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THE ENVIRONMENTAL IMPERATIVE FOR RENEWABLE ENERGY: AN UPDATE

by Adam Serchuk

*E*very option for generating electricity affects the environment. As this survey makes clear, conventional generating options can damage our air, climate, water, land and wildlife, as well as raising levels of harmful radiation. Renewable technologies are substantially safer. The environmental imperative remains clear: The future must be renewable.

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A Message from the Staff of the Renewable Energy Policy Project

Environmental questions have sometimes hindered consumer acceptance of renewables. For instance, the National Audubon Society has opposed wind turbines for their impact on birds. Some people question the effect of heavy metals in solar panels. Others wonder whether geothermal plants could damage protected areas. These concerns help make renewables as environmentally friendly as possible. But they can also obscure a more essential truth: while ALL energy sources affect the environment, renewables impose lighter damages than conventional alternatives. Most important, rejecting renewable energy without cutting energy use equates implicit support of coal, nuclear and other harmful sources of power.

In many states, Americans can now buy electricity generated from renewable energy, much as they choose organic food, dolphin-safe tuna, and energy-efficient washing machines. As a result, Americans have a new opportunity for "direct action" in support of clean power. Slowly but surely, in parallel with continuing support for sound environmental policy, latent interest in renewables will blossom into more renewable energy installations.

And people in states with open electricity markets are buying renewable energy. In Pennsylvania, almost 70,000 customers have chosen renewables-based "green power." In California, 1.4% of all customers (and 20% of industrial customers) have done so, despite an electricity market that is essentially rigged in favor of the big, incumbent utilities.

Will voluntary purchases ensure that renewables substantially improve the environment? That is not clear. The higher cost of renewable energy does not help. But the market is booming for SUVs with $10,000 profit margins; clearly, many Americans could afford more renewable energy.

With these facts in hand, electric consumers reviewing their choices must ask themselves: "If I don't buy green, what am I buying?" As this report shows, failing to buy green means choosing energy that has a greater effect on air, land and water, and which affects the health of humans, plants and animals. And because low-income and minority communities suffer the most from the harm caused by conventional energy, failing to take responsibility for one's energy choices by supporting clean power creates great social injustice as well.

The relative environmental impacts of different fuels must now matter even more—not just in the lobbies of the public utility commission and legislature, but in every living room where consumers scan their monthly electric bills. And, because sound choices requires good information, we need to better understand our electricity system's impact on the environment. We hope that the following report will help further understanding of the environmental imperative for renewable energy.

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March 31, 2000

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by Dr. Adam Serchuk

PART I. DOES THE ENVIRONMENT STILL MATTER?

A. Introduction: A Look Back

In late 1995, the newly formed Renewable Energy Policy Project released its first publication, an issue brief by Irving Mintzer, Alan Miller, and Adam Serchuk. *The Environmental Imperative: A Driving Force in the Development and Deployment of Renewable Energy Technologies* outlined the environmental rationale for developing renewable energy resources for electricity generation, with an emphasis on the air pollution and greenhouse gases emitted by burning fossil fuel. We concluded that "global energy systems developed their current appetite for fossil fuel…through an economic sleight of hand which permits energy consumers to ignore the staggering environmental costs of their choices." We affirmed that "future energy systems, whether they rely on markets or governmental mandates, must manifest greater economic honesty. Once they do so, we believe the world will turn increasingly toward renewable energy."

Has anything changed since 1995? Not the environmental imperative itself: it has become even clearer that renewable energy must play a growing role in our long-term electricity strategy. (We must also boost energy efficiency and replace coal with cleaner fuels.) As we acknowledged then, all technologies for producing energy levy an impact on the environment. The nature of that impact often depends on project-specific characteristics; there exist both renewable and nonrenewable energy installations with unfortunate consequences. Nevertheless, on the whole, renewable energy proves far more benign than the alternatives. The future must be renewable.

> *The future must be renewable.*

Yet much *has* changed in the past half-decade. Most significant, policy makers and regulators worldwide increasingly allow individual suppliers and users to decide how to produce and deliver electricity. This "restructuring" of the electricity business will change the role of environmental issues in energy decision-making.

To take one example, our original *Environmental Imperative* discussed the calculation of environmental "adders" for conventional generating resources. These hypothetical sums represent the cost to the environment of using a given generating technology. In theory, they help identify the generating (or demand-side) option with the lowest total social cost.

While still illustrative as a conceptual tool, and arguably still warranted on theoretical grounds, regulators in many jurisdictions have abandoned environmental externalities as a ratemaking device. In coming years, as regulators relinquish their authority to determine what kind of power plants get built, and how much customers must pay to use them, power companies will produce the power that they think their customers want—in accordance with a very large body of environmental and other regulation—and customers will buy the power that best suits their needs. Presumably, customers will consider price, price volatility, power quality, reliability—and, perhaps, environmental impact.

In short, the environmental impact of making electricity may remain important. We expect that in coming years, environmental action will consist of living green, voting green, and buying green. As citizens, Americans must continue to support public policy and policymakers who protect the environment; as consumers, we will also increasingly have to take responsibility in the marketplace for personal environmental stewardship. The challenge for renewable energy businesses and advocates will be to make environmental information available to consumers, and to show them why it matters.

> *In coming years, environmental action will consist of living green, voting green, and buying green.*

This updated *Environmental Imperative* outlines the main environmental impacts of current conventional electricity generation, as well as those resulting from renewable energy technologies.[1] It represents a primer, not the final word. Due to space and resource limitations, it does not consider all the options available; regrettable gaps remain for solar thermal, microturbines, and a range of experimental renewable and conventional technologies. Readers should remember that some data presented here are uncertain, and many issues remain controversial. Although we have tried to avoid errors in the sources consulted, REPP does not take responsibility for any that remain.

This report does not review environmental regulation, outline a social marketing campaign, or present a policy program. Readers interested in appropriate responses to the material presented here may consult other REPP publications (see inside back cover). Rather, the report surveys major impacts of electricity generation on air, climate, land, water, wildlife, and radiation levels, thereby outlining the environmental imperative for renewable energy.

B. What is the Environmental Imperative?

A complete life-cycle comparison of different electricity options remains beyond the scope of this survey.[2] More important, we already know the basic outline of our environmental dilemma. The beginnings of a response to the dilemma seem equally clear. Taken together, the following issues constitute the environmental imperative facing us:

- All energy use affects the environment: Gathering energy for useful purposes alters the natural cycles of planetary ecology. At their most severe, effects include perturbation of the global climate; threats to endangered species and thereby to biodiversity; health risks through respiratory disease, cancer, and other ailments; irreparable destruction of public land; and the production of toxic waste.

- For a given resource, technology choices and management practices can often alter environmental consequences: For instance, pollution controls can reduce the emissions of combustion-based power plants, and wind turbines can be designed and sited so as not to threaten birds.

- Renewable energy technologies are, in the vast majority of cases, preferable to conventional technologies: Renewable energy technologies carry their own risks. In general, these are far less than those of conventional technologies.

- Most conventional energy technologies are ultimately unsustainable: Some of the impacts of conventional energy production, such as the production of greenhouse gases by coal combustion, land disturbance due to coal mining, and the generation of nuclear waste, seem so intractable as to exclude these technologies from a sustainable energy strategy.

In short, renewable energy resources pose less environmental risk than conventional sources. With careful management, we can use renewable energy without perturbing natural ecological activity in a harmful way—although no energy technology has zero environmental cost. By contrast, reliance on conventional energy sources seems by definition to alter the balance of material and energy in the ecosystem in a dangerous manner. For this reason, renewable energy represents a vital element of a sound energy strategy.

PART II. AIR POLLUTION

All combustion releases gases and particles into the air. These can include sulfur and nitrogen oxides, carbon monoxide, and soot particles, as well as smaller quantities of toxic metals, organic molecules, and radioactive isotopes. In general, coal combustion presents the greatest risk to air quality. Oil and waste wood also release pollutants when burned. Natural gas and gas obtained from biomass, followed by virgin wood, tend to burn most cleanly, although older gas-fired combustion turbines produce much higher levels of nitrogen oxides than cooler burning, more efficient, modern gas turbines.

A. The "criteria" pollutants

In general, the quality of America's air has improved in recent decades. This partly reflects the regulatory requirements of the Clean Air Act (CAA), passed in 1970 and amended in 1977 and 1990. The CAA identifies six "criteria" pollutants as especially dangerous: sulfur dioxide (SO_2), nitrogen oxides (NO_X), ozone (O_3), particulate matter (PM), carbon monoxide (CO), and lead. The U.S. Environmental Protection Agency (EPA) regulates emission rates of criteria pollutants by particular activities, and in some cases overall tonnage on a national basis. While NO_X emissions rose 11% between 1970 and 1997, including a 44% increase from coal-burning power plants, overall tonnage of the other five criteria pollutants has dropped since 1970.[3] As Table 1 indicates, U.S. power plant emissions account for 64% of total SO_2, 26% of total NO_X, and smaller quantities of other criteria pollutants.

