VARIANTS OF A LOW CO_2-EMITTING ENERGY SUPPLY SYSTEM (LESS) FOR THE WORLD

Prepared for the IPCC Second Assessment Report Working Group IIa, Energy Supply Mitigation Options

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October 1995

Report No. PNL-10851
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This report provides detailed analysis in support of the "bottom-up" constructions of five variants of a Low Emissions Energy Supply System (LESS) for the World, which were presented in Section 3 of Chapter 19 (Energy Supply Mitigation Options) of the Second Assessment Report of Working Group IIa of the Intergovernmental Panel on Climate Change (IPCC, forthcoming).[1]

The Purpose of the LESS Constructions

Each of the energy technological options discussed in Chapter 19 (Energy Supply Mitigation Options) of the draft WG II SAR has the potential to contribute to GHG emissions reductions. To assess their combined potential in a future energy supply system, assessments are needed at the level of the global energy system. Such assessments should consider internal functional aspects of the energy system (such as the intermittency of solar and wind energy resources), and the linkages between the energy system and other areas of societal concern (such as land use competition and security issues).

To begin an assessment of this nature, alternative versions of a Low Emissions Supply System (LESS) were constructed. These LESS constructions illustrate the potential for reducing emissions by using energy more efficiently and by using various combinations of low CO_2-emitting energy supply technologies--including shifts to low-carbon fossil fuels, shifts to renewable or nuclear energy sources, and decarbonization of fossil fuels, in alternative combinations. Energy supply systems were constructed for this exercise by Working Group II both from "the bottom up" and "the top down." This report is restricted to bottom-up constructions. The analysis in support of the top-down constructions is presented elsewhere (Edmonds et al., 1994).

The LESS alternatives are not forecasts but rather are self-consistent energy supply constructions indicative of what might be accomplished by pursuing particular technological strategies; it is assumed for each LESS construction that societal commitments are made in the near term to accelerate the development of the highlighted technologies. These alternative paths to the energy future should be regarded as "thought experiments" exploring the possibilities of achieving deep reductions in emissions without large cost burdens to society.

Emphasis in the LESS constructions is on the long term (2025-2100), the prospects for achieving deep reductions in CO_2 emissions from the energy sector, and prospective costs. A long-term focus reflects the importance of long-term impacts in WG I evaluations and the emphasis on new or improved technologies.[2] By the year 2100 the global commercial energy system will have been totally replaced two to three times, providing many opportunities to change system performance through the use of new technologies at the time of investment, both for capacity expansion and for replacement.

In examining alternative energy strategies, emphasis is given here to identifying options that are

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[1] Three sets of detailed tables were prepared as supporting material for this report. They are attached as Appendices A, B, and C:

Appendix A: *Energy Balances for the Biomass-Intensive Variant of the LESS Constructions*

Appendix B: *Summary Tables (Biomass-Intensive Variant of the LESS Constructions)*

Appendix C: *Electricity Generation, Fuels Used Directly, and Primary Energy by Region for the Biomass-Intensive Variant of the LESS Constructions*

[2] As many economic studies have shown, deep reductions in CO_2 emissions can be achieved with existing technologies only at relatively high costs.

prospectively cost-competitive. The WG IIa found that there is no shortage of ways to reduce emissions; however, some options may never be cost-effective, even with massive public-sector support for R&D and commercialization. The challenge for energy analysts is to identify potentially low-cost strategies for reducing emissions and explore their strengths and weaknesses.

How one technology will compare with another 25 or 100 years from now is unpredictable, especially if the technologies are not yet commercial. But it is not realistic to probe the deep future taking into account only commercial technologies. The prospective performance and relative cost characteristics for the technologies selected for emphasis in the LESS constructions can be described with a reasonable degree of confidence with present knowledge; all are commercial, or commercially ready, or have good prospects for becoming commercial products within the next one or two decades, if adequate incentives are provided for the needed R&D and for launching the new industries involved. Moreover, all the technologies considered offer the potential for providing energy services at costs that are comparable to those projected for conventional energy technologies. And some of the technologies considered offer multiple benefits other than the potential for reducing greenhouse gas emissions.

With this approach, technologies that are so little advanced that their prospective performance, cost, and value cannot be described with a reasonable degree of confidence may well be unjustifiably under-represented in the LESS constructions.

Despite this limitation, a number of relatively robust conclusions can be drawn about future prospects (*e.g.* regarding the relative costs in the long term of producing hydrogen electrolytically from renewable or nuclear sources vs. thermochemically from natural gas, biomass, or coal).

