of the future to expanded use of renewable energy sources, the technology solution is already creating environmental benefits and savings in energy costs."

Current projections suggest that a carbon emissions reduction of 390 million metric tons (MMT) would be required to reduce U.S. emissions in 2010 to 1990 levels. The study models a scenario that combines a vigorous national technology program with a domestic system of carbon trading to achieve the reduction. The study concludes that such an approach could reduce emissions by up to 390 MMT. A new generation of technologies and international carbon emission trading could result in further reductions over the next quarter century.

This study estimated the potential costs of the reductions at \$50 to \$90 billion per year. Costs include incremental investments to deploy clean energy or energy efficient technologies by consumers and industry. In addition, Energy Department experts reviewed energy cost savings resulting from the use of these technologies; these estimated savings through 2010 total \$70 to \$90 billion per year. This indicates that the clean energy investments could produce energy cost savings roughly equal to or greater than the costs of implementation.

The "bottoms-up" approach in the study examines 200 specific technologies in four major sectors of the economy -- buildings, industry, transportation and electric utilities -- and analyzes the possible advances in each sector. For the buildings, industry and transportation sectors, the study analyzes the impacts of end-use energy-efficiency improvements and low-carbon technologies on carbon emissions. The utility sector analysis estimates the impacts of clean energy activities, such as increased use of natural gas and renewable energy. While no one measure can address the entire problem, technologies already in development could contribute substantially to the reductions. For example:

- **Transportation:** The Partnership for a New Generation of Vehicles is developing advanced automobiles that will be three times more fuel-efficient than today's vehicles but still safe and affordable. In the biofuels area, cellulosic ethanol, a promising biofuel made from agricultural and forestry wastes, produces no net carbon emissions; the Energy Department projects cutting the cost of ethanol to under 70 cents/gallon by 2010.
- **Buildings:** The study projects promising carbon reductions from energy-efficient appliances supported by the Energy Department, including a 1kilowatt-hour/day refrigerator and advanced lighting. Advanced fuel cells powered by natural gas will produce electricity and provide heating at 80-percent efficiency, while lowering the current cost of power.
- **Utilities:** Wind turbines are expected to produce power at less than 3 cents/kilowatt-hour by 2010. Biomass co-firing with coal at some plants could produce significant emissions reductions.
- **Industry:** Advanced turbines are expected to achieve 80-percent system efficiency, producing electricity and steam in industrial plants at less than today's costs. Advanced motor systems and clean industrial technologies can cut emissions and costs while increasing productivity.

The Department of Energy's Oak Ridge and Lawrence Berkeley National Laboratories led the comprehensive one-year analysis, with contributions by the National Renewable Energy Laboratory and Pacific Northwest and Argonne National Laboratories. The findings, which were reviewed extensively by representatives from industry and academia, are consistent with those of two previous studies. Those studies, released by the National Academy of Sciences and Office of Technology Assessment in 1991, also concluded that technology could play a prominent role in reducing U.S. greenhouse gas emissions.

To request a summary or full copy of the study, titled *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficiency and Low-Carbon Technologies by 2010 and Beyond*, media can call the Department of Energy Press Office at 202/586-5806; others can call Public Inquiries at 202/586-5575.

- DOE -

DRAFT

**Key Points for the Report "Scenarios of U.S. Carbon Reductions:
Potential Impacts of Energy Technologies by 2010 and Beyond"**

Clean Technologies Can Achieve Significant Reductions of Greenhouse Gas Emissions

A major new study by five leading national laboratories concludes that redoubled national investment in energy-efficiency and clean energy technologies can reduce U.S. emissions of global warming gases and produce energy savings that roughly equal or exceed the costs to implement them.

The study concludes that energy efficiency and low-carbon technologies have the potential to reduce U.S. carbon emissions to 1990 levels in the medium term (i.e. 2010) while meeting the full energy needs of U.S. businesses and families. Many consumers and businesses would save money through reduced energy use and lower overall energy bills.

This study, led by Oak Ridge and Lawrence Berkeley National Laboratories is a comprehensive, peer-reviewed, one year "bottom-up" analysis of the role technology can play in stabilizing U.S. carbon emissions.

It is the most authoritative and documented study of this subject since the National Academy of Sciences and the Office of Technology Assessment reports in 1991.

This study presents a scenario in which a vigorous nation commitment to emissions reduction - in the form of an aggressive program of clean technology research, development, and deployment combined with carbon permit trading - result in carbon emissions reductions of up to 390 million metric tons in 2010.

The study is not a prediction of the future, but rather a description of a scenario of a possible future in which greenhouse reductions occur through increased technology investments that are both technically and economically feasible together with domestic trading of carbon such as presently exists for sulphur. The study estimates the direct costs and energy bill savings for this scenario, but does not offer a full macroeconomic analysis. What it does offer is a detailed scenario showing that what is good for the environment can be good for the economy.



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SCENARIOS OF U.S. CARBON REDUCTIONS

Potential Impacts of Energy-Efficient and Low-Carbon Technologies
by 2010 and Beyond

Prepared by the
Interlaboratory Working Group on
Energy-Efficient and Low-Carbon Technologies

Oak Ridge National Laboratory*
Lawrence Berkeley National Laboratory*
Pacific Northwest National Laboratory
National Renewable Energy Laboratory
Argonne National Laboratory

Prepared for
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

*Coordinating laboratories for this study

EXECUTIVE SUMMARY

This report presents the results of a study conducted by five U.S. Department of Energy national laboratories that quantifies the potential for energy-efficient and low-carbon technologies to reduce carbon emissions in the United States.¹ The study documents in detail how four key sectors of the economy – buildings, transportation, industry, and electric utilities – could respond to directed programs and policies to expand adoption of energy-efficiency and low-carbon technologies, an increase in the relative price of carbon-based fuels by \$25 or \$50/tonne (e.g., as a result of a cap on domestic carbon emissions and a market for carbon "permits"), and an aggressive program of targeted research and development. Current projections suggest that a carbon emissions reduction of 380 million metric tons per year (MtC/year) is required to stabilize U.S. emissions in 2010 at 1990 levels.

The study, which has been peer-reviewed by industry and academic experts, uses a technology-by-technology assessment as well as an engineering-economic modeling approach. It draws upon a wide variety of technology cost and performance information to assess potential impacts. Analysis of the buildings, industry, and transportation sectors quantifies the impacts of end-use energy-efficiency improvements on carbon emissions. The utility sector analysis estimates the impacts of those improvements on utility carbon emissions, and quantifies additional emissions reductions through conversion of a number of coal power plants to natural gas, dispatching of the utility grid with \$25 and \$50/tonne carbon permit prices, the accelerated use of biomass cofiring and wind energy, and other low-carbon electricity supply options. Finally, a number of other promising low-carbon technologies are examined to determine their potential for reducing emissions in the end-use sectors, including advanced gas turbines in industry, transportation biofuels, and fuel cells in buildings.

Three overarching conclusions emerge from the analysis of alternative carbon scenarios. First, a vigorous national commitment to develop and deploy energy-efficient and low-carbon technologies has the potential to restrain the growth in U.S. energy consumption and carbon emissions such that levels in 2010 are close to those in 1997 (for energy) and 1990 (for carbon). We analyze a case in which energy efficiency can reduce carbon emissions by 120 MtC/year by 2010. We analyze a second case, with policies that promote adoption of energy-efficient and low carbon technologies and a \$25/tonne carbon permit price, with emission reductions of 230 MtC/year in 2010. Under a \$50/tonne carbon permit price and aggressive policies, 2010 emissions could be cut by about 380 MtC/year. The analysis also suggests that substantial additional savings are available if permit prices were to begin to rise above the \$50/tonne level.

The second conclusion is that, if feasible ways are found to implement the carbon reductions as described above, all the cases (with reductions varying between 120 and 380 MtC/year by 2010) can produce energy savings that are roughly equal to or exceed costs.² The analysis includes only technologies estimated to be cost-effective under 2010 energy prices (with a \$25/tonne and \$50/tonne carbon permit price for the respective cases); it has not, however, analyzed specific policies to achieve the cases, identified the political feasibility of policies, or described a pathway to achieve the cases.