> ***Power plants account for 64% of the United States' SO_2 emissions and 26% of NO_X emissions.***

Electricity generation is linked to five criteria pollutants in particular. (See Tables 1 and 2 for emissions from some generating sources.) Except where otherwise noted, the following material draws on EPA findings:[4]

- Sulfur dioxide (SO_2): A gas that forms from airborne oxygen and the sulfur in fuels such as coal and oil, SO_2 impairs breathing, especially for those with existing respiratory or cardiovascular disease and asthmatics.[5] (Natural gas and virgin wood

Table One. 1997 Air Emissions from Electric Utilities: Thousand short tons

Pollutant / Resource	Criteria Pollutants				Volatile organic compounds[B]	Mercury[C]
	Nitrogen oxides	Sulfur dioxide	Particulate matter (10 microns)	Carbon monoxide		
Coal	5,588	12,529	265	254	29	0.0516
Oil	131	486	6	12	3	0.0002
Gas	286	4	0	79	8	<0.0001
Internal combustion	159	61	10	62	10	Unk.
Total from utilities	6,178	13,082	290	406	51	0.0518
Utility contribution to national total	26.2%	64%	1.0%[A]	0.5%	0.2%	32.8%

Note: Criteria pollutants and VOCs from U.S. EPA, *National Air Quality and Emissions Trends Report, 1997,* EPA 454-R-98-016 (December 1998), viewed 13 March 2000 at <www.epa.gov/oar/aqtrnd97>. Data apparently do not include emissions from non-utility electricity generation. Ozone is not listed, as it can form far from the point where its precursors (NO_X and VOCs) are emitted, in response to local conditions.

a These data include only particulates emitted as such, rather than the fine particulates under 2.5 microns that form from SO_2 and NO_X emissions, for which utilities bear larger responsibility and that have a greater impact on human health. The largest sources of PM_{10} are fugitive dust (e.g., from roads and construction) at 64%; natural wind erosion at 17%; agriculture and forestry at 15%; and fires at 3%. Utilities account for 9.3% of PM_{10} emissions from the combined industry and transportation categories.

b Most VOCs result from solvents and automobile use.

c Annual data for 1994–95. U.S. EPA, *Mercury Study Report to Congress, Volume II: An Inventory of Anthropogenic Mercury Emissions in the United States,* EPA 452-R-97-004 (December 1997), table ES-3, viewed 14 March 2000 at <www.epa.gov/ttn/uatw/112nmerc/volume2.pdf>.

contain little or no sulfur.) SO_2 seems especially toxic in the presence of particulate matter. SO_2 emissions harm ecosystems through acid rain, fog, snow, mist, and dry deposition. After emission as gases, both SO_2 and NO_X can take a particulate form in the atmosphere. Very minor amounts of SO_2 may result from the oxidation in air of hydrogen sulfide (H_2S) escaping from geothermal reservoirs.

- Nitrogen oxides: High-temperature combustion causes the formation of NO_X from nitrogen and oxygen in the surrounding air; additional NO_X can be formed from the nitrogen in fuels such as coal, oil, and wood.[6] While older, high-temperature combustion turbines burning oil and natural gas release high amounts of NO_X, new models run cooler and therefore cleaner. Healthy adults experience respiratory problems from even brief exposure (i.e., under three hours) to NO_X; asthmatics, the elderly, the infirm, and children suffer much more severe problems. Exposure may also weaken immune systems. Excessive airborne NO_X can harm ecosystems by elevating nitrogen levels. Atmospheric NO_X can turn to nitric acid, a component of acid rain. NO_X is a precursor to the formation of ozone and, with SO_2, to particulate pollution.

- Ozone: The major constituent of smog, ozone forms from the chemical reaction of NO_X with organic hydrocarbons, such as those in automobile exhaust or in cleaning solvents, in the presence of sunlight. Ozone damages the lungs, increases susceptibility to infection, and decreases ability to exercise. Studies correlate emergency room visits and hospital visits for respiratory causes to elevated ozone levels. Children playing outside are particularly vulnerable. Because ozone often forms far from where its precursors were emitted, in response to local conditions, it is difficult to pinpoint power plants' contribution to the problem, but it is substantial.

- Particulate matter (PM): Particulate matter includes droplets or particles from smoke, dust, fly ash (i.e., the airborne portion of noncombustible fuel contaminants), or condensing vapors. Usually classified by the particles' diameter in microns (e.g., PM_{10} or $PM_{2.5}$), PM also encompasses sulfate and nitrate particles formed as a byproduct of SO_2 and NO_X emissions. Several large-scale studies correlate particle concentrations to increased mortality rates.[7] Data published in 1999 rule out coarser particles as the major threat to human health,[8] increasing certainty that the finer ones present the most pernicious risk. Coarser matter enters the atmosphere from windblown dust, unpaved roads, and crushing or grinding operations; fine $PM_{2.5}$ comes from fuel combustion in cars, power plants, industrial sites, and fireplaces. High levels of particulate pollution harm the elderly, children, and individuals with cardiopulmonary disease, such as asthmatics. PM also reduces visibility. Airborne sulfate and other particles ("aerosols") complicate and partially offset the effects of greenhouse gases, as explained in Part III. Power plants emit only a small fraction of PM_{10}, but much larger proportions of smaller particles.

- Carbon monoxide (CO): The incomplete combustion of fuel releases CO, a colorless, odorless, poisonous gas. When breathed, CO impairs oxygen delivery. Those who suffer from cardiovascular diseases such as angina

Table Two. Comparative Emissions: Pounds per million British thermal units

Resource \ Pollutant	NO_X	SO_2	CO_2
Avg. of top 15 NO_X emitters[A]	1.07	n.a.	n.a.
Avg. of top 15 SO_2 emitters[A]	n.a.	3.11	n.a.
All operating U.S. coal plants[B]	0.53	1.2	206
Coal plants built before 1975[C]	0.7	1.7	Unknown
Coal plants built after 1975[C]	0.4	0.7	Unknown
All operating U.S. oil plants[B]	0.29	0.92	157
All operating U.S. gas plants[B]	0.21	0	119
NSPS for fossil[D]	0.15	0.3	NA
New, gas-fired combined cycle[B]	0.01	0	119
Range for virgin wood[E, F]	0.10-0.25	<0.01	0
Range for waste wood[E, F]	0.10-0.25	<0.01-0.120	0

[a] Average of the 15 U.S. plants emitting the highest total tonnage of NO_X and SO_2 in 1996. Data from Elizabeth Thompson, *Poisoned Power: How America's Outdated Electric Plants Harm Our Health and Environment* (Washington, DC: Clean Air Network, 1997), appendices 2 and 3. Individual plants included here have NO_X rates up to 1.80 lb/mmBtu and SO_2 rates up to 5.67 lb/mmBtu. Some high-NO_X plants are lower-SO_2, and vice versa.
[b] 1998 data on fossil fleet from David Schoengold, MSB Energy Associates, Inc., personal communication, 14 March 2000.
[c] Bruce Biewald et al., *Grandfathering and Environmental Compatibility: An Economic Analysis of Air Emission Regulations and Electricity Market Distortions*, June 1998, viewed 28 February 2000 at <world.std.com/~biewald/Grandfathering-NARUC.zip>.
[d] EPA's New Source Performance Standards for all new fossil-fueled generating plants; no standards exist for carbon dioxide.
[e] Pollutants emitted by typical virgin and waste wood boilers, as described in Environmental Risk Limited, *Summary of Biomass Emissions Data: New England Region*, prepared for the Center for Resource Solutions, ERL-07331-41 (March 1999), tables 6, 7.
[f] Assumes zero net carbon; see text for explanation.

pectoris are especially at risk, but CO may affect even healthy individuals. Elevated CO levels can impair vision and learning ability, and reduce work capacity and manual dexterity. Power plants release only a small amount of CO; over 75% comes from the transportation sector.

In 1998, EPA warned that during the previous year, 107 million Americans lived in counties where the air failed health standards for at least one of the six criteria pollutants. These conditions make people sick, and occasionally kill them. Research conducted in Toronto links up to 50% of respiratory hospital admissions during pollution peaks with high levels of acid particles and ozone.[9] In New Jersey, emergency room visits for asthma increase substantially at ozone levels well below the current U.S. standard.[10] A Los Angeles study associates a 10% increase above average ozone levels with about two additional deaths per 1,000 people, and a 50% increase (not uncommon in the summer) with 10 additional deaths per 1,000.[11] Equally pertinent, air pollution, like many other environmental problems, weighs on poor communities with disproportionate severity (see Box 1).

Box 1: Environmental Justice

The environmental impacts of electricity production weigh most heavily on poor communities and communities of color—terms that in the United States often overlap. In some cases, this situation may reflect a perceived need within the community for economic development at any cost. In others, it may reflect a lack of political influence, a lack of information about environmental risks, or a lack of awareness of alternative development and energy strategies.

- Indian Country as a whole holds one-third of the country's uranium mining and milling waste.[12]
- At 20%,0 the poverty rate of communities located within one mile of coal-fired power plants is almost double that of the general population (11.3%). Such communities are 21.5% non-white, compared with 17% in the general population.[13]
- Compared with families with incomes over $35,000 per year, families with annual incomes below $10,000 suffer more than twice the incidence (per thousand people) of asthma, making them much more susceptible to pollution-related illnesses.[14]

B. Other airborne toxins

In addition to the criteria pollutants just described, power plant combustion can release a variety of other substances, characterized by regulators as hazardous air pollutants (HAPs). EPA regulates emission rates of HAPs from specific activities, although not overall tonnage. (See Table 3 for HAP emissions from several generating technologies.)

Organic HAPs include carcinogenic dioxins, furans, and polycyclic aromatic hydrocarbons. Because these compounds result from incomplete combustion, as does carbon monoxide, measures to prevent the release of CO also generally limit organic toxins.