To help clarify the options, alternative versions of the LESS were constructed with features that make each variant markedly different from the others. Some important features distinguishing the alternatives are highlighted. In the real world, there would be mixing of some options, while other options might not be realized at all. Focussed attention is given to five alternative LESS constructions.[3] Primary energy consumption at the global level for these five variants for the period 1990-2100 is presented in Tables 1 through 5. Global primary energy requirements for these five variants are compared in Figure 1; annual CO_2 emissions for these variants are shown in Figure 2, alongside the emissions for the IPCC's IS92a "Reference" Scenario (IPCC, 1992).

For all variants it is envisaged that renewable energy sources play important roles. Modernized biomass energy systems become well established in all variants, but dependence on biomass varies markedly from one variant to another. Nuclear power is emphasized in one variant and deemphasized in the others. The deemphasis on nuclear power in four of the five variants is intended to help better understand the prospects for achieving low CO_2 emissions without a revival of the nuclear option, in light of the uncertainties regarding public acceptance of nuclear power.

Four of the variants involve a high degree of decoupling of energy demand from economic growth as

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[3] No claim is made that any of these five paths to the energy future is optimal; they were chosen for emphasis because, on the basis of present information, they offer the potential for both low emissions and the provision of energy services at costs comparable to those for conventional energy. Moreover, much more work is required to provide a comprehensive understanding of the prospects for and implications of these alternative global energy supply systems.

a result of emphasis on the efficient use of energy, to the extent that over the course of the next century global energy demand only doubles:

- biomass-intensive (BI) and nuclear-intensive (NI) variants of a Reference Case that is characterized by oil and natural gas production schedules that are consistent with mid-range estimates of remaining oil and natural gas resources,

- a natural gas-intensive (NGI) variant that is based on assumed high estimates of remaining recoverable natural gas resources, along with modest amounts of decarbonization of natural gas, and

- a coal-intensive (CI) variant based on intensive use of coal with a high degree of decarbonization of coal, biomass, and natural gas supplies, with oil and natural gas production schedules that are consistent with mid-range estimates of remaining oil and natural gas resources.

A fifth construction, a high-demand (HD) variant, involves a quadrupling of primary energy demand over the course of the next century, in line with projections such as the IPCC's IS92a Scenario (IPCC, 1992). This variant involves intensive use of coal, natural gas, biomass, and intermittent renewable energy sources, and a high degree of decarbonization of all three of these carbon-rich primary fuels.

The central finding of the LESS construction exercise is that *there are various alternative paths to the energy future that can be pursued for achieving deep reductions in CO_2 emissions over the long term (to ~ 2 GtC/year by 2100), at projected costs for energy services that would be plausibly comparable to the projected costs of these services provided by conventional energy systems.* This finding is contingent on society's active pursuit of technological innovation in the energy sector. It is assumed that in energy R&D programs major commitments are made to accelerate the development of a diversified portfolio of the highlighted technologies over the next two decades, so that, as the result of cost reductions through technological improvement and "learning-by-doing," there are good prospects that a significant fraction of these technologies will be successfully developed and ready for large-scale applications in time for the target years in the scenario, to the extent justified by prospective costs.

While some of the highlighted technologies might not be successfully developed, even with a strong energy innovation policy, there appears to be such a diversity of options for achieving deep reductions in emissions that society would have flexibility in choosing among alternative paths largely on the basis of considerations other than greenhouse warming, if it decides to seek deep reductions. However, the LESS construction exercise also shows that there would be much less flexibility to choose among technological alternatives if energy demand growth were fast than if it were slow.

The LESS Constructions in the Context of Previous Analyses

For its 1990 Assessment Report, the Response Strategies Working Group of the IPCC prepared high and low economic growth variants of alternative global energy scenarios (see Table 6) to help policymakers understand the prospects for alternative energy paths to the year 2100 and their implications for global warming (RSWG, 1990). These included Accelerated Policy (AP) scenarios that involve a high rate of energy efficiency improvement and emphasis on non-fossil energy technologies (solar and nuclear) in the first half of the 21st century, such that the concentration of total greenhouse gases (in CO_2-equivalent terms) is kept below a doubling throughout the next century. In particular, the AP scenario variant characterized by high economic growth involved bringing about a reduction in global CO_2 emissions from fossil fuel burning to 3.5 GtC by the year 2100. A key feature of this scenario was emphasis on biomass as a fossil fuel substitute, with biomass use rising to 245 EJ per year (nearly 2/5 of total primary energy) by 2050.

The LESS Constructions are intended to update the 1990 IPCC analysis in light of the increased understanding of opportunities for achieving deep reductions in emissions at relatively low cost, by synthesizing the analyses of energy supply options presented in Section 2 of Chapter 19 of the WG IIa SAR.