The third conclusion is that a next generation of energy-efficient and low-carbon technologies promises to enable the continuation of an aggressive pace of carbon reductions over the next quarter century. This report documents a wide array of advanced technology options that could be cost-competitive by the year 2020, assuming a vigorous and sustained program of energy R&D beginning now and extending beyond 2010.

¹ The five national laboratories participating in the study were: Argonne National Laboratory (ANL), Lawrence Berkeley National Laboratory (LBNL), National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL). LBNL and ORNL were the co-leaders of the effort.

² Here we count as benefits only the energy savings to the nation. We have not credited reduced CO₂ emissions or other external benefits. Costs include the increased technology cost plus an approximate estimate of the costs of program and policy implementation.

AUTHORSHIP

Marilyn A. Brown (Oak Ridge National Laboratory) and Mark D. Levine (Lawrence Berkeley National Laboratory) were responsible for the overall leadership of the project. They jointly authored the Executive Summary, Chapter 1 (Analysis Results), and Chapter 2 (Introduction and Background).

Chapter 3 (Buildings) authorship is best described in terms of the analysis for 2010 (Sections 3.2 and 3.3 and associated appendices) and R&D potential in 2020 (Section 3.4). Jonathan Koomey (Lawrence Berkeley National Laboratory) was the lead author for the 2010 analysis. Nathan Martin, Lynn Price, and Mark Levine (LBNL) were co-authors. Marilyn Brown was the lead author for the R&D section, with support from staff at Oak Ridge National Laboratory and Lawrence Berkeley National Laboratory.

Gale Boyd (Argonne National Laboratory), Joseph M. Roop, and Madeline G. Woodruff (Pacific Northwest National Laboratory) were the lead authors of Chapter 4 (Industry) with the exception of Section 4.3 (Low-Carbon Technologies), which was prepared by Helena Chum and Ralph P. Overend (National Renewable Energy Laboratory), Tony Schaffhauser and Marilyn Brown (Oak Ridge National Laboratory), and Tina Kaarsberg (Vista Technologies).

David Greene (Oak Ridge National Laboratory) and Steve Plotkin (Argonne National Laboratory) were responsible for Chapter 5 (Transportation).

Stanton Hadley and Eric Hirst (Oak Ridge National Laboratory) were the authors of Chapter 6 (The Electricity Sector's Response to End-Use Efficiency Changes).

Chapter 7, Electricity Supply Technologies, consists of a variety of topics: Conversion of Coal-Based Power Plants to Natural Gas (Section 7.2) was prepared by David South and Jack Siegel (Energy Resources, Inc.); Renewable Electricity Technologies (Section 7.3) was written by Eldon Boes and Erik Ness with contributions from National Renewable Energy Laboratory staff; the section on Advanced Coal Technologies (Section 7.6) was written by Stanton Hadley (Oak Ridge National Laboratory); and the sections on Efficiency Improvements in Generation and T&D (Section 7.4) and Nuclear Plant Life Extension (Section 7.5) were written by Marilyn Brown (Oak Ridge National Laboratory). Other sections of this chapter are summaries of published materials.

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Staff at Lawrence Berkeley National Laboratory (LBNL) and Oak Ridge National Laboratory (ORNL) put enormous efforts into producing this report, especially as contributions came from many different places. We gratefully acknowledge Barbara Maximovich, Leslie Shown, Sam Webster, and Nathan Martin (LBNL) and Tonia Edwards and Kathi Vaughan (ORNL) for word processing (BM and TE), copy editing (LS and NM), and cleanup of figures (KV and SW).

The completion of this study was guided by a committee of experts from industry, universities, and utility research organizations. The committee was chaired by Bill Fulkerson (University of Tennessee) and included: Morton H. Blatt (Electric Power Research Institute), Daniel E. Steinmeyer (Monsanto Chemical Company), Robert A. Frosch (Kennedy School, Harvard University), Douglas C. Bauer (National Academy of Sciences), Hillard G. Huntington (Energy Modeling Forum, Stanford University) and Thomas Roose (Gas Research Institute).

This report benefited from the contributions and assistance of numerous experts on energy efficiency and electricity production. The authors would like to acknowledge contributors by chapter:

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Chapter 7 (Electricity Supply Technologies): Helena Chum, David Kline and Ralph P. Overend (NREL), Jack Siegel (Energy Resources International, Inc.), Claud Pugh and Mike Sale (ORNL). Ronald Wolk contributed to Appendix G-1 and Ronald Fisher contributed to Appendix G-4.

Staff members of DOE's Energy Information Administration (EIA) participated in the planning process for this report, provided advice and assistance with the modelling described in the report, and offered insightful comments on previous drafts. Leading this group were Mary Hutzler, Andy Kydes, and Barry Cohen. Sector-specific assistance and feedback was provided by EIA's Erin Boedecker and John Cymbalsky (buildings), Crawford Honeycutt (industry); David Chien and Mark Friedman (transportation); and Art Holland and Dave Schoeberlein (electricity).

Non-participating DOE laboratories were asked to comment on various draft materials. This group of reviewers included Jerome LaMontagne (Brookhaven National Laboratory) and Dan Arvizu (Sandia National Laboratory). Additional valuable comments on earlier drafts of this report were received from John Sheffield (ORNL), Jay Braitsch and Doug Carter (DOE's Office of Fossil Energy), and several staff of the American Council for an Energy-Efficient Economy. Economists Al Link (University of North Carolina at Greensboro) and Stephen DeCanio (University of California at Santa Barbara) also provided review comments on the report.

By acknowledging the involvement of the above individuals and the extensive review process in which they participated, we do not mean to imply their endorsement of the report. Final responsibility for the content of this report lies solely with the authors.

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Chapter 2

INTRODUCTION AND BACKGROUND

This report presents the results of a multi-laboratory study aimed at quantifying the potential for energy-efficient and low-carbon technologies to reduce carbon emissions in the United States. The stimulus for this study derives from a growing recognition of the link between energy-efficiency R&D and the nation's ability to respond to international calls to reduce the growth of greenhouse gas emissions. According to a recent report of the Intergovernmental Panel on Climate Change (IPCC), the earth's surface temperature has increased about 0.2 degrees Celsius per decade since 1975. Further, the IPCC report concluded that "the balance of evidence suggests that there is a discernible human influence on global climate" as the result of activities that contribute to the production of greenhouse gases (IPCC, 1996, p. 5). By preventing heat radiated from the sun-warmed earth from escaping into space, the increased concentration of greenhouse gases in the atmosphere contributes to global warming.

The major greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_2O), and a host of engineered chemicals such as chlorofluorocarbons (CFCs). CO_2 accounts for a majority of recent increases in the heat-trapping capacity of the atmosphere, with worldwide atmospheric concentrations of CO_2 increasing at about 0.5% annually. Anthropogenic CO_2 has resulted in atmospheric CO_2 concentrations that exceed pre-industrial levels by 30%. Of all the human activities that contribute to these increases, fossil fuel combustion is by far the largest, accounting for almost 60% of the greenhouse warming resulting from anthropogenic sources in recent years (NAS, 1992, Table 2.2, p. 8). Energy-efficient technologies reduce CO_2 emissions by displacing the need for fossil fuel combustion; this report focuses on this single greenhouse gas. Throughout the report, the climate benefits of energy-efficient and low-carbon technologies are quantified in terms of reductions in millions of metric tons of carbon (MtC) emitted.¹

Analysis by a number of key climate and energy modelers indicates that significant research and development on greenhouse-friendly technologies is essential to achieving meaningful targets at affordable costs. As a result, climate change is becoming a major impetus for energy R&D programs and is likely to grow in importance in the future. By documenting the emissions reductions that past energy-efficiency R&D can deliver by the year 2010, and by describing the potential for future research to reduce carbon emissions even farther, this report is intended to inform a broad public about technology-based approaches to reduce greenhouse gas emissions.