In addition to organic HAPs, combustible fuel may contain small quantities of toxic metals and other inorganic pollutants. These substances leave power plants as airborne particles or vapor. They also concentrate in bottom ash and collect in pollution control devices. While coal and oil combustion release the greatest quantities of inorganic HAPs, wood can present a problem as well, depending largely on bark surface and growing conditions. Waste wood may also contain metal contaminants from paint, sealant, and other sources.

Measures to limit particulate emissions also generally control inorganic HAPs. Volatile metals such as mercury and selenium represent important exceptions; only about 10% of mercury emitted from power plants takes a particulate form. The remainder takes either an ionic or an elemental form. Ionic mercury usually binds after emission to airborne particles that carry it to earth, where it enters land and aquatic ecosystems. Elemental mercury, on the other hand, may travel the atmosphere for up to two years before converting to ionic form and precipitating down. Some data suggest that 5–10% of mercury comes down within 100 kilometers (km) of its source, and another 50% within 1,000 km. The rest enters the global pool. EPA models suggest that only 30% of U.S. mercury emissions come down inside this country.[15] Utility coal and oil boilers accounted for 32.8% of American mercury pollution in 1995.[16]

Utility coal and oil boilers accounted for about one-third of American mercury pollution in 1995.

Mercury tends to accumulate in aquatic ecosystems, where it works its way up the food chain to top predators such as tuna, sharks, and swordfish—and to the humans who eat them. The developing fetus may be particularly vulnerable to mercury. Po-

Table Three. Hazardous Air Pollutants From Various Generating Technologies: Pounds of pollutant emitted per trillion British thermal units

fuel / pollutant	Wood[A]		Gas[B]	Oil[B]		Coal (EPA)[B]		Coal (E&ERC)[C]
	Virgin	Waste	No PM control	PM control	No PM control	PM control	PM and SO_2 control	Various fuels and configurations
Antimony	Unk.	Unk.	Unk.	Unk.	Unk.	1.4	0.13	0.04-2.4
Arsenic	0.8	22.0	0.14	0.32	5.3	2.9	0.9	0.14-42.0
Beryllium	0.18	0.75	Unk.	0.33	0.21	0.45	0.14	0.04-1.7
Cadmium	1-1.7	0.12-2.1	0.044	0.32	1.6	0.72	1.0	0.03-3.0
Chromium	0.3-33	2.7-6.6	0.96	3.7	5.7	8.4	4	0.13-51.0
Cobalt	Unk.	Unk.	0.12	6.1	27	2.7	1	0.07-6.8
Lead	6-21	18-140	0.37	2.6	9	4.8	5.8	0.60-29.0
Manganese	30-90	1-120	0.3	15	16	15	15	2.6-30.0
Mercury	0.3-5.1	0.3-0.76	<0.38[D]	0.24	0.48	3.9[E]	3.4[E]	1.9-22.0[E]
Nickel	Unk.	Unk.	2.3	180	410	8.3	5.2	0.3-40.1
Selenium	0.6-2.0	1-120	Unk.	1.4	3.8	62	8	0.02-193
Hydrogen chloride	n.a.	Unk.	Unk.	2,900	2,300	21,000	1,290	176-132,000 (HCI + CI_2)
Total organic HAP	Unk.	Unk.	Unk.	Unk.	Unk.	Unk.	Unk.	182-731
Radionuclides	n.a.	n.a.	n.a.	n.a.	n.a.	Unk.	Unk.	1-47

Note: Small sample sizes and other factors may introduce substantial uncertainty to these data. Ranges reflect different combustion technologies and fuel sources with varying chemical composition.

[a] Data refer to pollutants emitted by typical virgin and waste wood boilers, as described in Environmental Risk Limited, *Summary of Biomass Emissions Data: New England Region*, for the Center for Resource Solutions, ERL-07331-41 (March 1999), tables 6, 7.

[b] Data in column from EPA, *Profile of the Fossil Fuel Electric Power Generation Industry*, EPA/310-R-97-007 (September 1997), Tables 21–23, viewed 3 February 2000 at <es.epa.gov/oeca/sector/sectornote/pdf/fossilsn.pdf>. These data reflect emission tests on 52 units, and are intended by EPA to be “generally representative” of normal operating procedure in the industry as a whole.

[c] Data derived from Energy & Environmental Research Center, *A Comprehensive Assessment of Toxic Emissions from Coal-fired Plants: Phase I Results from the U.S. Department of Energy Study* (Grand Forks, ND: University of North Dakota, 1996), table ES-1, pp. E-16, E-17. The UND report summarizes data for nine specific facilities typical of certain plant configurations.

[d] Compare to 0.008 lb of Hg per 10^{12} Btu in EPRI, *Mercury in the Environment—A Research Update*, EPRI-TR-107695 (December 1996), table 2.7.

[e] Compare to mean estimates of different coal types, ranging from 3.22–12.65 lb of Hg per 10^{12} Btu for coal with particulate control only, and 1.38–10.81 lb of Hg per 10^{12} Btu for coal with combined particulate and SO_2 controls, in EPRI report, table 2.7, cited in note D.

tential effects on human health include losses of sensory or cognitive ability, delays in development, birth defects, tremors, and death. In most circumstances, one would not expect electricity-related emissions to cause such severe effects, although mercury poisoning represents a particular hazard to subsistence and fishing communities, such as Native Alaskans. While much uncertainty remains about the impact of mercury on humans, some experts note that present knowledge is at least as solid as that for other federally regulated pollutants.[18]

HAP emission rates vary widely among power plants, depending on combustion and pollution-control technology as well as the chemical composition of fuel, which in turn depends on geographic source or (for wood) growing conditions. One study, which compares testing data from nine coal plant with different configurations, finds the following very broad ranges of hazardous air pollutants in stack emissions:[19]

- organic pollutants between 182 and 731 pounds per trillion British thermal units ($lb/10^{12}$ Btu),
- trace metals between 17 and 284 $lb/10^{12}$ Btu,
- cyanide emissions between <2.2 and 180 $lb/10^{12}$ Btu,
- radionuclides between <1 and 47 $lb/10^{12}$ Btu (see Part V, Section D), and
- total chlorine emissions between <176 and 132,000 $lb/10^{12}$ Btu.

In all, total emissions of hazardous air pollutants at single plants examined in the study referred to ranged between 2.8 and 1,852 tons per year.[20]

C. Acid rain

In addition to making people sick, airborne sulfur and nitrogen compounds damage ecosystems and buildings when they return to Earth as acid rain—augmented by acid snow, acid mist, acid fog, and dry deposition of acid gases and particles. A combination of high emissions and acid-sensitive soils makes the Adirondacks, upper Appalachian and southeastern Canada particularly vulnerable to these phenomena. Trees such as red spruce at high elevations and lakes suffer the most. Acid accumulates in snow packs, which jar fragile streams and lakes with an acid pulse in the spring thaw. Acid rain also damages buildings. In 1997, electric utilities contributed 64% of national SO_2 emissions and 26% of NO_X emissions; coal-fired facilities accounted for almost the entire utility share (see Table 1).

Largely in response to reports that rain and snow in the northeastern United States had become increasingly acidic, Congress established the Acid Rain Program in Title IV of the 1990 Clean Air Act Amendments, best known for its innovative "cap and trade" provisions. Following implementation of the program, SO_2 emissions from more than 400 affected electricity-generating units (mostly coal-fueled) fell from 15.8 million to 11.9 million tons per year. Emissions crept up in the subsequent three years, reaching 13.1 million tons in 1998.[21]

Notwithstanding measures to reduce sulfur emissions, sulfur concentrations have fallen more modestly, and acidity continues to trouble large regions of North America.

Notwithstanding earnest and successful public policy measures to reduce sulfur emissions, sulfur concentrations in many ecosystems have fallen more modestly, and acidity continues to trouble large regions of North America. Moreover, forests are recovering only slowly—in some cases, researchers suggest, failing to grow at all. Some analysts speculate that the continuing acidity problem reflects simultaneous reductions in particulate dust; these basic (i.e., in terms of Ph factor) particles may previously have buffered airborne acids, as well as furnishing reserves of basic compounds in the soil. Other analysts note that NO_X, a precursor of nitric acid, received comparatively less attention in the Clean Air Act than SO_2; there currently exists no national cap on NO_X emissions.[22]

D. The nitrogen cycle

The planet's nitrogen stock cycles between soil, living organisms, water, and the atmosphere. Viewed globally, emissions from power plants represent a modest but nontrivial additional stress on the nitrogen cycle, which is already changing rapidly due to human activity.[23]

Until very recently, the scarcity of available nitrogen was a limiting factor in most planetary ecosystems. As a result, abundant nitrogen leads quickly to increased growth. (For that reason, nitrogen is the primary ingredient in fertilizer.) Living organisms depended for their nitrogen largely on the slow process of "nitrogen fixing," by which symbiotic microbes associated with plants pull molecular nitrogen (N_2) from the air and convert it to ammonium (NH_4), nitrate (NO_3), and other inorganic compounds. Previously fixed nitrogen resides in soil, where microbes recycle it into usable form.

Human activity has altered this cycle. Natural, land-based nitrogen fixation amounts to up to 140 million metric tons per year,[24] mostly from microbes, plus perhaps 5 million metric tons fixed by lightening strikes. Since 1900, human activity has doubled this rate. The burning of coal and oil in power plants, which frees nitrogen previously sequestered in fossilized organic matter, contributes perhaps 6 million metric tons per year—some 4% of the global increase.