One of the constructions, the BI variant, draws on analyses in two major studies (completed since publication of the 1990 and 1992 IPCC Reports) that assess the prospects for accelerated development of renewable energy over the course of the next several decades. The World Energy Council's assessment of these prospects (WEC, 1994) in the context of a strong emphasis on efficient energy use is reflected in its Ecologically-Driven global energy scenario (WEC, 1993), which involves CO_2 emissions in 2020 at a level only 5% higher than in 1990 and 25% less than for the WEC Reference scenario. Also, a Renewables-Intensive Global Energy Scenario (RIGES) was constructed (Johansson et al., 1993a) in connection with an assessment of the global prospects for renewable energy prepared for the 1992 Conference on Environment and Development (Johansson et al., 1993b). For this scenario, which also emphasizes opportunities to use energy more efficiently, it was estimated that global CO_2 emissions from fossil fuel burning would be about 12% less in 2025 than in 1985 and about 25% less in 2050, without increases in energy prices (via carbon taxes) above what energy prices are expected to be under business-as-usual conditions.

The recent WEC and RIGES scenario constructions reflect some of the potential of these advanced technologies for reducing CO_2 emissions at low costs, although the long-term potential is not fully apparent in the period 2020-2050, because of the long time required to turn over the capital stock of energy-producing and -using equipment.

The Biomass-Intensive (BI) variant of the LESS represents an extension of Renewables-Intensive Global Energy Scenario (RIGES) developed earlier (Johansson et al., 1993a). The BI variant differs from the RIGES in that: (i) while the RIGES looked only to 2050, the BI variant of the LESS looks to 2100; (ii) the BI variant (like all the LESS variants) is based on 1994 estimates of remaining oil and gas resources of the US Geological Survey (Masters et al., 1994), which are much higher than the 1990 estimates on which the RIGES projections were based, leading to much less development of biomass synthetic fuels and thus biomass plantations in the near term (2025) than in the RIGES; (iii) the LESS includes CO_2 sequestration in natural gas wells, while the RIGES focussed exclusively on renewable energy options. For a detailed discussion of the RIGES the reader should consult the original RIGES analysis (Johansson et al., 1993a).

The Energy Demand Projections Assumed for the LESS Constructions

The point of departure for the construction of the Low Emissions Supply System (LESS) is a set of demand projections for electricity, solid, liquid, and gaseous fuels, by world region, for the years 2025, 2050, 2075, and 2100, developed by the Response Strategies Working Group (RSWG) of the IPCC for its 1990 Assessment Report (RSWG, 1990).

The RSWG projections were for 9 world regions. For the LESS constructions, the number of regions was expanded to 11 (separating Japan from Australia/New Zealand and Canada from Western Europe)--see Table 7. The population projections underlying the RSWG scenarios and adopted for all the LESS constructions (see Appendix A) are from the World Bank (Zachariah and Vu, 1988).

The RSWG prepared high and low economic growth variants of alternative global energy scenarios to help policymakers understand the prospects for alternative energy paths to the year 2100. The RSWG scenarios included Accelerated Policy (AP) scenarios characterized by high rates of energy efficiency improvement and emphasis on non-fossil (solar and nuclear) energy sources. The AP energy demand scenarios provide a 1990 perspective as to what might reasonably be achievable with public policies targeting the exploitation of cost-effective opportunities for making more efficient use of energy.

The demand profiles of an AP scenario were assumed as exogenous inputs to the energy supply analysis for four of the LESS variants (BI, NI, NGI, and CI), because there are large untapped opportunities for reducing CO_2 emissions at low costs via investments aimed at improving energy efficiency.[4] The high economic growth variant of the AP scenarios was chosen in part to make clear that reductions would not be achieved as a result of economic stagnation and in part because the introduction of the alternative energy supply systems involves rapid rates of technological change, while a slowly growing economy offers a poor theater for innovation.[5] The regional economic growth projections assumed for the LESS are presented in Appendix A for the BI variant but are the same for all LESS variants. The assumed GDP growth rates, 1990-2050, average 2.8%/year for industrialized countries and 4.4%/year for developing countries (see Appendix A).

The total electricity generation levels and the levels for direct use of solid, liquid, and gaseous fuels and total direct use of fuels[6] adopted from the AP scenario are tabulated as Tables A, B1, B2, B3, and B4 of Appendix B.

In terms of primary energy, the emphasis on efficient use of energy in the AP scenario essentially eliminates energy demand growth in the industrialized world, as illustrated for the BI variant of the LESS constructions (see Figure 3 and Table 8).