2.1 OBJECTIVES OF THE STUDY

The purposes of this study are threefold:

1. To provide a quantitative assessment of the reduction in energy consumption and carbon emissions that could result by the year 2010 from a vigorous national commitment to accelerate the development and deployment of cost-effective energy-efficient and low-carbon technologies;
2. To document the costs and performance of the technologies that underpin a year 2010 scenario in which substantial energy savings and carbon emissions reductions are achieved;
3. To illustrate the potential for energy-efficiency and renewable energy R&D to lead to further reductions in energy use and carbon emissions by the year 2020.

The report focuses on energy-efficiency and renewable energy R&D. The coverage of additional selected low-carbon end-use and electricity supply options was based in large measure on their perceived potential to contribute significantly to stabilizing carbon emissions by 2010 at their 1990 level, which is one possible national target under discussion.

2.2 METHODOLOGY

2.2.1 Overview

To achieve these objectives, we started with the *Annual Energy Outlook 1997* (AEO97) reference case forecasts for the year 2010 (Energy Information Administration, 1996). After thoroughly reviewing these forecasts on a sector-by-sector basis, and working with EIA staff, we chose to accept the EIA "business-as-usual" (BAU) scenario as is for buildings and industry and to modify some of the assumptions and data and produce a new BAU case – not greatly different from the EIA case – for the transportation and the electric utility sectors.

We then assembled existing information on the performance and costs of technologies to increase energy efficiency or, for selected end-uses, to switch from one fuel to another (e.g., from electricity to natural gas for residential end-uses or from gasoline to biofuels for transportation). For the buildings sector, the technology performance and cost data base are extensive. For transportation, the data base – although less fully developed than for buildings – is sufficient for our purposes. For industry, only partial information on technologies and costs is presently available. As a result, the analysis for industry relies primarily on historical relations between energy use and economic activity and much less on explicit technological opportunities. The industrial analysis also includes some examples of industrial low-carbon technologies. The analysis of low-carbon supply technologies in the electricity sector is based on a review of the literature including detailed technology characterizations prepared by DOE in conjunction with its national laboratories and industry.

Next we created scenarios of increased energy efficiency and lower-carbon emissions using the technology data (or, in the industrial sector, historical relations) as a key input. We chose to run three scenarios other than the BAU case. We have termed the first the "efficiency" case. It assumes that the United States increases its emphasis on energy efficiency through enhanced public- and private-sector efforts. The general philosophy of the efficiency case is that it reduces, but does not eliminate, various market barriers and lags to the adoption of cost-effective energy-efficient technology.

The other two cases, dubbed the "high efficiency/low carbon" (HE/LC) cases, describe a world in which, as a result of commitments made on a climate treaty or other factors, the nation has embarked on a path to reduce carbon emissions. They assume a major effort to reduce carbon emissions through federal policies and programs (including environmental regulatory reform), strengthened state programs, and very active private sector involvement. They include a focused national R&D effort to develop and transform markets for low-carbon energy options (e.g., fuel cells for microcogeneration in buildings and advanced turbine systems for combined heat and power in industry). The difference between the two HE/LC cases is in the assumption of a carbon permit price resulting from a domestic trading scheme for carbon emissions with a cap on U.S. emissions (or from equivalent policy measures that increase the price of carbon-based fuels relative to those with less carbon). We assume a domestic permit price of \$25 and \$50 per tonne of carbon for the two cases. Both of these HE/LC cases include a program of research, development, demonstration and diffusion that is more vigorous than in the efficiency case. In some sectors (buildings and industry), the carbon price signal, combined with policies promoting energy efficiency, is believed to trigger the bulk of the additional carbon reductions portrayed in the HE/LC cases. In the transportation sector, it is

the R&D-driven technology breakthroughs that generate the bulk of the carbon reductions beyond the efficiency case. For the electricity sector, higher prices for carbon based fuels cause larger shifts from coal to natural gas; for this sector, these same higher relative prices combined with federal and private research, development, and demonstration can bring advanced low-carbon technologies to market.

Although the work focuses on 2010, we also look beyond this date. Here we describe new technologies, materials, processes, manufacturing methods, and other R&D advances that promise to offer significant energy benefits by the year 2020; for this time period, we make no effort to forecast specific levels of market penetration, energy savings, or carbon reductions. Thus, instead of creating scenarios we describe the technological innovations that could enable the continuation of an aggressive pace of decarbonization well into the next quarter century, if appropriate investments in R&D were made.

2.2.2 Time Frame

Analysis for all sectors focuses on two base years (1990 and 1997) against which future progress is benchmarked, and a target year of 2010 for assessing emissions reduction potential. Energy use and emissions for 1990 and 1997 are reported as base years against which we compare future energy consumption and carbon emissions.

The report examines a "snapshot" of energy use and carbon emissions, by sector, in 2010. The increased use of energy-efficient technologies combined with the development of new technologies based on past R&D plus an invigorated R&D effort initiated in 1998 are needed to achieve our 2010 scenarios.

We also highlight the likely post-2010 benefits of an intensified investment in energy R&D. This captures the effects of technologies that may not be widely commercial for some years but that could deliver cost-effective energy savings and emissions reductions, if public and privately supported R&D were to accelerate their proof of concept and reduce their developmental risks.

2.2.3 End-Use Efficiency Scenarios

Each of the three end-use sector chapters is consistent in terms of overall approach, scope, and time frame. They each analyze three scenarios for the year 2010: a business-as-usual case, an efficiency case, and a high-efficiency/low-carbon case. (In the integration of this work, we later assess two different HE/LC cases – one with a \$25/tonne carbon charge and the other with a \$50/tonne carbon charge. The buildings sector also presents a "frozen efficiency" baseline, for additional comparison purposes. While there is variation in the methodologies used to estimate the energy savings and emission reductions potential of each sector, the three sector chapters are similar in using a combination of technology analysis and model-based forecasting. Specifically, the buildings and transportation sectors use stock models with technology characteristics and other parameters taken from assessments of individual technologies. The industrial sector forecasts conservation investment behavior based on econometric modeling with industry-specific conservation supply curves as inputs.

All of the scenarios described in this report use the AEO97 forecasts of national economic output as measured by gross domestic product (GDP), which is projected to increase by 1.9% per year through 2015. Similarly, the buildings sector uses the AEO97 forecast of growth in residential and commercial floorspace; the industrial sector uses the AEO97 assumption of a 2.1% annual growth rate for manufacturing production; and the transportation sector uses the AEO97 forecast of a 3.7% annual increase in air travel.

The scenarios for each sector also use the AEO97 energy price forecasts. World oil prices are assumed to rise from \$17 per barrel in 1995 to \$20.4 per barrel (in 1995\$) in 2010. In AEO97, natural gas prices in the industrial, electricity, and transportation sectors increase throughout the forecast period; natural gas prices for the residential and commercial sectors decrease significantly. Between 1995 and 2010, the average price of electricity is projected to decline by 0.6% a year as a result of competition among electricity suppliers. Electricity prices are forecast to decrease the most for industrial customers and the least for residential customers.

Such macroeconomic and fuel price assumptions strongly influence the rate of penetration of energy-efficient technologies in each sector. Further details regarding these assumptions can be found in EIA (1996c).

Frozen Efficiency Baseline. This case, which is analyzed only for the buildings sector, assumes that energy-consuming equipment and systems existing in the year 1997 remain at the same efficiency until they are retired. This equipment and these systems retire over the 1997-2010 period at a rate based on standard equipment lifetimes. It assumes that all new equipment employed after 1997 remains at the efficiency of new devices in the year 1997. The frozen efficiency baseline provides an upper bound to likely energy demand (under the economic assumptions applied to all the cases), because it ignores all forces leading to higher efficiency of new equipment in the business-as-usual case. It also ignores any retrofits that might take place if there were economic reasons for early retirement of equipment.

This case is presented primarily for heuristic reasons: it describes an easily-understood case in which technology does not change. This is useful for exploring the impacts of technology change. Also, the case is not necessarily divorced from reality: in the era of low energy prices preceding the oil embargo of 1973-74, the energy efficiency of many household, transportation, and industrial technologies changed very little.