Nitrogen entering the planetary ecosystem harms the environment in several ways. Other sections of this review discuss rising concentrations of the greenhouse gas nitrous oxide, and increased regional concentrations of other oxides of nitrogen, which form smog and acid rain. As nitrogen compounds precipitate out of the atmosphere, they accumulate in soils as nitrates. Ultimately, excess nitrates leach into streams and groundwater, carrying with them soil nutrients such as calcium, magnesium, and potassium. As the level of these nutrients in the soil falls, they become the factor limiting plant growth. Plants lacking them may absorb toxic aluminum salts instead.

Power plants deposit 11–15% of the nitrogen in the Chesapeake Bay, thought to have contributed to the rapid growth of toxic organisms in recent years.

Meanwhile, nitrogenated runoff pouring into lakes, streams, estuaries, and coastal waters feeds explosive growth of algae and other plants, a condition known as “eutrophication.” This process creates several problems, including:

- falling oxygen levels, resulting in die-off of more complex plants and animals;
- the proliferation of nuisance algal species, which may prove toxic to fish, humans, and other mammals; and
- through surface algae growth, decreased sunlight and photosynthesis for species below.

Power plants deposit 11–15% of the nitrogen in the Chesapeake Bay, thought to have contributed to the rapid growth of toxic organisms in recent years.[25] Worldwide, scientists believe that such changes have accelerated the loss of biodiversity, especially of plants adapted to low-nitrogen soils and the animals that depend on them.[26]

E. Pollution at long range

While the public generally associates energy-related air pollution primarily with the heavy traffic and clustered industry characteristic of urban areas, high atmospheric winds can carry pollution long distances. Air pollution now troubles remote locales, including many national parks. Visitors to Great Smoky Mountains National Park could once see up to 93 miles; haze now shrinks these vistas by 60%, and by as much as 80% during summer months.[27] Ontario’s Ministry of Energy and the Environment estimates that over half the ground-level ozone in Toronto on hot summer days originates in the United States, and Ontario contributes substantially to sulfur pollution in Vermont and New Hampshire.[28] In fact, researchers believe that pollution from Asia can reach the western United States, and some evidence hints that U.S. pollution reaches Europe as well.[29]

High atmospheric winds carry air pollution to remote locales, including many national parks.

Some scientists (and regulators) assert that pollution vented originally by coal-burning power plants in the Midwest exacerbates already severe local air quality problems in the Northeast, making it even more difficult for Northeastern states to meet federal air standards.[30] Evidence of long-distance transport includes, for example, ozone detected at night high over Eastern cities, when the absence of sunlight suggests that it could not have been produced locally and must therefore have arrived on prevailing easterly winds.

The question of transport aside, the states closest to power plants tend to suffer as much or more from pollution than their downwind neighbors. For example, while Northeastern cities such as Portland, Maine, often experience higher short-term ozone “peaks,” Midwestern cities such as Huntington, West Virginia, and Marietta, Ohio, suffer longer, higher ozone “plateaus.” That is, cities near Midwestern power plants experience more total hours of unhealthy air. As a result, their residents are more often hospitalized for ozone-related complaints.[31]

F. The effect of shifting energy markets

In addition to the obvious effects of environmental regulation, changes in energy markets have also affected air quality. For example, the Natural Gas Policy Act of 1978 eliminated gas price controls, stimulating exploration and competition. As a result, supplies rose and prices dropped, ultimately making gas—substantially cleaner than coal—the fuel of choice for new power plants. The restructuring of the electric sector under way in many states and pending in most of the rest may advance this trend by opening up competitive opportunities for highly efficient combined-cycle gas plants.[32] Depending on the rules governing the new electric sector, distributed energy resources may also thrive; these include relatively clean gas-powered microturbines, fuel cells, photovoltaic (PV) and small wind systems, energy efficiency measures, and energy storage devices. Fuel cells, for example, generate power chemically, with no combustion at all.[33]

On the other hand, restructuring may increase the competitiveness of old, dirty coal plants concentrated in the Midwest. In the 1970s, legislators struggling to build a consensus in favor of the Clean Air Act chose to exempt ("grandfather") existing and planned coal-fired plants from the act's most stringent requirements. As a result, these facilities may emit up to 10 times more pollution than new plants.[34] Most members of Congress presumably shared the accepted industry view that the plants' owners would retire them after their expected lifetime of 30 or so years. Unfortunately, the exemption itself provided a competitive advantage for the plants in question, and their owners have kept many in operation.

Until fairly recently, most of the grandfathered plants operated at relatively low capacity due to saturated local demand. In 1992, however, the Energy Policy Act ("EPAct") freed the national market for wholesale power, allowing power plants to serve distant customers. But EPAct did not standardize environmental requirements for all generating facilities. In the four years preceding EPAct, the nation's fleet of coal plants increased generation by about 2%; in the six years after its passage, generation grew by almost 16%, as the plants boosted operations from 60% to 67% of capacity.[35] To take a specific example, the Northeast States for Coordinated Air Use Management calculates that between 1995 and 1996, a single, large Midwestern utility, American Electric Power, increased coal-fired generation by 10%, largely to meet increased sales of wholesale power.[36] The resulting annual increase in NO_X emissions—over 50,000 tons—exceeded the total 1996 NO_X emissions from all the fossil fuel generating plants in Massachusetts and New Hampshire combined.

A further complication concerns nuclear power. Although nuclear plants present complex environmental costs and risks, they do not directly emit air pollution. One recent analysis finds one to three dozen of America's 100 or so nuclear plants at risk of shutdown by their owners should industry restructuring expose them to competitive pressure.[37] In any case, licenses for the entire nuclear industry will begin to expire in this decade, and prospects for relicensing remain unclear. Replacement of either early or "naturally" retired plants by anything other than zero-emission power plants could increase air emissions (although, of course, it would stanch the mounting problem of nuclear waste).

Finally, the uncertainty created by restructuring initially damped enthusiasm for the construction of new renewable energy facilities. More recently, seven states have integrated renewable energy into their restructuring packages through policies known as renewable portfolio standards, which require that renewables supply a certain percentage of the electricity sold. Twelve states have also created clean energy investment funds from charges levied on electricity sales.[38] In addition, restructuring has allowed electric suppliers to sell "green power" generated from renewables. Although only a small number of renewable energy facilities have so far been built to meet this market, it may in the future prove significant.[39]

G. Biopower and air pollution

Burning plant material, like all combustion, releases gaseous and particulate pollutants, although gasifying the biomass generally produces fewer emissions than direct combustion. In several ways, however, biopower poses less environmental risk than fossil fuel combustion. Virgin wood contains essentially no sulfur, greatly reducing SO_2 emissions. In addition, most wood fuel sources contain only one-tenth to one-third the nitrogen of coal, thus limiting fuel-caused NO_X emissions. (See Tables 1 and 2.)

> *Mixing biomass with coal—"cofiring"—may actually lower the coal's own NO_X emissions.*

In fact, biopower may provide a NO_X-control dividend. When biomass is burned in the same boiler as coal ("cofiring"), the wood's moisture cools the combustion process, reducing the formation of thermal NO_X. Best-case results reported by the Electric Power Research Institute suggests that co-firing coal with 7% wood (by heat content) reduces NO_X by 15%. Other research suggests that introducing wood to a coal boiler between the primary combustion zone and the chimney (i.e., as a "reburn" fuel) can destroy some of the NO produced in a coal boiler. In addition, cofiring wood in coal boilers, whose efficiency averages 33%, offers efficiency gains over stand-alone biopower plants, which generally run at around 20%, with resultant reductions in pollution per unit of energy produced.[40]

PART III. CLIMATE CHANGE

To the now-familiar litany of problems associated with conventional air pollution comes the additional threat of global warming and resultant climate change. Because the climate naturally exhibits both statistical variability and long-term patterns of change, it remains difficult to distinguish "natural" from human-caused climate effects. (See Box 2 on physical evidence of climate change.) Yet many scientists now conclude that human activity has altered natural climactic processes at a geologically rapid pace by boosting atmospheric concentrations of several greenhouse gases. In the words of the Intergovernmental Panel on Climate Change (IPCC), "the balance of evidence suggests a discernible human influence on global climate."[41]

Underlying the threat is a well-known phenomenon, the greenhouse effect. That phrase describes the tendency of several gases to trap heat in the atmosphere, much like the transparent walls of a greenhouse. Visible sunlight passes through Earth's layer of "greenhouse gases" unhindered, but much of the resultant heat (characterized by infrared wavelengths longer than those of visible light) radiating upward from the warming planet cannot. Instead, the gas layer absorbs and re-emits some of the heat back down to Earth's surface.

The planet's natural greenhouse process forms part of a complex pattern that creates the conditions that allow life to flourish. In particular, carbon, which as carbon dioxide (CO_2) represents a major greenhouse gas,[42] follows a cycle of storage and circulation, passing among living plants and animals, the atmosphere and oceans, and earthbound mineral deposits—which prominently include coal, oil, natural gas, and other fossilized substances used as fuels.

Box 2. Physical Evidence of Climate Change

In assessing the threat of climate change, scientists draw on a variety of physical evidence, including the following:

- Bubbles ice cores from deep in stable Antarctic formations indicate the composition of the preindustrial atmosphere. Scientists conjecture that chemical differences between the current atmosphere and that captured in the bubbles reflect human activity.