The energy model used by the RSWG to generate the AP scenario was made up of a "bottom-up" part and a "top-down" part. Energy demand for the period beyond 2025 (aggregated at the sectoral level) as well as energy supply and energy prices in all years were estimated using a top-down sub-model--a variant of the energy-CO_2 model of Edmonds and Reilly (1986). A bottom-up sub-model, developed at the World Resources Institute and the Lawrence Berkeley Laboratory, was used to project energy demand to the year 2025, using data on historical energy use and activity patterns to estimate future activity levels, energy intensity, and energy use. Using this "bottom-up" approach, estimates of future activity and intensity levels are functions of the assumed rates of growth in population, real GDP growth, rates of changes in energy prices, rates of improvement in engineering efficiency of energy use, and estimates of the elasticity of demand to changes in income and energy price. Details of the "bottom-up" construction to 2025 are described elsewhere (Lashof and Tirpak, 1990). Here a cursory indication is provided of the AP energy demand construction for 2025.

Table 9 shows the world-wide AP projections for automobiles for all regions except China (for which autos were not modeled explicitly): between 1985 and 2025 the number of cars was projected to increase 90%

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[4] The assumptions regarding the energy demand projections for the High Demand (HD) variant are discussed below in *High Demand (HD) Variant of the LESS Constructions*.

[5] The high economic growth variant of the AP scenario was also adopted for the energy supply construction of a Renewables-Intensive Global Energy Scenario (RIGES) to the year 2050 developed in Johansson *et* al. (1993a).

[6] The "direct use" of fuels refers to the use of fuels by final consumers and does not include the use of fuels for power generation or the processing losses associated with producing synthetic fuels.

(up by a factor of 5.8 in developing countries), but the average fuel economy of cars increases from 7.42 km/l (17.5 mpg) to 17.8 km/l (42 mpg) (e.g. as a response to an appropriate public policy, which might be the introduction of automotive fuel economy standards), and the amount of driving per car declines about 10%, so that worldwide fuel consumption for cars declines 30%. The assumed fuel economy for 2025 represents what is achievable with US-size gasoline internal combustion engine cars with technology that could become average technology for new cars by 2002-2005 at an average cost of saved energy of about $0.13/liter ($0.50/gallon) (DeCicco and Ross, 1993); little new technology would be required to achieve this performance level. [Much better performance is achievable with new technology: gasoline-equivalent fuel economies of the order of 32 km/l (75 mpg) with fuel cell vehicles (Williams, 1993; 1994a).]

Table 10 shows the AP projections for the production of energy-intensive basic materials and energy consumption in these industries for the industrialized countries. Production of these materials is expected to grow in these countries much more slowly than GDP and to actually decline in the case of iron and steel, reflecting a continuation of the "dematerialization" trends of these economies in recent years (Williams et al., 1987; Bernardini and Galli, 1993). Complementing these production trends are expectations that the energy intensity of production will decline at average rates ranging from 0.5-2.0%/year. The net effect is that energy use by these industries is about the same in 2025 as in 1985 or less.

As shown by the analyses of the energy demand panels of Working Group II, the AP demand projections assumed for the BI, NI, NGI, and CI variants of the LESS constructions are ambitious but plausible. It is not likely, however, that the assumed rates of improvement in energy efficiency would be realized without new public policies. Because of the inherently favorable economics of a wide range of opportunities for making energy efficiency improvements, many students of energy demand analysis believe the targeted rates of energy efficiency improvement are plausible with appropriate institutional innovations--including the pricing of energy to reflect its true costs (starting with the elimination of permanent subsidies for energy), imaginative approaches to implementing integrated resource planning goals for electric utilities,[7] automobile and appliance energy efficiency standards, and creative policies for fostering technological innovation.[8]

Constructing Alternative Low CO_2-Emitting Energy Supply Systems

Assuming the demand levels from the AP Scenario of the RSWG, alternative energy supply systems were constructed. In what follows, the details of this energy supply construction exercise are described--with respect to the production of and trade in petroleum and natural gas, biomass production, electricity generation, synthetic fuels production from biomass, coal and natural gas, and hydrogen production from intermittent renewable sources.

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[7] Two attractive examples (Williams, 1989) are the Cicchetti/Hogan proposal for competitive energy service companies (Cicchetti and Hogan, 1988) and the Cicchetti/Curkendall proposal for energy service company roles by electric utilities (Cicchetti and Curkendall, 1987).

[8] For example, the Clinton Administration's Partnership for a New Generation of Vehicles (a partnership involving the Big Three US automakers and the Clinton Administration) is aimed at introducing, in ten years, production-ready prototypes for a new generation of autos. These new cars would have 3 times the fuel economy of today's cars that have the same performance, but they would cost no more to own and operate than today's cars, while meeting all air emissions and safety criteria.

A key consideration for the technologies included in the LESS constructions is prospective cost.