Business-as-Usual Case. The business-as-usual (BAU) case represents the best estimate of future energy use given current trends in service demand, stock turnover, and natural progress in the efficiency of new equipment. It assumes that R&D and implementation programs at DOE and EPA continue at more or less current levels, without a significant influx of new funding. It captures likely changes in efficiencies of new equipment over the analysis period. It also allows for some early retirement of equipment where cost savings from new energy-efficient products are high relative to purchase and installation costs, as in some industrial motor and drive systems and commercial lighting retrofits.

To create this scenario, the buildings and industry sectors adopted the AEO97 reference case as their BAU cases. For the transportation sector, we modified AEO97 somewhat. Specifically, the AEO97 reference case forecasts that the efficiency of passenger cars will increase from 27.5 MPG in 1997 to 31.5 MPG in 2010. We believe such improvements are unlikely in the absence of increases in real gasoline prices and hence our BAU case for transportation leaves the MPG performance of light-duty vehicles in 2010 unchanged from 1997 performance.

Efficiency Case. The efficiency case describes the potential for cost-effective, energy-efficient technologies to penetrate the market by the year 2010, given an invigorated public- and private-sector effort to promote energy efficiency through enhanced R&D and market transformation activities. This case assumes that national policy, possibly in combination with exogenous events, leads to an increase in the cost-effectiveness and deployment of energy-efficient technologies. Cost-effectiveness is improved because R&D, in combination with increased deployment efforts, result in declining capital costs. We do not specify the policies or exogenous events that could precipitate

such changes. Instead, we examine the potential for technology-based energy and carbon reductions, assuming that significant efforts are undertaken to enhance the attractiveness of these technologies.

To be attractive to these manufacturers and consumers, a technology must be cost-effective. Thus, this scenario limits itself to describing the potential for cost-effective technologies to reduce energy use and carbon emissions. A technology is defined as "cost-effective" if it delivers a good or service at equal or lower life-cycle costs relative to current practice.² Externalities are not internalized in this definition of cost-effective. An energy-efficient technology may be societally cost-effective, for instance by taking into account its air quality or safety benefits, but not be judged cost-effective by our narrower economic criteria. This scenario reflects the view that "policy options exist that would slow climate change without harming American living standards, and these measures may in fact improve U.S. productivity in the longer run" (Arrow et al., 1997).

Compared to the business-as-usual case, the efficiency case assumes (1) better technology and (2) higher penetration rates for energy-efficient and low-carbon technologies.

1. "Better technology" results from an invigorated public- and private-sector investment in R&D such that energy-efficient technologies become more cost-competitive based on current fuel prices. Performance improvements between 1997 and 2010 are mostly incremental in this scenario, but by 2020 they could be revolutionary.
2. "Higher penetration rates" result from an invigorated set of policies and market transformation programs that remove or reduce market failures which inhibit the use of energy-efficient and low-carbon systems. Through improved information and risk reduction, capital markets for energy-efficiency investments could be strengthened and consumer investment hurdle rates for the purchase of high-efficiency equipment could be lowered.

Despite its assumption of an aggressive public commitment to energy efficiency, this scenario also takes into account real-world experience and program implementation constraints which suggest that it is not reasonable to assume that every consumer will purchase the least-cost, high-efficiency technology option. There are many reasons to expect a shortfall from such a maximum case: capital rationing, imperfect information, misplaced incentives, and the unevenness of supply, installation, and maintenance networks (DOE, 1996b).

High-Efficiency/Low-Carbon Case. The high-efficiency/low-carbon (HE/LC) case assumes a greater commitment to reducing carbon emissions through federal policies and programs, strengthened state programs, and very active private sector involvement. One way to view this case is to see it as an attempt to model a world where an international global warming treaty is negotiated over the next few years and where the outcome for the United States (and other Annex I nations) is to stabilize carbon and other greenhouse gas emissions in 2010 at 1990 levels. The United States pursues those reductions by (1) aggressively instituting federal policies to develop and deploy energy-efficiency and low-carbon technologies, such as increased funding for market transformation and R&D efforts and (2) by issuing tradable emission permits.

In this rendition of the HE/LC case, policies are put into place by 2000 and progressively phased in until they are fully in place by 2010. The permit price for carbon would presumably rise steadily through 2010. Thus, we have multiple factors affecting consumer and business behavior, including the following:

- The recognition that policies to reduce carbon emissions will necessarily follow the signing of an international agreement, including an anticipation of higher relative prices for carbon-based fuels;

- The actual increases over time in the permit price of carbon (which we model as averaging either \$25 or \$50 per tonne for much of this period);
- Increased federal effort to accelerate R&D and diffusion of low-carbon technologies;
- The development and introduction by other countries of advanced low-carbon technologies; and
- The change in consumer preferences and behavior that would result from an international treaty and national commitment to stabilize greenhouse gases, much like changes in consumer behavior in the aftermath of the oil embargo of 1973-74.

In summary, this scenario for 2010 describes a combination of better technology, "readier" markets, and a price of carbon that results in a significantly increased willingness to manufacture, purchase, and use low-carbon technologies.

2.2.4 Methodological Differences Across Sectors

The operational definitions used to model these scenarios for the individual end-use sectors reflect the above conceptual definitions, but are nevertheless distinct (Table 2.1). These differences are due partly to the modeling approaches used for each sector. They also reflect the authors' sense of what could "drive" significant increases in energy efficiency in each sector. For instance, to achieve a high-efficiency/low-carbon scenario, the transportation analysis postulates a set of technology breakthroughs. The industrial analysis, on the other hand, achieves its high-efficiency/low-carbon scenario by doubling market penetration rates and assuming that energy-efficiency decisions are treated as strategic investments with correspondingly lower hurdle rates.

The sectors also differ in the way that life-cycle costs and benefits are calculated to determine the cost-effectiveness of technologies in their efficiency scenarios.

- The buildings sector employs a 7% real discount rate to value the stream of benefits accruing from an investment. These benefits accumulate throughout the specific operational lifetimes assumed for individual technologies. The efficiency case assumes market penetration of about one-third of the technologies that are cost-effective at a 7% real discount but not adopted in the business-as-usual case. The HE/LC case doubles this penetration.
- The industrial sector assumes a capital recovery factor (CRF) of 15%, rather than 33% (which is the BAU assumption). Thus, to be considered cost-effective in this sector, an investment must pay back in no more than approximately seven years.
- The transportation sector uses a 7% discount rate, but it is applied only to the first five years of operation, even though the expected lifetime of a vehicle may be much longer. This five-year period is meant to reflect the realities of purchase behavior in this sector, and results in decisions that are based on considerably less than the full life-cycle of benefits.

Table 2.1 Conceptual and Operational Definitions of Scenarios for 2010

Scenario/ Definition	Business-as-Usual (BAU)	Efficiency (EFF)	High-Efficiency/ Low-Carbon (HE/LC)
Conceptual Definition	Best estimate of future energy use given current trends in service demand, stock turnover, and natural progress in the efficiency of new equipment, including advances supported by current public-sector programs; assumes no changes in federal energy or environmental policies.	Potential for cost-effective, energy-efficient technologies to penetrate the market given an invigorated effort to promote energy efficiency through enhanced public and private-sector R&D and market transformation activities.	Optimistic but feasible potential for energy efficiency and low-carbon technology based on a greater commitment to reduce carbon emissions resulting from actions that might include the creation of a market value for carbon of \$25 and \$50 per tonne.
Operational Definitions:			
Buildings	AEO97 reference case developed using the NEMS model. ^a	35% of the difference in total energy savings between the BAU and cost-effective energy savings potential. ^b	65% of the difference in total energy savings between the BAU and cost-effective energy savings potential.
Industry	AEO97 reference case; LIEF is calibrated to this case and then is modified to produce the two efficiency scenarios.	The capital recovery factor (CRF) for energy-efficiency investment used in LIEF is lowered from 33% to 15%. ^c	The CRF is lowered to 15% and the penetration rates for energy-efficient technology used in the BAU are doubled.
Transportation	AEO97 reference case modified to hold new light-duty vehicle fuel economy constant at current levels.	Assumes earlier introduction of advanced fuel economy technology and adds certain key technologies that are not in the BAU.	Postulates breakthroughs in hybrid vehicle technology, major aerodynamic and engine efficiency gains for commercial aircraft, and other technological achievements.