- Analyses of radiocarbon, which reflect the differing proportions of heavy carbon-14 molecules in samples from different sources, show that emissions from fossil fuel burning have been a major contributor to increased atmospheric concentrations of CO_2.

- The temperature record includes land data and sea data collected since the late 1800s with a variety of instruments, by a variety of institutions. Scientists have worked hard to rectify the data sets and to eliminate inconsistencies due, for example, to instruments located in urban hot spots. Nevertheless, residual inconsistencies remain.

- Since the early 1960s, weather balloons (radiosondes) have reliably measured atmospheric temperatures. Since 1979, weather satellites using microwave sounding units have provided atmospheric measurements as well. While the satellite data show no warming trend in the troposphere (lower atmosphere), some radiosonde data do. Both data sets show cooling in the stratosphere (upper atmosphere).

Even a decision to cut drastically all greenhouse gas emissions might not return the climate to its previous state for a century or longer.

The industrial age has seen the following:[43]

- rises in atmospheric CO_2 concentrations from under 280 to about 360 parts per million by volume;

- escalation in methane concentrations from about 700 to over 1700 parts per billion by volume (ppbv);

- growth in nitrous oxide concentrations from about 270 to 310 ppbv ;

- increasing levels of ground-level ozone, carbon monoxide, and other short-lived but potent greenhouse gases; and

- the fabrication of several chemicals with extremely high warming potentials, including hydrofluorocarbons and perfluorocarbons—introduced, ironically, as substitutes for ozone-depleting substances used in refrigeration, electronics, and other industrial applications—and sulfur hexafluoride (SF_6).

Greenhouse gases remain in the atmosphere for varying lengths of time; for example, perhaps 12 years for methane, 50-200 years for CO_2, and 50,000 years for carbon tetrafluoride.[44] For this reason, even a decision to cut drastically all greenhouse gas emissions (say, in response to a series of dramatic climactic disasters) might not return the climate to its previous state for a century or longer.

TABLE FOUR. TOTAL U.S. GREENHOUSE GAS EMISSIONS AND EMISSIONS FROM ENERGY SECTOR, 1997: MILLION METRIC TONS OF CARBON EQUIVALENT

Greenhouse Gas	Source	Million metric tons of carbon equivalent
Carbon dioxide (CO_2)	Fossil fuel combustion	1,466.0
	Natural gas flaring	4.2
	Non-energy sources	17.7
	Total CO_2	*1487.9*
Methane (CH_4)	Stationary sources, including power plants	2.2
	Mobile sources	1.4
	Coal mining	18.8
	Natural gas systems	33.5
	Petroleum system	1.6
	Non-energy sources	122.1
	Total CH_4	*179.6*
Nitrous oxide (N_2O)	Stationary sources, including power plants	4.1
	Mobile sources	17.5
	Non-energy sources	87.4
	Total N_2O	*109.0*
Other gases (HFCs, PFCs & SF_6)	Electrical transmission and distribution (SF_6)	7.0
	Non-energy sources	30.1
	Total other gases	*37.1*
Total emissions	All greenhouse gases	1,813.6
CO_2 sinks		(208.6)
Net Emissions	All greenhouse gases	1,605.0
Emissions from energy-related activity		1556.3
Emissions from electricity-related activity[A]		653.2

Note: Data from U.S. EPA, *Inventory Of U.S. Greenhouse Gas Emissions And Sinks: 1990 – 1997,* EPA 236-R-99-003 (April 1999), p. ES-3, table 2-3; viewed 18 January at <www.epa.gov/oppeoee1/globalwarming/publications/emissions/us1999/index.html>. In addition to these greenhouse gas sources, geothermal energy production may release a small amount of CO_2 or methane from underground reservoirs; quantities for 1997 round to 0.0 million metric tons of carbon equivalent.

[a] Includes emissions from fossil fuel combustion, coal mining, gas flaring, and gas and petroleum systems, proportionate to the use of those fuels in generating electric power: 87% of U.S. coal production, 13.5% of natural gas, and 2% of petroleum.

Table 4 lists U.S. emissions of greenhouse gases released by human activity ("anthropogenic" greenhouse gases). For ease of comparison, the table lists each gas in tons of CO_2 equivalent,[45] calculated from each gas's global warming potential. In the United States, energy-related activity accounts for about 86% of anthropogenic greenhouse gas emissions. As Table 4 indicates, electricity use as a whole accounts for about 36% of U.S. greenhouse gas emissions.[46]

Electricity use accounts for about 36% of total U.S. greenhouse gas emissions.

A. Carbon dioxide

Rising carbon concentrations largely reflect increasing use of fossil fuels.[47] Globally, fossil fuel use results each year in the release of about 6 billion metric tons of carbon (GtC), growing recently at about 2% annually. The United States accounts for about 23% of global carbon emissions.[48]

Among the fossil fuels, petroleum and natural gas contain respectively about 75% and 55% as much carbon per unit of energy as coal. The higher efficiency of gas-burning technology enhances its inherent carbon advantage; a gas-fired combined-cycle turbine with 48% efficiency releases only half the CO_2 of a conventional coal plant of the same capacity and 38% efficiency.[49] As a result, natural gas represents a climate "winner" when it replaces coal-burning capacity, but part of the climate problem when it meets new energy demand or replaces zero-emission facilities such as decommissioned nuclear plants. Given the huge projected need for energy, especially in the developing world, even an energy system reliant on natural gas would impose substantial stress on the climate—albeit less than one reliant on coal and oil.[50]

Because energy demand is growing so fast, even an energy system reliant on natural gas would impose substantial stress on the climate.

Geologists have identified approximately 1,050 GtC from coal, oil, and natural gas that can be economically recovered with current technology; improved technology may ultimately bring a total of 4,100 GtC from fossil fuels into that economically recoverable resource base.[51] For purposes of comparison, the IPCC estimates that the emission of 1,030 GtC between 1991 and 2100 will raise atmospheric concentrations of CO_2 to more than double preindustrial levels, from 280 to 650 ppmv. Emissions of 1,410 GtC during that period would almost quadruple concentrations compared to preindustrial levels, to 1,000 ppmv.[52]

B. Methane

Like all fossil fuels, natural gas releases CO_2 when burned. In addition, the primary constituent of natural gas, methane (CH_4), is itself a much more potent greenhouse gas than carbon dioxide. On the other hand, methane remains in the atmosphere for a relatively short time, perhaps a dozen years, compared with 50–100 years for CO_2. Given these countervailing factors, the IPCC calculates the 100-year global warming potential of methane as 21 times that of CO_2.[53] In other words, one unit by mass of methane will heat the Earth as much in 100 years as 21 units of CO_2.

Energy-related sources account for almost one third of U.S. methane emissions. Sources, and their contribution to 1997 U.S. methane emissions, include:[54]

- *Oil and natural gas systems* (19.5%): Natural gas contains perhaps 90% methane, making leaky pipelines not just an economic problem, but also an environmental one. Oil exploration, production, refinement, transportation and storage also release methane.
- *Coal mining* (10.5%): To lower the possibility of explosions, most mines circulate underground air, thus venting large amounts of coal-associated methane.
- *Incomplete fossil fuel combustion* (2.0%) also may release small amounts of methane.

In addition to its physical presence in deposits of solid and fluid fossil fuels, methane is also formed by the anaerobic (i.e., without oxygen) breakdown of organic matter—for example, garbage rotting in landfills, or plant matter decaying underwater. Some 37.1% of U.S. methane emissions seep out of landfills, suggesting a useful step toward staunching greenhouse emissions: landfill owners currently capture and burn almost 15% of total landfill methane to generate electricity.[55] While this practice releases CO_2, it remains both environmentally and often economically preferable to venting the gas.[56]

More than a third of U.S. methane emissions seep out of landfills. Capturing and burning this gas to generate electricity provides a useful product and lowers the landfill's net environmental impact.

A potentially important aspect of the methane problem, about which little certain information exists, concerns large hydropower facilities. The World Commission on Dams (WCD), set up by the World Bank and the World Conservation Union (IUCN) to assess the role of dams in energy and water development, notes that oxygen-poor hydropower reservoirs can vent substantial quantities of methane, especially early in their lifetime, due to rotting vegetation beneath the waterline.[57] (Well-oxygenated reservoirs emit CO_2 rather than methane.) For this reason, large, shallow hydropower reservoirs that inundate large quantities of biomass may not be justifiable on the basis of contributions to the mitigation of climate change.

For example, the Petit-Saut hydroelectric dam in French Guiana, which supplies power to the launch site of Europe's Ariane rocket program, submerged 365 square kilometers of tropical forest. One study reckons that during its first 20 years Petit-Saut will emit the equivalent of 66 million metric tons of CO_2—about 85% from methane and the remainder from CO_2 itself—making French Guiana one of the world's largest per-capita emitters of greenhouse gases.[58] While nontropical and more mature hydroelectric systems (including most U.S. facilities) have much lower emission rates, it is clear that tropical hydropower does not necessarily provide climate-safe energy, and may represent an important and poorly understood part of the climate problem.[59]

Tropical hydropower does not necessarily provide climate-safe energy, and may represent an important and poorly understood part of the climate problem.