The Comparable Cost Criterion for Climate-Friendly Energy Technologies

The economic cost criterion that guided the LESS construction exercise is that, for a low CO_2-emitting technology to be included in a LESS variant, costs for energy services provided by that technology must be plausibly comparable to the costs of energy services based on advanced conventional energy technologies. The economic cost criterion is illustrated by examples from the electric power and automotive sectors.

The Comparable Cost Criterion for Electric Power Generation

New renewable electric technologies are major options for achieving deep reductions in CO_2 emissions from the power sector. The comparable cost criterion relating to biomass vs. coal power generation and for the management of utility systems with large contributions from renewables, including various levels of penetration of intermittent electric generating sources (wind power, pv power, and solar thermal electric power) on the electric utility grid are of particular interest.[9]

Biomass vs. Coal: In thinking about biomass vs. coal for power generation in the longer term, it is helpful to frame the analysis in terms of using the same conversion technologies for biomass and coal, to help ensure that a fair comparison is made. The integrated gasifier/intercooled steam injected gas turbine (IG/ISTIG) is an advanced technology that appears to be well-suited for this comparison (see Box A).

The coal version of this technology (CIG/ISTIG) was advanced by the General Electric Company in 1986 (Corman, 1986) as a promising option for using coal in an integrated gasifier/combined cycle that would give rise to a very low cost for electricity generation at very low cost configuration. On the gas turbine side, this concept requires the commercialization of intercooling for steam-injected aeroderivative gas turbine cycles--an option that is expected to result in both substantial increases in gas turbine efficiency and reductions in unit capital cost ($/kW$_e$), as a result of getting about twice as much power out of a given steam-injected gas turbine (Williams and Larson, 1989). On the gasification side, CIG/ISTIG involves shifting from the use of an oxygen-blown gasifier (which characterizes commercial CIG/CC technology) to an air-blown gasifier, which can greatly reduce capital investment requirements. But this gasifier shift requires "hot-gas cleanup" technology for sulfur removal, which (like intercooling) is not yet commercially available. GE proposed to the US Department of Energy (US DOE) that CIG/ISTIG be demonstrated under the US DOE's Clean Coal Program. But the proposal was not funded, and GE has not pursued the concept further.

The IG/ISTIG concept is also an attractive option for biomass--offering high efficiency and low unit capital costs at a modest scales (Williams and Larson, 1993). With this technology biomass has the advantage over coal that it has little sulfur, so that the commercialization of hot gas sulfur cleanup technology does not have to be proven before the technology can be developed for biomass applications. BIG/ISTIG technology is not suitable for all biomass feedstocks, as the fixed bed gasifier requires feedstocks of high bulk density--e.g. wood chips but not grasses. This should not be a major constraint, however, as fast-growing trees will be the preferred biomass energy crops in many areas.

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[9] While in the near term, much of the interest in photovoltaic power and some of the interest in wind power is for applications that are remote from utility grids, most intermittent renewable electric systems will be connected to electric utility grids in the long term.

Box A: IG/ISTIG as a Framework for Comparing Biomass and Coal in Power Generation

In looking to the long term, IG/ISTIG for both coal and biomass provides a very good context for examining the competition between these two feedstocks. In the long run only the inherent differences between these feedstocks matter, and IG/ISTIG is well-suited for examining these differences quantitatively.

Unlike the situation with synfuels, where reactivity and H/C ratio are also important, only sulfur content and fuel moisture are key distinguishing characteristics between coal and biomass in power generation activities.[10] While conventional wisdom is that biomass power plants must be much smaller than coal plants, scale is not likely to be an important distinguishing feature with advanced technology.[11]

The capital and operating cost penalties for the hot sulfur cleanup system are included in the base parameters for the coal IG/ISTIG plant described in Table 11. In the case of biomass, which is often provided in feedstocks that have 50% moisture, drying is necessary prior to gasification. Today this is done with flue gas dryers, that involve an energy efficiency as well as a capital cost penalty. But if the biomass is dried in superheated steam the water evaporated from the fuel can be recovered as extra steam that can be utilized in the process, thus virtually eliminating the efficiency penalty.[12]

Parameters characterizing CIG/ISTIG and BIG/ISTIG technologies and their costs for both coal and

[10] The higher H/C ratio of biomass provides more hydrogen in the product gas, which improves flame stability for low-heating-value gaseous fuels. But this is a marginal advantage.

[11] In a pioneering analysis exploring the scale issue for biomass energy facilities, taking into account the geographical dispersion of biomass supplies for specific sites, Marrison and Larson (1995) have shown that for pressurized biomass integrated gasifier/gas turbine systems [which are likely to be preferred in the long run to unpressurized systems] the optimal scale for sites in the US Midwest and Southeast and in Brazil is in the range 230 to 320 MW--far larger than sizes most people have thought is optimal for biomass.