^a NEMS = National Energy Modeling System developed by DOE's Energy Information Administration.

^b The cost-effective energy savings potential is defined as the difference between the energy demand that results from using the most energy-efficient of the cost-effective technology currently available or forecasted to be available by 2010, and the energy demand in 2010 assuming business-as-usual rates of technology change and use in the economy.

^c LIEF = Long-Term Industrial Energy Forecasting model developed by Argonne National Laboratory and Lawrence Berkeley National Laboratory.

2.2.5 What the Study Does Not Do

This report does not describe the policies that might be implemented to achieve higher penetrations of energy-efficient and low-carbon technologies. (Reviews of a wide range of possible policy options can be found in several recent publications, including OTA (1991), NAS (1992), and DOE (1996b)). Rather, this report highlights the potential performance and impacts of technological developments and transformed markets. The existence of cost-effective technologies is a prerequisite for public policies to work. Without the technologies, policies to reduce greenhouse gas emissions will be very costly. Indeed, this analysis suggests that carbon stabilization could produce net benefits if the nation invests significantly in cost-effective energy-efficiency and low-carbon technologies.

Thus, we believe it is critical to understand the availability of technologies, their performance, and their costs for as many end-uses of energy as possible. Armed with this knowledge, discussion of policies becomes much more meaningful. Without it, such discussion is less likely to lead to good decisions. Thus, we choose to focus this report on the more narrow topic of technologies in the belief that doing a credible job in this area will ultimately further the policy dialogue.

A second reason for focusing on technologies is our belief that the role of R&D on energy-efficient and low-carbon technologies as a means to deal with climate change and other environmental impacts has been inadequately recognized. If effective energy technologies are not developed, then the cost of reducing greenhouse gas emissions (and other environmental impacts of energy) will be very high.

As in the AEO97 reference case, each of the scenarios is completed at the national level. Thus, regional variations in population and economic activity are not considered, nor are regional differences in fuel price, weather, or air quality and environmental conditions that might create regional niche markets for particular technologies. As a result, our analyses have undoubtedly overlooked the possible development of regional markets for advanced energy technologies. A valuable next step would be to conduct analyses at a finer geographic scale to produce national estimates that reflect such regional variations.

2.3 OVERVIEW OF THE REPORT

The rest of Chapter 2 sets the stage for the remainder of this report. It describes historical energy and carbon trends, both at the national level and by sector, as a backdrop for assessing energy consumption and carbon emission forecasts. It also discusses the government's role in energy R&D, including the rationale for government support and some evidence of past energy-efficiency technology successes that benefited from government sponsorship.

Chapters 3 through 5 address each of the major energy end-use sectors: buildings (Chapter 3), industry (Chapter 4), and transportation (Chapter 5). Four tasks are completed for each sector:

1. Energy scenarios with and without a strong efficiency push, focusing on the year 2010, and including comparisons with the AEO97 projections from the National Energy Modeling System;
2. Documentation of the cost and performance assumptions for individual energy-efficient and low-carbon technologies;
3. Development of three scenarios (business-as-usual, efficiency, and high-efficiency/low-carbon cases) for the year 2010 and an explanation of how the scenarios were developed; and

4. Descriptions of new technologies that could become available in the 2010 to 2020 time period, as the result of R&D over the next two decades.

Each of these chapters is accompanied by appendices that provide detailed documentation of the technology assumptions and the forecasting methodologies used. These are labeled Appendices C (buildings), D (industry), and E (transportation).

Chapter 6 analyzes the electricity sector to forecast the effect of electricity and demand savings in the year 2010 on CO₂ emissions from power plants. It also assesses the impact of a \$25/tonne and \$50/tonne permit price for carbon on the generation mix used by the electricity sector in 2010. The results of these analyses are used in the buildings and industry sector chapters to convert electricity savings into carbon reductions. Results from this chapter reveal the importance of fuel choice for new power plants and fuel switching for existing power plants as determinants of carbon emissions in 2010. Specifically, the cost and magnitude of fuel switching from coal to natural gas for power generation, the possible early retirement of some coal-fired plants, and the upgrading/repowering of existing plants were identified as key issues for Chapter 7.

The possible conversion of coal plants to natural gas combined cycle technologies is analyzed in Chapter 7, as one of many electricity supply-side options for reducing carbon emissions by 2010. Other options are addressed in Chapter 7, albeit more briefly, including cofiring coal with biomass, efficiency improvements in generation and T&D, advanced coal technologies, and nuclear plant life extension. The chapter also characterizes the carbon reduction benefits that could accrue by the year 2020 from a sustained renewable energy R&D effort.

2.4 HISTORICAL ENERGY TRENDS

2.4.1 National Trends

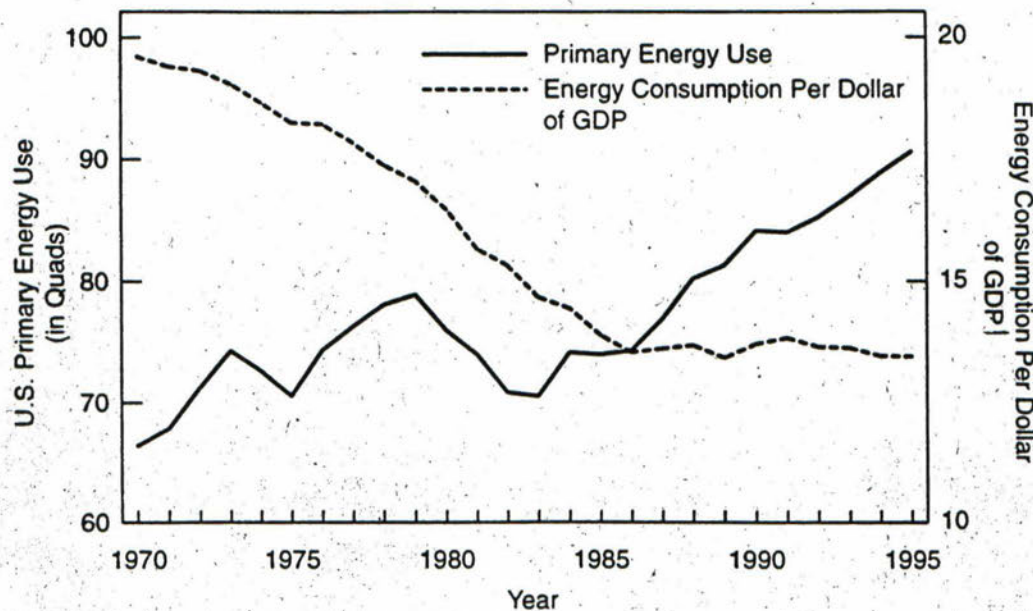
In studying historical trends in energy use and carbon emissions, we have chosen to highlight the years 1973, the beginning of rising energy prices to the nation; 1986, the year in which energy prices began a ten-year decline in real terms; 1990, the year generally used as a reference for carbon emissions; and 1997, the first year of our forecast period.

Between 1973 and 1986, the nation's consumption of primary energy froze at about 74 quads – while the GNP grew by 35%.³ People purchased more fuel-efficient cars and appliances, insulated and caulked their homes, and adjusted thermostats. Businesses retrofitted their buildings with more efficient heating and cooling equipment and installed energy management and control systems. Factories adopted more efficient manufacturing processes and purchased more efficient motors for conveyors, pumps, fans, and compressors. These investments in more efficient technologies were facilitated by higher energy prices and by federal and state policies that were enacted and implemented to promote energy efficiency. About one-third of the freeze in energy use during this period was the result of structural changes such as declines in energy-intensive industry and increases in the service sector; two-thirds was due to increases in energy efficiency (DOE, 1995).