C. Other energy-related sources of greenhouse gas

Like those of methane, nitrous oxide emissions by weight are low compared with CO_2 emissions. However, the substance packs a greenhouse wallop about 310 times more powerful than CO_2 on a per-weight basis.[60] Some 3.8% of America's total nitrous oxide emissions result from chemical reactions initiated by fossil fuel combustion in stationary sources, chiefly power plants.[61]

One final greenhouse culprit merits mention here. Sulfur hexafluoride has the highest global warming potential of any substance yet evaluated—23,900 times more potent than CO_2 on a per-weight basis.[62] Once leaked or released, it persists in the atmosphere for an extremely long time. Eighty percent of SF_6 in use worldwide insulates electrical transmission and distribution lines.[63]

D. The greenhouse impact of renewables

As plants grow, they absorb carbon dioxide. When burned, they relinquish an equal quantity of CO_2 back to the atmosphere. For this reason, many analyses consider biopower roughly greenhouse-neutral. For instance, U.S. emission figures (see Table 4) do not include the 57 million metric tons of CO_2 released by biomass combustion during 1997.[64] In general, biopower can be near-neutral over reasonably short time periods, assuming that it is not fueled by old-growth forests and provided that forest soils are managed so as to permit continuing regrowth.

In fact, biopower may provide net greenhouse advantages. Most biomass fueling the biopower industry would otherwise decompose in landfills, releasing CO_2 and methane. Natural forest fires and purposeful burning would account for the rest, also releasing CO_2. (Lack of pollution controls means that these fires emit copious conventional pollutants as well.) The National Renewable Energy Laboratory (NREL) suggests that although the California biopower sector releases 1,330 grams of CO_2 equivalent per kWh directly, avoiding the alternative outcomes, especially the emission of methane, actually makes biopower a net greenhouse winner, at -1,747 grams of CO_2 equivalent/kWh. According to the NREL report, subtracting the emissions that would otherwise be released by burning natural gas to generate an equivalent amount of electricity further lowers the figure, to -2,802 grams CO_2 equivalent/kWh.[65]

Biopower actually provides greenhouse benefits when it replaces the uncontrolled burning of organic waste, the decomposition of biomass in landfills, and power generation by fossil fuel.

Depending on the technology used, geothermal power may also have a greenhouse impact, although a more modest one than fossil fuel plants. Geothermal power exploits reservoirs of hot, underground fluid. Composed primarily of steam (90–99%), these fluids can also contain varying fractions of carbon dioxide, hydrogen sulfide, methane, and ammonia. One type of geothermal technology, binary systems, never exposes geothermal fluids to the air, and therefore has no direct emissions; binary plants account for about 260 MW of total U.S. geothermal capacity of 2,900 MW.[66]

A second geothermal technology, flashed steam systems, does vent the working fluids, but the actual greenhouse impact of flashed steam plants varies. California (which accounts for about 85% of U.S. capacity) requires plants to control hydrogen sulfide. Several facilities, including the largest in the country, the 1300-MW Geysers complex, do so by removing the H_2S, incinerating it, and reinjecting the combustion products into the reservoir. Serendipitously, this process also removes methane (as well as other gases and contaminants such as mercury, arsenic, and selenium). However, all flashed steam plants release the native CO_2.[67]

In some future circumstances, geothermal power production may offer net climate advantages. New technology allows the extraction of minerals including zinc, manganese, and silica from the geothermal brine, offsetting greenhouse emissions that would otherwise be produced by mining and processing. For example, the mining-related energy use avoided by a geothermal zinc extraction plant now under construction in California may cancel out half the flashed steam plant's reservoir-derived greenhouse gas emissions.[68] Mineral coproduction is being examined at several other geothermal sites, as well.

E. Global warming

Since climate change first appeared in the news, scientists have refined and to some extent moderated initial estimates of future warming. (See Table 5.) It would be a mistake to interpret falling estimates as evidence of a dissipating threat. For one thing, estimates have started to creep back up. Perhaps more significant, scientists became more convinced in the 1990s that climate change is indeed occurring.

Computer-generated climate models have gradually improved their ability to generate today's known conditions when given data about the past—a crucial test of a model's accuracy regarding the future. Models prepared in 1990 were based on emissions of greenhouse gases dating to the rise that began in the 19th-century industrial era. Their "predictions" of the present were too warm, and they generated distorted temperature maps. Subsequent models from the mid-1990s incorporated the cooling effect of sulfate aerosols strewn into the air by volcanoes and burning coal, which tend to reflect sunlight back into space and thereby inhibit the greenhouse effect.[69] While more accurate, these models nevertheless produced snapshots of "today" that were too cool, as well as being spatially disproportionate. The current generation of models, however, adds a third factor: periodic variation in the strength of the sun itself. Not only do the resultant temperature maps resemble current conditions on Earth, but the temperature predicted by the models matches what we know about the past fairly well. In short, there is better reason to trust today's predictions than there was 10 or even 5 years ago.[70]

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Table Five. Estimates of Global Mean Temperature Rise by 2100, Compared to 1990 Levels

Source \ Estimate	Degrees Celsius			Degrees Fahrenheit		
	Low	**Best**	High	Low	**Best**	High
1990 IPCC BAU[A]	1.9	3.0	5.2	5.2	6.2	9.4
1995 IPCC IS92c, a and e[B]	1.0	2.0	3.5	1.8	3.6	6.3
1999 Pew SRES[C]	1.3	1.9-2.9	4.0	2.3	3.4-5.2	7.2

[a] Refers to a "business as usual" scenario, with the high and low estimates representing boundaries of scientific uncertainty regarding climate response to increasing concentrations of greenhouse gases (i.e., its "sensitivity"). J. Houghton, G. Jenkins, and J. Ephraums (eds.), *Climate Change: The IPCC Scientific Assessment* (Cambridge: Cambridge University Press, 1990), p. xxii.

[b] Refers to scenarios developed by the IPCC: IS92c combines low emissions and low climate sensitivity; IS92a consists of mid-range emissions and the IPCC's best estimate of actual climate sensitivity; and IS92e represents high emissions and a highly sensitive climate. J. Houghton et al. (eds.), *Climate Change 1995: The Science of Climate Change* (Cambridge: Cambridge University Press, 1996), p. 6.

[c] Refers to a preliminary version of the IPCC's *Special Report of Emission Scenarios*, described in Tom Wigley, *The Science of Climate Change: Global and U.S. Perspectives* (Washington, DC: Pew Center on Climate Change, 1999), p. 16. The best estimate shown here represents the range of those scenarios. The low and high estimates reflect the full range of climate sensitivity, emissions, and other factors.

Nevertheless, climate modeling remains a challenge. In addition to its complexity, the climate may not behave as a linear system. Just as a ball rolling toward a table edge may alter its velocity and direction precipitously, steady stress on the climate may provoke sudden, large effects as the system crosses a threshold. Such changes may be out of proportion to the incremental pressure.

Many scientists accept that we may be seeing the first signs of climate change. In 2000, the National Research Council found evidence that surface temperatures have risen about 0.4–0.8° C (0.7–1.7° F) over the last century.[71] The report's authors acknowledged that the upper atmosphere does not seem to be warming, and may in fact be cooling, and they characterized this difference as evidence that scientists do not yet fully know how Earth's climate works. But the report dismissed the possibility that the scientific community might be mistaken about surface warming: the phenomenon, the report concludes, is "undoubtedly real."[72]

In recent years, scientists have catalogued a variety of circumstantial evidence consistent with a changing climate. None of these factors prove or disprove a link between human behavior and long-term climate change. Considered as a group, however, they are suggestive. To take just a few examples:

- The National Aeronautic and Space Administration (NASA), the National Oceanic Atmospheric Administration (NOAA), and the World Meteorological Organization agreed that 1998 was the hottest year on record. NOAA measured the global mean temperature that year as 0.66° C (1.20° F) above the long-term average of 13.8° C (56.9° F); NASA noted that 1998's global temperature exceeded that of the previous record year, 1995, by about 0.2° C (0.4° F).[73]

- NASA calculated that from 1993 to 1998, the thinning Greenland ice sheet lost two cubic miles of mass per year.[74]

- Some marine ecologists link increasing reports of diseases affecting marine organisms to climate-induced changes. For example, they suggest that widespread coral bleaching in 1998 may reflect long-term exposure to unusually warm water, caused by longer, more frequent occurrences of the weather event known as the El Niño Southern Oscillation.[75]

- Researchers hypothesize that rising nighttime temperatures during milder springs in New Mexico and Colorado are to blame for the spread of exotic and native weed species. These newcomers have preempted the most common native grass, blue grama, on which ranchers depend.[76]

A changing climate could cause myriad other environmental shifts. For example, sea levels would rise, most obviously because of melting alpine glaciers and polar ice caps, but also because warming water expands. Yet the mechanics of the climate are complex: greenhouse heating might carry warmer, wetter air to Antarctica, adding to the ice pack.[77] Tom Wigley's report for the Pew Center on Climate Change suggests that seas might rise 46–58 centimeters by 2100.[78] The prospect of such changes alarms coastal communities and, especially, inhabitants of island nations. Most monitors in the South Pacific now record rises of up to 25 millimeters per year.[79] Closer to home, rising salt seas could pollute fresh aquifers, for instance in Florida and Long Island.

Global warming would lead to climate change primarily by affecting evaporation and precipitation. Computer modelers have only recently become able to hypothesize specific regional changes—although with substantial caveats and uncertainty. For instance, with respect to the continental United States, one recent report suggests overall warmer weather, especially during winters.[80] The frequency of hot spells will increase, and that of cold spells will decrease. A warmer climate may increase the frequency of intense rain and snowstorms, and also of dry days and longer dry spells. Although a warming climate might produce more frequent, wetter, windier North Atlantic hurricanes and tropical storms, most scientists remain cautious regarding the ability of current climate science to predict this with any accuracy.