At the same time advanced technologies may take away some of the incentive for building large coal plants. If hot gas sulfur cleanup technology becomes commercially available for coal, coal integrated gasifier/gas turbine systems could use air-blown instead of oxygen-blown gasifiers. The scale economies of oxygen plants drive one to large coal integrated gasifier/gas turbine systems that involve oxygen-blown plants. But the relative insensitivity to scale of air-blown gasifier and gas turbine costs makes it feasible to consider building coal plants smaller--a prospect that is enhanced if steam injection is used instead of a steam-turbine bottoming cycle (for which the cost is very scale-sensitive). For these reasons, CIG/ISTIG is a very good candidate for small-scale coal plants.

Thus during the time frame of interest for the LESS constructions there may be no significant scale differences between coal and biomass plants in many circumstances, if a comparable technological development effort is directed to each.

[12] When biomass is dried in superheated steam and the water recovered this way from the biomass is utilized as steam by process integration with the biomass integrated gasifier/gas turbine power system such as BIG/ISTIG, the efficiency is independent of the moisture content of the feedstock (Hulkkonen et al., 1993). The need for drying gives rise to a capital cost penalty, however. For a 111 MW_e BIG/ISTIG system steam drying would add about $\$100/kW_e$ to the installed capital cost (see Table 11). If a biopower industry were successfully launched, it is very likely that this technology would be commercialized quickly.

biomass systems are presented in Table 11.[13,14]

Table 10 also shows the breakeven costs that would make the busbar cost with coal equal to that for biomass, assuming biomass prices of \$2.0/GJ and \$1.5/GJ, respectively. A biomass price of \$2.0/GJ could be typical in many areas of the world that are well-suited for growing biomass for energy, in the longer term of interest for the LESS constructions. Moreover, prices as low as \$1.5/GJ might be expected in some regions.[15]

Two values are shown in Table 11 for these breakeven costs. The first would hold in the early days when the CIG/ISTIG industry is being launched but after costs have fallen to the indicated levels; this breakeven cost takes into account a credit for sale of the H_2SO_4 byproduct of the sulfur hot-gas cleanup system. This credit would be reduced to zero in the long-run, however, because if CIG/ISTIG technology is truly successful in the market, the H_2SO_4 market would become saturated and its byproduct value would fall. The second breakeven price (shown in parentheses) is based on zero market value for this byproduct.

These coal breakeven costs are as follows:.

For biomass @ \$2.0/GJ: \$1.67/GJ if an H_2SO_4 byproduct credit can be taken, and \$1.39/GJ if not.

For biomass @ \$1.5/GJ: \$1.18/GJ if an H_2SO_4 byproduct credit can be taken, and \$0.90/GJ if not.

A comparison of these breakeven prices for coal with recent price projections for coal delivered to electric

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[13] The cost calculations presented in Table 11 neglect NOx cleanup costs. Unlike the situation for natural-gas-fired gas turbine cycles, thermal NOx generation is negligible for gasification-based systems because of the low flame temperatures that arise from the low heating value of the gas. But NOx from fuel-bound nitrogen can be a an issue demanding attention where there are tight air quality constraints but the difference between these costs for the two systems is probably in the noise level. For most biomass fuels, NOx control for fuel-bound nitrogen would be less costly for biomass than for coal. Typical coals have nitrogen contents of 0.3 to 0.4 kg/GJ. Most biomass feedstocks have nitrogen contents in the range 0.03 to 0.30 kg/GJ.

[14] While refinements can undoubtedly be made for this technological comparison, the "level" basis for comparing coal and biomass offered by IG/ISTIG technology provides a much more meaningful basis for making comparisons than most other comparisons, which involve "apples and oranges."

[15] Very detailed analyses have been done for the northeast of Brazil to estimate costs and yields based on actual commercial experience with Eucalyptus plantations (Carpentieri et al., 1993). In this study it is estimated that about 11 EJ/year of biomass could be produced at an average yield of 14.5 t/ha/yr on 38 Mha of land in the northeast of Brazil, at a cost for delivered wood chips of less than \$1.9/GJ. (Note that in the Biomass Intensive Variant of the LESS constructions, the amount of plantation biomass in all of Latin America is 6.4 EJ in 2025 and 50.2 EJ in 2050.)