The gains in energy productivity achieved by the U.S. in the two decades following the 1973-74 Arab oil embargo represent one of the great economic success stories of this century. The extent to which the U.S. economy improved its energy productivity can be quantified by examining the relationship between total energy consumption and gross domestic product (GDP), as depicted in Figure 2.1. In Figure 2.1, primary energy use is measured in quads and energy consumption per dollar of GDP is measured in thousands of Btus per 1992\$. In 1970, 19.6 thousand Btu of energy were consumed for each dollar of GDP (1992\$). By 1995, the energy intensity of the economy had dropped

to 13.4 thousand Btu of energy per dollar of GDP (1992\$) (EIA, 1996a, p. 17). DOE estimates that the country is saving \$150 to \$200 billion annually as a result of these improvements.

Figure 2.1 Energy Consumption Per Dollar of Gross Domestic Product: 1973-1995



Starting in 1986, energy prices began their descent in real terms that has continued to the present. As a result, energy demand grew from 74 quads in 1986 to 91 quads in 1995, and it continues to increase. One of the major lessons of the period since 1973 is that the economy will and can respond to energy price changes. In addition to prices, other factors are also important and can slow the decline in conservation activity that otherwise would be expected with declining energy prices. Federal policies, as well as federal, state, and utility programs and consumer preferences for energy-efficient appliances, houses, and cars can increase the purchase and use of energy-efficient products. Technological developments can improve the energy efficiency, reduce the carbon emissions, and often improve the performance of the product. Demand for energy-efficient products and low-carbon energy technologies is also strengthened by factors such as environmental concerns.

2.4.2 Sectoral Trends

Each end-use sector functions differently in the U.S. energy marketplace. One of the reasons for these differences is the differing market structure for delivering new technologies and products in each sector. Residential and commercial building technology is shaped by thousands of building contractors and architectural and engineering firms, whereas transportation technology is in the hands of a few manufacturers.

The principal causes of energy inefficiencies in manufacturing and transportation are not the same as the causes of inefficiencies in homes and office buildings, although there are some similarities (Hirst and Brown, 1990). For example, in the manufacturing sector, energy-efficiency investments are hindered by a preference for investments that increase output compared with investments that reduce operating costs. The cost and relative difficulty of obtaining reliable information often prevents energy-efficient features of buildings from being capitalized into real estate prices. This is

partly due to the lack of widely accepted building energy rating systems. These same information gaps do not characterize the transportation sector, which has a well understood labeling system for vehicles, in the form of miles per gallon. Misplaced incentives inhibit energy-efficient investments in each of the sectors. Consumers often must use the energy technologies selected by others. Specialists write product specifications for military purchases that limit access to alternatives. Fleet managers select the vehicles to be used by others. And architects, engineers, and builders have great control over the energy integrity of buildings, even though they do not pay the energy bills. The involvement of intermediaries in the purchase of energy technologies limits the ultimate consumer's role in decision making and leads to an emphasis on first cost rather than life-cycle cost (DOE, 1996b).

The end-use sectors also differ in terms of their ability to respond to changing energy prices. The transportation and residential sectors can respond relatively rapidly to price spikes, through reduced driving and by adjusting thermostat settings, respectively.

The vast differences in the R&D capability of the various sectors also influence their ability to respond quickly to changing energy prices and market signals. The private sector as a whole spends more than \$100 billion per year on R&D, dwarfing the government expenditure on all non-defense technology R&D. Of this R&D expenditure, the automobile manufacturers stand out – Ford alone spends more than \$8 billion per year on R&D. Next comes the rest of the industrial sector. Here, manufacturers account for a majority of the R&D expenditures. Finally, in the buildings sector, the construction industry has virtually no indigenous R&D. The Council on Competitiveness in 1992 estimated that the construction industry spends less than 0.2% of its sales on R&D, far less than other industries, which average 3.5%.

Finally, each of the sectors is distinct in terms of their dynamics and primary societal benefits from improved energy efficiency. Improving the efficiency of transportation is needed to improve air quality and reduce dependence on imported oil. Improving the efficiency of the industrial sector improves economic competitiveness and is often effective in preventing pollution. Opportunities for energy-efficiency improvements are most widespread in the buildings sector because of market barriers in the form of information that is difficult to obtain, energy consumers who do not make purchase decisions on energy-using equipment, etc. Such differences make analysis by end-use sector essential for understanding the U.S. energy, carbon, and innovation picture as a whole.

Table 2.2 presents the primary energy consumed annually by the buildings, industry, and transportation sectors between 1973 and 1997. It shows significant sectoral differences in energy consumption trends. For instance, during the 1973-86 period when the country's primary energy use was steady at 74 quads, energy use in buildings and transportation increased by 2.7 quads and 2.2 quads respectively; industry experienced a compensating decline of 4.9 quads.

Table 2.2 Primary Energy Use in Quads: 1973-1997

	1973	1986	1990	1995	1997
Buildings	24.1	26.9	29.4	32.1	33.7
Industry	31.5	26.6	32.1	34.5	32.6
Transportation	18.6	20.8	22.6	24.1	25.5
Total	74.3	74.3	84.2	90.6	91.8

Source: Energy use estimates for 1973-95 come from EIA (1996a, Table 1.1, p. 39). Energy use estimates for 1997 come from EIA (1996c).

Over the entire period from 1973 to 1997, energy use increased in buildings from 24.1 to 33.7 quads (40%); in industry, from 31.5 to 32.6 quads (3.5%); and in transportation, from 18.6 to 25.5 quads (37%). As shown in Table 2.3, the growth in buildings and transportation has been relatively steady, at less than 1% per year from 1973 to 1986, and between 1.3 and 2.9% per year from 1986 to 1997. Growth in energy demand in industry has been much more volatile during the period, showing substantial declines during the period of rising prices (a negative 1.3% annual growth for the 13 years of increasing energy prices), an increase of 2.7% per year from 1986 to 1995, and a 2.9% per year decline from 1995 to 1997.

Table 2.3 Historical Energy Growth Rates: 1973-1997

	AAGR 1973-97	AAGR 1973-86	AAGR 1986-90	AAGR 1990-95	AAGR 1995-1997
Buildings	1.41%	0.85%	2.25%	1.77%	2.46%
Industry	0.14%	-1.31%	4.81%	1.45%	-2.87%
Transportation	1.32%	0.86%	2.10%	1.29%	2.86%
Total	0.89%	0.0%	3.18%	1.48%	0.66%

AAGR = Average Annual Growth Rate

The growth of carbon emissions during the period roughly follows that of energy demand growth. Table 2.4 shows estimated carbon emissions from 1973 to 1997. Like energy, carbon emissions were flat between 1973 and 1986. The increase in the fraction of coal in the final mix from 17.5% in 1973 to 23.2% in 1986 was offset by the increasing fraction of primary energy from nuclear power, from 0.1% in 1973 to 6.0% in 1986. From 1986 to 1997, carbon emissions grew more slowly than energy consumption. This was a result of an increase in the share of natural gas from 22.5% in 1987 to 25.4% in 1997 and in electricity from nuclear power from 4.5% to 7.2%, combined with a small decrease in coal (23.3% to 22.5%) and a larger decrease in petroleum (43.3% to 39.7%).