PART IV. LAND, WATER, AND WILDLIFE IMPACTS

A. Land use

While power plants themselves take up relatively little space, provisioning the plants can require extensive land use. Table 6 estimates the land required by some energy technologies. Not only the quantity but the nature of energy-related land use can vary widely. For example, some forms of biomass cultivation can promote more biodiversity of birds than row crops do, although not as much as forests.[81] Similarly, while a 25-MW wind farm may occupy between 475 and 1,150 hectares, depending on the arrangement of the turbines, the machines themselves only require 5–10% of that area, leaving the remainder for customary agricultural or range use.[82]

Wind turbines can coexist with traditional land uses such as farming and ranching.

Table Six. Land, Water and Solid Waste Impacts of Various Generating Technologies

Technology / Resource	PV[A]	Wind[A]	Geothermal[A]	Biopower[A]		Coal	Nuclear
	0.02- to 20-MW utility-scale, thin film	25-MW wind farm	50-MW flashed steam or binary	75-MW gasification	50-MW direct-fired	360-MW w. desulfur-ization	1000-MW light water
Land (ha/MW)	5	20-46 (non-exclusive)	0.2 (plant) 3.2 (steam field)	0.54 (plant)+ 318 (crops)	0.90 (plant)+ 487 (crops)	0.69 (plant)+ 2.18 (mining)[B]	0.40 + mining[B]
Fuel (metric tons/yr/MW)	0	0	0	3,560	5,420	3,140[C]	0.03[E]
Water (m^3/MWh)	0	0	0	0.07 (power plant)	0.81 (power plant)	1.81 (90.4)[D]	1.79 (112)[D]
Solid waste from plant (metric tons/yr/MW)	0	0	0	269 (ash)	185 (ash)	475 (ash and sludge)[C]	0.03[E] + low-lev. wa.

[a] EPRI and U.S. DOE, *Renewable Energy Technology Characterizations*, EPRI TR-109496 (December 1997), pp. 2-16, 2-18, 2-25, 2-29, 2-32, 3-22, 3-44, 4-30 and 6-31. Figures in schematics on p. 2-29 and 2-16 are incorrect per Richard Bain and Kevin Craig, NREL, personal communication, 23 and 24 February 2000.

[b] Land-use data assumes 500-MW coal plant with on-site fuel preparation and solid waste storage. Nuclear plants with cooling ponds may occupy an additional 1.01 ha/MW. Richard Ottinger et al., Pace University Center for Environmental Studies, *Environmental Costs of Electricity* (New York: Oceana Publications, Inc., 1991), p. 326, table 22. Coal mining area an average of shaft and surface mines, from calculation described in note 85; assumes 314 GW of national coal generating capacity, from DOE, EIA, *Annual Energy Outlook 2000*, DOE/EIA-0383(2000), December 1999, table A9.

[c] Pamela Spath, Margaret Mann, and Dawn Kerr, *Life Cycle Assessment of Coal-fired Power Production*, NREL/TP-570-25119 (Golden, CO: NREL, 1999), tables 3, 21, viewed 1 February 2000 at <www.eren.doe.gov/biopower/library/coal_life_cycle.html>. Does not count ~25% of solid waste used for productive purposes.

[d] Figures in parentheses represent nonconsumptive use. Based on USGS data in Wayne Solely, Robert Pierce, and Howard Perlman, *Estimated Use of Water in the United States in 1995*, U.S. Geological Survey Circular 1200, table 25, accessed 17 February 2000 at <water.usgs.gov/watuse/pdf1995/html>; DOE, EIA, *Annual Energy Outlook 1997*, DOE/EIA-0383(97), 1996, table A9.

[e] Mark Holt, Congressional Research Service, *Issue Brief for Congress 92059: Civilian Nuclear Waste Disposal* (8 November 1999), pp. 8-9, viewed 8 March 2000 at <www.cnie.org/nle/waste-2.html>. Waste includes only spent fuel.

Coal mining imposes some of the most severe energy-related environmental costs on American land. Historically, mining operations harvested the timber over coal beds to furnish burgeoning railroads with ties, and the mines themselves with props. Timber cutting left remaining land cover vulnerable to forest fires and subsequent pest infestations, and facilitated flooding and erosion, thereby clogging steams.[83]

Since 1930, coal mining has disturbed about 2.4 million hectares of American land, the vast majority of which once held forests.[84] In addition to old, abandoned mines, coal mines supplying electric power plants currently disturb about 680,000 hectares.[85] The Surface Mining and Control and Reclamation Act of 1977 (SMCRA) requires mine owners to post bonds for land rehabilitation, although land is rarely if ever restored to original conditions. Partly as a result of SMCRA's requirements, mining firms increasingly resort to "mountaintop removal," explicitly exempted from the 1977 law. This technique employs heavy equipment to lop several hundred feet off the peak of a mountain, and cache the resultant debris in hollows and valleys. In West Virginia, surface mines produced only 10% of the state's coal in the 1960s; the figure now stands at about one third, and each site can occupy 10,000 hectares.[86] As a result of the Clean Air Act, which in recent years has helped drive many utilities toward low-sulfur Western coal, the Powder River Basin of Wyoming and Montana hosts comparable mining activity on, in some cases, an even larger scale.[87]

Coal mines supplying electric power plants currently disturb about 680,000 hectares of American land.

In addition to conventional mining-related land disruptions, uranium mining presents special hazards. These include the release of radon gas and airborne radioactive dust from uranium mines and mills, as well as radioactive seepage from waste rock piles and contaminated groundwater pumped out of mines.[88] The United States now imports about three-quarters of its uranium, mostly from Canada. The remainder comes from processing waste rock and "in situ leaching" rather than conventional mines; these techniques use ammonium carbonate or sulfuric acid to remove the uranium from mine walls. (While leaching avoids accumulation of radioactive and potentially toxic tailings, the leaching liquid represents a hazard, especially to groundwater, if not contained.) But tailings from historic mining operations, unregulated until 1980, represent the huge bulk of low-level radioactive waste in the United States. The principal radioactive components of mill tailings, thorium-230 and radium-226, have half-lives of about 75,000 and 1,600 years, respectively. Toxic heavy metals contained in the tailings, such as molybdenum and manganese, pose a threat to groundwater as well. Nearly one-third of uranium milling waste is found on Navajo lands.[89]

B. Acid Mine Drainage

As coal and uranium mining expose rock rich in iron sulfide (pyrite) to oxygen and water, the resulting acid drainage endangers aquatic ecosystems, in some cases for centuries. Acid drainage harms 12,000 miles of American rivers, damaging and in some cases eliminating aquatic life.[90] Mitigation options include neutralizing acid runoff with limestone, impounding pyrite-bearing waste rock, and other techniques. Unfortunately, such solutions can be impermanent. Where owners abandon the mine or declare bankruptcy, acid drainage can constitute an environmental threat long afterward. Because most acid-producing metal mining takes place in the drier West, coal mining—historically concentrated in the wetter Northeast—gives rise to 75% of acid mine drainage sites and perhaps 95% of total acidic gallons.[91]

Coal mining accounts for about 95% of acidic mine drainage.

C. Water use

In 1995, U.S. fossil-fueled power stations required about 135 billion gallons of water per day (Bgal/d). Nuclear plants used 55 Bgal/d, and geothermal less than 2 Bgal/d. These "thermoelectric" facilities use water mostly for cooling condensers and reactors. Surface fresh water supplied some 69% of the total, and surface saline water the rest. As a group, thermoelectric plants represent the largest single category of U.S. water use (fresh and saline), and the largest by far in the East.[92]

The "once-through" cooling systems in place at most power plants return water heated to approximately 40° C to its source, where it can disrupt marine life (see the next section). Plants using closed cooling systems require only enough water to replace that lost to evaporation during passage through cooling towers and ponds. Overall, the power sector returns about 98% of the water it uses back to the source. Hydroelectric plants require 3,160 Bgal/d, virtually all of it fresh. While hydroelectric generation itself consumes little or none of this water, a certain amount evaporates from reservoirs and during repeated reuse at pumped-storage hydropower facilities.[93]

Energy-related activities also contribute to water use. Mining accounts for 3,770 Bgal/day, of which 40% is fresh surface water, 28% is fresh groundwater, and the rest is saline.[94] Consumptive use accounts for 27% of the total. It is not clear, however, what fraction of that total is used in coal mines. Petroleum refining requires a large amount of water as well. On a longer time frame, global climate change would certainly alter the distribution of water in the global ecosystem, and the quantity available for human use.[95]

Plant operators at the Geysers geothermal facility have successfully injected reclaimed sewer water into the geothermal field. In addition to disposing of an environmental liability, this process raises pressure in the affected portion of the field, and, in this case, increased electricity production by 10%. While other fields may respond similarly to the same process, reinjection of reclaimed water remains so far an experimental technique.[96]

D. Wildlife impacts

Most human health risks due to energy production potentially threaten wildlife as well. For example, the nesting habits of insectivorous birds change in areas with high levels of sulfur dioxide.[97] A literature review in 1988 indicated that biological effects in animals occur at or below the levels set by regulatory standards for SO_2, ozone, and particulates.[98] Hazardous air pollutants also have an impact—for instance, high levels of cadmium can cause death, reduced blood enzyme levels, and joint lesions in songbirds, shrews, and badgers. However, normal energy-related emissions by themselves would presumably not produce such effects.