For the US, a major study has been carried out by a large team at the US Departments of Energy and Agriculture in preparation for a biomass energy initiative that had been the focus of a major Administration effort. In this study it was estimated that, with a committed biomass production R&D effort, about 5 EJ/year of plantation biomass could be grown on US croplands by 2020 at a marginal production cost of \$1.5/GJ (1990\$) and an average harvested yield of 14.2 dry tonnes/ha/y (assuming an energy content of 20 GJ/tonne), with marginal costs rising only slowly at this production level (Graham et al., 1995). Using the same biomass yield and cost data, a multicrop model of McCarl indicates a higher marginal production cost of \$2/GJ for biomass grown on US cropland in 2020 at a level of 5 EJ/year (Graham et al., 1995).

utilities[16] suggests that there would be many opportunities for biomass to be competitive with coal in power generation, if both biomass and coal were utilized in IG/ISTIG units.

If coal prices decline substantially from present levels, as some have suggested (Turnure et al., 1995), it would be tough for biomass to compete. However, if biomass cost $2/GJ and coal $1/GJ, in the era when the market for H_2SO_4 is saturated, BIG/ISTIG power would cost only 9% more than CIG/ISTIG power (see Table 11)--which still might be regarded as meeting a "comparable cost" criterion, even though the biopower would be more expensive.

Managing renewable energy systems: Managing grid-connected renewable electric technologies poses new challenges for utilities.

Many of renewable electric technologies (and fuel cell technologies as well) produce electricity in plants that are much smaller than those used in today's power systems--at scales ranging from 1 kW_e for some photovoltaic and fuel cell systems to 25-300 MW_e for biopower systems (Marrison and Larson, 1995), because costs per unit of capacity for such technologies will be relatively insensitive to scale; for these systems the economies of mass-produced standardized units are more important than the economies of scale (Williams, 1994b). And many of the smaller scale technologies will be sited not in central-station plants but at or near customers' premises; some photovoltaic and fuel cell systems can be operated unattended and installed even at individual houses. Electricity produced from such "distributed power systems" is worth more to the utility than central-station power whenever the electrical output is highly correlated with the utility peak demand, largely because such siting makes it possible to defer transmission/distribution investments (Shugar, 1990; Hoff, Wenger, and Farmer, 1995).

Moreover, unlike the thermal power plants utilities are accustomed to managing, intermittent renewable power plants are not dispatchable.

New analytical tools are being developed to understand better how to integrate such technologies into electric utility grids and how to value and manage power systems that involve various combinations of intermittent and dispatchable power sources. One such tool, the SUTIL simulation model (Kelly and Weinberg, 1993), calculates the average cost of electric generation as the result of an hour-by-hour simulation that takes into account demand, the variable output of intermittent renewable equipment, the load-leveling capabilities of hydroelectric facilities, and the dispatching characteristics of alternative thermal-electric plants.

Results of a SUTIL simulation of ten alternative renewable and conventional energy investment

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16 The following are alternative prices for coal (in 1990/GJ) delivered to electric utilities, as projected in a recent Energy Modeling Forum exercise (Weyant and Gaskins, forthcoming):

	2000	2005	2010	2020	2030
Edmonds-Reilly-Barnes	1.68	1.85	1.99	2.27	2.30
OECD GREEN	1.34	1.34	1.34	1.35	-
IEA	2.23	2.92	-	-	-
DGEM	1.25	1.32	1.19	1.14	-
MARKAL	1.62	?	1.08	1.22	-
Fossil2	1.47	1.49	1.57	1.80	1.83

portfolios for a US electric utility (Kelly and Weinberg, 1993) are shown in Figure 4.[17] The exercise was carried out as follows. The electricity demand profile was specified on an hour-by-hour basis throughout the year. (The actual demand profile was for a utility in northern California.) For this demand profile, the least-costly mix of electricity supplies was determined by designing a utility from alternative sets of specified supply technologies and specified 30-year levelized lifecycle fuel prices (see Figure 4). The alternative supply systems were configured as follows:

- The bar on the left is for a utility supplied with the least costly mix of conventional pulverized coal, steam-electric plants, typical new natural gas-fired peaking gas turbines, and typical new natural gas-fired gas turbine/steam turbine combined cycle plants.

- The second bar is for a utility that uses first-generation integrated gasifier/combined cycle technology for coal, and the best peaking turbine and combined cycle technologies now on the market.

- The third bar is for a utility that uses advanced fossil fuel technology (the CIG/ISTIG technology described in Table 11) for coal, natural gas-fired intercooled aeroderivative peaking gas turbines, and combined cycles that incorporate this intercooled aeroderivative turbine technology.

- All the rest of the bars except bar 7 are for utilities that get 21% of the electricity from dispatchable hydroelectric units (the actual contribution from hydroelectricity for the utility for which the demand profile is assumed).

- The BIG/ISTIG technology described in Table 11 is used for baseload power instead of CIG/ISTIG technology for the utilities represented by bars 9 and 10.