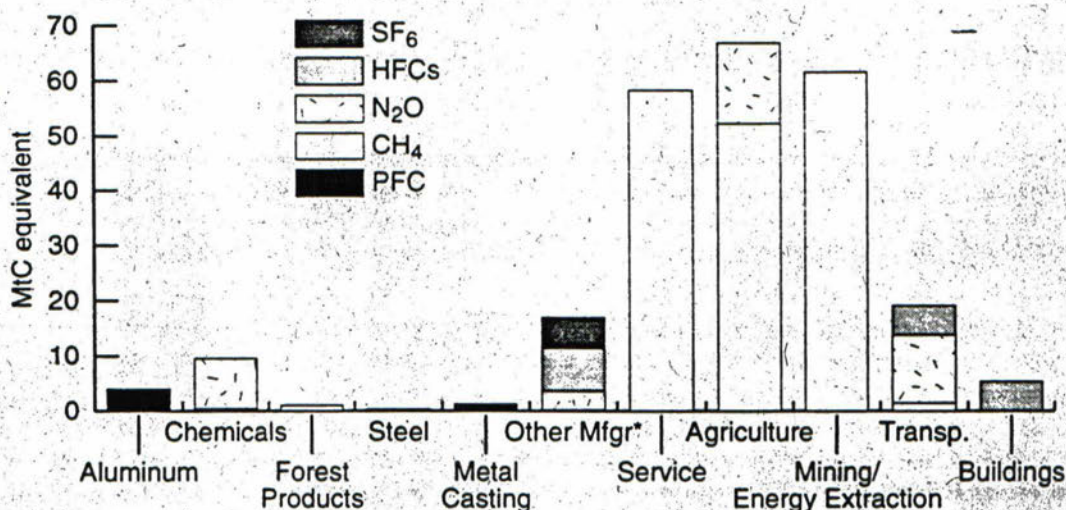
Table 2.4 Carbon Emissions from Fossil Energy Consumption: 1973 to 1997

	1973	1986	1990	1995	1997
Carbon emissions from energy in MtC	1260	1240	1344	1424	1480
	1973-97	1973-86	1986-90	1990-95	1995-97
Average annual growth rates (AAGR) for carbon emissions	0.67	-0.12%	2.03%	1.16%	1.95%

Sources: Carbon emissions estimates for 1990 are from EIA (1996b, Table 6, p. 16), and for 1995 are from EIA (1996b, Table A19, p. 120). Carbon emission estimates for 1973 and 1986 were derived using factors for carbon emissions from combustion of oil, natural gas, and coal for 1990. For 1997, they are from the end-use sector analyses described in Chapters 3 through 5 of this report.

Although non-CO₂ industrial emissions of greenhouse gases are small by weight, they have global warming potentials (GWPs) that range from 21 for methane to 23,900 for sulfur hexafluoride (SF₆). Carbon dioxide has a GWP of one by definition. Figure 2.2 shows the relative contribution of these other gases in MtC equivalent. The largest non-CO₂ greenhouse gas contribution is from methane (CH₄), which is responsible for 177.5 MtC equivalent and has a GWP of 21. Next is nitrous oxide (N₂O), which is responsible for 39.1 MtC equivalent and has a GWP of 310. Finally, in 1994, various halocarbons and other engineered chemicals amounted to 29.5 MtC equivalent. These engineered chemicals are a source of concern since their emissions are growing rapidly – and the United States is the major source. SF₆ alone is increasing at a rate of 0.5 MtC equivalent per year (EIA 1996b). Note also that many of these emissions are seen not only in energy-intensive industries but also in “high-tech” and service industries, as shown in Figure 2.2.

Figure 2.2 Non-CO₂ Greenhouse Gas Emissions by End-Use Sector and Industry



* Mainly semiconductors

Source: EIA (1996b)

2.5 THE GOVERNMENT'S ROLE IN ENERGY R&D

2.5.1 Rationale for Government Support

Most people agree that the federal government has a clear and important role in the funding of basic research, and that it should not fund research that the private sector would conduct on its own. Between these two extremes is a wide range of applied technology development and deployment activities where the rationale for federal sponsorship is often unclear.

Economists have identified at least three situations in which the government's role in the R&D process is justified. First is the situation where the potential aggregate benefits of the research are large, but the uncertainties are simply too great for the private sector to shoulder the full research costs. Second is the case where R&D activities will result in benefits that cannot be captured by private entities. Although benefits might accrue to society at large, no single firm can realize enough economic gain to justify the research costs. A recent Council of Economic Advisors report

(CEA, 1995) estimated that the private returns from R&D are 20 to 30%, while social returns (including energy and environmental benefits) are 50% or higher. This economic barrier limits the extent to which the private sector can supplant a government role in maintaining nationally beneficial R&D. The third situation occurs when the public sector is the primary consumer of the results of the R&D. This is characteristic, for instance, of much defense and crime prevention research.

Based on these three justifications, the rationale for government support of energy-efficiency and low-carbon technology R&D is strong. Much of this research is both long-term and high-risk and therefore cannot be afforded by private companies despite the possibility of substantial gains in the long run. Examples include high temperature superconductivity, fuel cell vehicles, and building materials with switchable thermal and optical properties. Advances in energy research also offer substantial public benefits that cannot be fully captured by private entities. Specifically, energy-efficiency and low-carbon resources improve energy security by reducing the nation's reliance on foreign sources of oil; they lead to reductions in waste streams; and they reduce greenhouse gas emissions, which contribute to global warming. Finally, it is possible that governments will in the future become the principal purchaser of greenhouse gas reductions as the result of future international agreements. In this case, the third rationale for federal sponsorship of energy R&D will also apply.

Industry's R&D priorities are shifting away from basic and applied research and toward near-term product development and process enhancements. Business spending on applied research has dropped to 15% of overall company R&D spending, while basic research has dropped to just 2%. In addition, corporate investments in energy R&D, in particular, are down significantly (DOE, 1996a, p. 2).

Great potential exists for public-private R&D partnerships to produce scientific breakthroughs and incremental technology enhancements that will produce new and improved products for the marketplace. U.S. industry spends more than \$100 billion per year on all types of R&D. The top 20 R&D performing companies all have R&D budgets exceeding \$1 billion per year. These expenditures dwarf the U.S. government's energy-related R&D appropriations. If climate mitigation policies reoriented even a tiny fraction of this private-sector expenditure and capability, it could have an enormous impact. One way to reorient private-sector R&D is through industry-government R&D partnerships that involve joint technology roadmapping, collaborative priorities for the development of advanced energy-efficient and low-carbon technologies, and cost-shared R&D.

2.5.2 Past R&D Successes

Some indication of the cost-effectiveness of energy-efficiency R&D can be gleaned from the experiences to date of DOE's Office of Energy Efficiency and Renewable Energy. From fiscal year 1978 through fiscal year 1994, DOE spent a total of about \$8 billion on energy-efficiency R&D and related deployment programs. Estimates of the benefits of several dozen projects supported by this funding were published in DOE/SEAB (1995). In response to a detailed review of these estimates by the General Accounting Office in 1995/96, DOE has revised and updated the estimated benefits accruing from five technologies that were developed with DOE support. Altogether, these five technologies alone have resulted in net benefits (i.e., the value of energy saved minus annualized cost premiums for better equipment) of approximately \$28 billion (1996\$) and annual emissions reductions of 16 MtC equivalent (Table 2.5).⁴

Thus, the value of the energy saved by these five technologies, alone, far exceeds the cost to the taxpayers of DOE's entire energy-efficiency R&D budget over the past two decades. Additional case studies and benefits are documented in Geller and McGaraghan (1996) and DOE/SEAB (1995).

Table 2.5 Cumulative Net Savings and Carbon Reductions from Five Energy-Efficient Technologies Developed with DOE Funding

Energy-Efficient Technology	Net Present Value of Savings Thru 1996 (billions of 1996\$)	Annualized Consumer Cost Savings in 1996 (billions of 1996\$)	Annual Carbon Reductions in 1996 (MtC equivalent)
• Building Design Software	11.0	0.5	8
• Refrigerator Compressor	6.0	0.7	3
• Electronic Ballast	3.7	1.4	1
• Flame Retention Head Oil Burner	5.0	0.5	3
• Low-E Windows	3.0	0.3	1
Totals	28	3.4	16

Note: Savings for the refrigerator compressor and flame retention head oil burner are through 1996 only; the remainder are savings from products in place by the end of 1996 and include estimated energy savings from the product's years in operation beyond 1996.

In addition to funding the development of numerous energy-efficient technologies, including those listed in Table 2.5, DOE has also developed and implemented energy-efficiency standards for equipment and building shells. For example, building efficiency standards became possible as a result of DOE's investment in "building design software" (the first line of Table 2.5). Because of a potential problem with "double-counting", Table 2.5 includes only energy savings achieved *beyond* the savings that resulted from the implementation of minimum energy-efficiency standards for buildings.

Moreover, results recently reported by Elliott et al. (1997) indicate that the total benefits – including both energy and non-energy savings – that accrue from so-called "energy-saving" projects in industry are typically much greater than those from the energy savings alone. In fact, based on numerous case studies, the authors conclude that the average total benefits received from these "energy-saving" projects are close to two to four times the value of the energy savings alone. They also noted that costs and benefits resulting from non-energy ramifications of energy-efficiency projects are often not included in cost/benefit analysis of energy-efficiency projects. Similarly, Romm and Ervin (1996) describe public health benefits that have resulted from advances in energy-efficient and renewable energy technologies, and Romm (1994) describes productivity gains that have accompanied investments in industrial efficiency improvements.

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ENDNOTES

¹ In this report, carbon dioxide is measured in carbon units, defined as the weight of the carbon content of carbon dioxide. Carbon dioxide units at full molecular weight (typically, million tonnes of carbon (MtC)) can be converted into carbon units by dividing by 44/12, or 3.67. This approach has been adopted for two reasons: (1) carbon dioxide is most commonly measured in carbon units in the scientific community, in part because it is argued that not all carbon from combustion is, in fact, emitted in the form of carbon dioxide, and (2) carbon units are more convenient for comparisons with data on fuel consumption and carbon sequestration (EIA, 1996b). Note that, in the U.S., a "ton" (sometimes referred to as a "short ton") equals 2000 pounds; a metric ton, or "tonne," equals 1000 kilograms (approximately 2204 pounds).

² We evaluate cost-effectiveness from several viewpoints, with real discounts between 7% and 20%. Even with the high discount rates, the efficiency case is cost-effective.

³ Primary energy use is the chemical energy embodied in fossil fuels (coal, oil and natural gas) or biomass, the potential energy of a water reservoir, the electromagnetic energy of solar radiation, and the energy released in nuclear reactors. For the most part, primary energy is transformed into electricity or fuels such as gasoline, jet fuel, heating oil or charcoal – these, in turn, are referred to as secondary energy. The end-use sectors of the energy system provide energy services such as cooking, illumination, comfortable indoor climate, refrigerated storage, transportation and consumer goods using both primary and secondary energy (NAS, 1992, p. 3)

⁴ The net present value (NPV) of cost savings, cumulative through 1996, is calculated as follows:

$$NPV = \sum_{t=\text{entry year}}^{\text{end of service}} (E_t - P_t) e^{0.07(1996 - t)}$$

where: E_t is the value in 1996\$ of energy saved in year t

P_t is the annualized cost premium (1996\$) of the better product

0.07 is the 7% real interest rate recommended by the Office of Management and Budget

Note that, for future years ($1996 - t < 0$), $(E_t - P_t)$ is discounted by 7% per year; for past years, $(E_t - P_t)$ is raised 7% per year.

Chapter 3

THE BUILDINGS SECTOR

3.1 INTRODUCTION

Energy is used in buildings to provide a variety of services such as lighting, space heating and cooling, refrigeration, and electricity for electronics and other equipment. In the U.S., building energy consumption accounts for nearly one-third of total primary energy consumption and related greenhouse gas emissions. The cost of delivering all energy services in buildings (such as cold food, lighted offices, and warm homes) will be over \$220 billion in 1997.

Our analysis shows that substantial reductions in future greenhouse gas emissions can be realized through the use of more energy-efficient technologies that save society money. In addition, these technologies often supply other benefits beyond energy, carbon, and dollar savings, including the following: (1) improved indoor environment, comfort, health, and safety, (2) reduced noise, (3) improved process control, and (4) increased amenity or convenience (Mills and Rosenfeld 1994). These indirect benefits, while difficult to quantify in economic terms, can be even more important than the energy cost savings, particularly when they improve the comfort of homeowners or the productivity of workers.

This chapter describes our detailed assessment of the achievable cost-effective potential for reducing carbon dioxide emissions in 2010.¹ We calculate carbon, energy, and dollar savings associated with adoption of more energy-efficient technologies. In addition, this chapter qualitatively describes the role of research and development (R&D) in providing a stream of advanced building technologies and practices after 2010 that will enable continued reduction in energy use and greenhouse gas emissions.

All costs in this chapter are reported in 1995 U.S. dollars (1995\$). Carbon dioxide emissions are reported in terms of their carbon equivalent. To convert carbon dioxide units at full molecular weight into carbon units, divide by 44/12 or 3.67. For further information on emissions data, see EIA (1995).

3.2 PROVEN AND NEAR-TERM TECHNOLOGIES

In developing scenarios of carbon dioxide emissions for the residential and commercial buildings sectors, we drew from a wide range of information and models available on end-use energy demand, consumption, efficiencies, and technologies (see Section 3.7 References). Using this information, we developed a spreadsheet model that incorporates the work of existing models and analyses as parameters while providing a transparent framework to display assumptions, calculations, and results. This model, developed specifically for the project, is described in Appendix C-1.

3.2.1 Generic Assumptions

Our approach is based on a stock accounting framework of building and equipment types. For all scenarios, base case growth in households and commercial floorspace tracks historical trends. This results in a net total 2010 stock that is greater than 1997 levels by 15% and 12% in residential and commercial buildings, respectively, taking account of new building construction and retirement of existing stock. Retrofit or replacement of existing "shells" (walls, roofs, windows, doors) and

equipment is a function of their average lifetimes. We assume that, on average, residential and commercial building shells last 100 and 50 years, respectively, and thus only a small portion of buildings are replaced during the study period with a much larger fraction undergoing some shell retrofit. In contrast, average equipment lifetimes range from one year (for lights) to 20 years (for furnaces). All equipment with lifetimes significantly less than the forecast period (13 years), such as residential lighting, will be replaced but only a portion of the equipment with lifetimes comparable to or longer than the forecast period will be replaced. The combination of shell and equipment turnovers results in four categories of buildings in our model: (1) old buildings with old equipment; (2) old buildings with new equipment; (3) retrofit building shells with new equipment; and (4) new buildings with new equipment.

After characterizing the building stock in 2010, we calculate energy intensities (end-use energy per household or per unit floor area) for all end-uses for 1997 and, in our initial assessment, use the factors from the Energy Information Administration's (EIA's) *Annual Energy Outlook* (AEO97) to establish baseline values in 2010 (EIA, 1996). In general, average 2010 energy intensities are lower than those in 1997, reflecting technology improvements that provide the same level of energy service with less energy.

We multiply each equipment end-use energy in 1997 (e.g. water heating, cooling, lighting) in the four building categories by applicable energy intensities to derive future energy use. If more services per household or unit of commercial floorspace are required by consumers, or if the size of the overall building stock (relative to 1997) increases, this will increase the energy required to provide energy services. Thus, energy demand in 2010 is a product of the rates of change in energy service requirements within the buildings and changes in the overall growth in the building stock.

To derive energy-efficiency scenarios, we use the cost of energy intensity improvements and electricity and fuel prices in 2010 to assess cost-effective reductions in energy use. For the residential buildings, the efficiency scenarios also account for fuel switching (the impact of switching from electric to gas water heaters, clothes dryers, and ranges) and for the use of high-albedo roof materials ("cool roofs") to reduce cooling requirements (see Appendix C-4). For the commercial sector, we include the analysis of cool roofs but do not include fuel switching.

3.2.2 Scenario Definitions

- * The model was used to generate results for three scenarios: "business-as-usual" (BAU), "efficiency" (EFF), and "high-efficiency/low-carbon" (HE/LC). The business-as-usual scenario was calibrated to the National Energy Modeling System (NEMS) model outputs, so that it corresponds to the same 2010 baseline currently used in AEO97.

For both the efficiency and high-efficiency/low-carbon scenarios, we first calculate the 2010 energy use assuming 100% implementation of maximum cost-effective efficiency improvements in new building shells and equipment. This maximum efficiency potential was calculated as the difference between the energy intensity of the most cost-effective energy-efficiency technologies currently available, and the energy intensity of new equipment in 1997. The maximum cost-effective efficiency improvements are based on detailed studies; measures were not included if they had a cost of conserved energy greater than the average cost of purchased fuel or electricity.² For comparative purposes, we have also analyzed a "frozen efficiency case" in which the efficiencies of all new equipment and building shell measures are kept at 1997 levels of new products.