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[17] Since the SUTIL modeling exercise presented in Figure 4 was carried out, expectations about future fossil fuel prices have changed markedly. In 1995 the US Department of Energy projected that prices for coal and natural gas delivered to electric utilities in 2010 will be $1.3/GJ for coal and $3.24/GJ for natural gas (in 1990$). More recent analyses are also projecting much lower biomass prices--e.g. a delivered price of $1.5/GJ for up to 5 EJ/year of plantation biomass in the US based on production technology projected for 2020 (Graham et al., 1995).

To show the implications of now lower expectations for future energy prices, the SUTIL model has been run for the same utility demand profile but assuming instead lifecycle costs of $1.30/GJ for coal, $3.24/GJ for natural gas, and $1.50/GJ for biomass (Terzian, 1995). To simplify the presentation, all the new SUTIL runs are for utility systems with 21% hydropower. Also "best new fossil" runs were not carried out this time, and, to clarify the coal/biomass competition, a new set of runs for advanced biomass + natural gas but no intermittent renewables was carried out. The results of this exercise with these new fuel price assumptions are as follows:

Utility investment portfolio		Average electric generation cost (1990 cents/kWh)
1.	Conventional fossil	3.60
2.	Advanced fossil	3.12
3.	Advanced biomass and natural gas	2.97
4.	#3 + 10% intermittents	3.05 to 3.14
5.	#3 + 30% intermittents	3.37 to 3.61
6.	#3 + 50% intermittents	3.83 to 4.23

If the biomass price were $2/GJ instead of $1.5/GJ, the average generation cost for #3 would be 3.29 cents/kWh.

o Bars 6, 8, 9, and 10 are for utilities for which the contribution from intermittent renewables[18,19,20] is specified as 10, 30, or 50%, as indicated, for which 21% of the electricity is provided by dispatchable hydropower, and for which the rest of the electricity is provided by the least costly mix of advanced fossil or biomass and natural gas power plants, as indicated.

o Bar 7 is for a utility for which the contribution from intermittent renewables is specified as 30%, and for which the rest of the electricity is provided by the least costly mix of advanced fossil power plants.

While the conditions in northern California are clearly not applicable everywhere, for the assumed fuel prices the results of this simulation should not be too sensitive to the location for areas that have insolation levels comparable to those in northern California (e.g. many areas in the US and many developing countries).

This SUTIL modeling exercise offers some relatively general insights about the integration of renewables into utility grid systems. For this set of alternative utility investment portfolios:

(*i*) all configurations involving advanced technology (cases 3-10) are less costly than the base case, which involves conventional fossil fuel technologies (case 1);

(*ii*) there is little variation in cost among the advanced technology options, although there are no less costly options than the advanced fossil fuel options (cases 3 and 4);

(*iii*) the fraction of electrical energy provided by intermittents can rise up to about 30%, without the use of new electrical storage technology, before costs start rising significantly;

(*iv*) at high levels of penetration of intermittent renewables, baseload thermal power becomes less important and load-following and peaking power become more important; (*v*) the advanced fossil fuel options offer relatively modest reductions in CO_2 emissions; (*vi*) the option offering the greatest reduction in CO_2 emissions [case 9, involving a 30% contribution from intermittent renewables and biomass for baseload power and for which emissions are only 4% of those for the least costly case (case 4)] has an average generation cost that is only slightly (7%) higher than for the least costly case (case 4).

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18 The wind output was derived from a randomized Rayleigh wind speed distribution and an equation that models the output of the wind turbine for this wind speed distribution. The wind turbine modeled was a variable speed turbine with a capital cost of $800/kW$_e$.

As the installed capacity of wind turbines was increased, the average wind speed was progressively decreased, from 8.0, to 7.5, to 7.0 m/s to reflect the range of available wind resources. For each 5% of total system load met by wind turbines a different uncorrelated wind distribution was used to simulate the effects of geographical diversity.

19 Two values were assumed for the installed photovoltaic system cost: $900/kW$_e$ and $1800/kW$_e$ (judged appropriate costs for the period > 2010). Distributed credits were also taken into account to reflect the reduced transmission and distribution costs and increased reliability associated with distributed pv generation instead of central station pv generation. A conservative estimate of these credits was made. The lower costs shown in Figure 4 for utilities with pv systems represents either the situation where the installed cost is $900/kW$_e$ and there is no distributed credit or the situation where the installed cost is $1800/kW$_e$ and this distributed credit is taken into account. Insolation for northern California was assumed.

20 The solar thermal system considered is a 200 MW$_e$ fully tracking central receiver system costing $1625/kW$_e$ (a cost judged to be appropriate for the period > 2010). Insolation for northern California was assumed.