> *Biological effects in animals occur at or below the levels set by regulatory standards for SO_2, ozone, and particulates.*

In many cases, air pollution harms wildlife by depleting forage and prey, such as aquatic invertebrates vulnerable to acidification of lakes and streams. Acid deposition can also trigger the ionic release of aluminum, which kills fish, and the depletion on land of calcium, resulting in weaker eggshells for calcium-deprived birds.[99] Coal mining endangers local waterfowl, primarily through acid mine drainage, but also through altering water availability, leaks of chemicals, and runoff from coal storage piles and tailings, among other factors.[100]

In many cases, careful management and judicious siting can mitigate the impact of energy projects on local wildlife. For example, it became apparent in the late 1980s that endangered (and federally protected) golden eagles and red-tailed hawks were dying among the 7,000-odd wind turbines of California's Altamont Pass. One two-year study of the area counted 182 dead birds, including 119 raptors; researchers attributed 55% of raptor deaths to collisions with turbines, 11% to collisions with wires, 8% to electrocutions, and 26% to unknown causes.[101] A few other locations, such as Tarifa, Spain, have experienced similar problems.

Yet the Altamont Pass, Tarifa, and a few other high-mortality wind farms appear to represent anomalies, whose danger to birds reflects comparatively rare combinations of such risk factors as proximity to migration routes, nearby development encroaching on habitat, the presence of prey, and the absence of alternative perches. Most locations have not experienced such problems, indicating the value of careful siting, installing no-perch tubular towers, burying transmission lines, and other techniques.[102]

It is worth comparing the wildlife impact of wind power to that of conventional energy use. In addition to the endemic effects of air pollution and acid mine drainage noted earlier, a single catastrophic event can have far greater impacts. For instance, 3,000 birds died in two successive nights in 1982 from collisions with four chimneys at the Florida Power Corporation's Crystal River Generating Facility.[103] Or, to take a notable example not centrally associated with electric power, the oil spill occasioned by the grounding of the Exxon Valdez tanker killed between 90,000 and 270,000 seabirds.[104]

Large environmental shifts such as global warming will certainly have large effects on wildlife as well. For example, 50–80% of the nation's duck population breeds in the prairie potholes of the northern Great Plains. Research suggests that warming of 1°C would cull duck populations by about 25% if rainfall remains constant. The same degree of warming plus a 15% increase in precipitation could boost duck populations by 25%, however.[105]

The operation of hydroelectric dams can have especially severe consequences for wildlife, in particular fish. Dams hamper ocean-going species such as salmon as they attempt to spawn in the rivers of their birth. They also hinder young fish seeking passage back to the ocean. Notwithstanding the installation of mitigation measures such as fish ladders and altered operating practices to facilitate fish migration (e.g., maintaining minimum water flows even during times of low electricity demand), many fish species have declined. In the 1960s, for instance, even after construction of dams on the Columbia River, some 100,000 steelhead and salmon per year migrated up the Columbia's tributary, the Snake River. In 1998, several years after the construction of four dams on the Snake, biologists counted only 9,300 steelhead, 8,426 spring-summer Chinook salmon, 927 fall Chinook, and 2 Sockeye salmon.[106] The federal government now classifies all these species as threatened or endangered, and in the 1980s declared the Snake River coho salmon extinct. Scientists at Oak Ridge National Laboratory hold federal dams primarily responsible for reducing the Pacific Northwest salmon population from 16 million to 300,000 wild fish per year.[107]

> *Federal dams are primarily responsible for reducing the Pacific Northwest salmon population from 16 million to 300,000 wild fish per year.*

In addition to the physical barriers represented by dams, hydroelectric power can alter the aquatic environment in other ways. On the Columbia River, for instance, enough pressure builds on water pouring from high spillways to supersaturate it with airborne gases that, when absorbed by fish, can injure or kill them. In the Tennessee Valley, system operators allow only limited flow in the summer. As a result, cooler water—which holds less oxygen than warm—collects at the bottom, suffocating striped bass and other fish. Low-oxygen water can absorb toxic metals from surrounding rocks, as well. In many hydroelectric systems, rapid fluctuations in response to changing demand for power disturbs habitat and strands fish in shallow water.[108]

The use of water in nuclear and fossil power plants harms marine life too. Many plants discharge heated water from their once-through cooling systems, introducing substantial thermal pollution to rivers and coastal waters. In addition, fish and other animals can be sucked into and crushed against filters in water intake pipes, or swept into the plant itself. Over 40 million fish per year die in the inlets of 90 Great Lakes power plants using once-through systems; the annual toll at New York's Indian Point Two and Three nuclear reactors exceeds 1.5 million fish.[109] Since 1983, some 187 federally protected harbor seals and California sea lions have died in the ocean intake structures of the San Onofre nuclear plant. Other coastal plants cause similar fatalities.[110]

Since 1983, some 187 federally protected harbor seals and California sea lions have died in the ocean intake structures of the San Onofre nuclear plant.

E. Solid waste:

Coal-fired facilities produce ash equivalent to 10% of fuel input, compared with biomass plants at under 2%, oil plants at about 0.1%, and gas plants at close to zero. Bottom ash, or slag, collects at the bottom of the boiler, while particulate collectors and other elements trap the finer fly ash borne up on the flue gas. According to EPA, about a third of the ash generated by U.S. coal plants finds its way to some sort of productive use, for example in cement production; electricity producers manage most of the rest in onsite impoundments and landfills. In addition, many facilities must condition flue gases to remove sulfur, giving rise to a separate variety of waste, known as flue-gas desulfurization sludge, most of which ends up in onsite landfills and impoundments.[111] Sludge can also be used in asphalt production and wallboard fabrication.

While most of the volatile selenium and mercury contained in coal leaves power plants in the flue gas, other toxic metals collect in the ash and sludge. For instance, solid waste from average current coal plants contains over twice the arsenic, cadmium, and nickel as the stack effluent; triple the lead; and four times the chromium.[112] By contrast, biomass ash, which is not toxic, generally represents a management issue rather than a hazard. While solid wastes can be managed more easily than airborne pollutants, the Resource Conservation and Recovery Act of 1980 exempts most coal and oil waste from hazardous waste rules, pending a decision by EPA to regulate.[113]

F. Land impacts of biopower:

Among energy technologies, biopower presents perhaps the widest swing between potential environmental benefits and possible environmental damage. Part of the range reflects the variety of technologies and practices included under the rubric of biopower. As Box 3 illustrates, the term encompasses a wide variety of fuels, conversion technologies, and production strategies. Biopower is appealing precisely because it can bring nonenergy benefits.

Currently, most if not all biomass used for power production in the United States comes from wastes rather than purpose-grown crops. For instance, California's biopower industry relies on residues from mills, agriculture, forests, and urban uses. In the absence of a biopower sector in that state, landfills would receive 62% of waste biomass used as fuel, with attendant land use and water quality issues. Some 10% of the rest would accumulate in forests, increasing the risk of catastrophic fires, reducing water yield, and impairing forest health.[114]

In the case of energy crops, specific areas of environmental uncertainty in which energy crop cultivation can help or harm the environment include:[115]

- soil quality, including the capacity of energy cropping to restore degraded soils and sequester carbon;
- levels of agricultural chemicals on soil and wildlife;
- chemical levels in riparian zones and groundwater;
- capacity to prevent or contribute to erosion;
- air pollution or its reduction through cofiring biomass in coal plants;
- greenhouse gases or their reduction through avoiding methane- and CO_2-emitting alternative fates;
- wildlife, including the use of plots as habitat, buffers, or corridors; and
- ecosystem health, including biodiversity and considering the potential of energy cropping to restore degraded ecosystems.

As this list illustrates, the environmental consequences of energy crop production will depend heavily on the practices at individual plantations; it should be possible to manage bioenergy so as to maximize its advantages and minimize its environmental costs.

Box 3: The Many Faces of Biopower

Fuel sources:

- Urban plant waste, e.g. lawn clippings and brush
- Wood and construction waste, e.g. pallets
- Other processed waste, e.g. garbage, shredded tires, paper pellets, etc.
- Landfill gas
- Animal waste, e.g. dung, chicken litter, etc.
- Agricultural residues, e.g. corn stover, wheat straw, rice hulls, nut shells, sugarcane bagasse, etc.
- Forest brush
- Logging residue, e.g. unusable or rotten trees, bark, polewood, etc.
- Mill waste, e.g., sawdust, scrap and bark ("hog fuel"), and black liquor (the toxic residue of paper production)
- Plantation energy crops, e.g. switchgrass, alfalfa, poplar, willow, etc.
- Other.

Conversion technologies:

- Co-firing coal plants
- Direct combustion in dedicated, utility-scale, grid-connected facilities
- Cogeneration at industrial plants that require heat or steam, e.g. mills
- Gasification for combustion in a grid-connected gas turbine
- Gasification for small-scale power production close to where user requires electricity
- Gasification for fuel cell applications
- Other.

Market Strategies

- Dedicated energy production
- Energy production as a byproduct of existing industrial processes, e.g. at mills
- Production of useful nonenergy byproducts from biopower facilities, e.g. dyes, chemicals, ash, etc.
- Energy production as part of an integrated forest management strategy, e.g. for fire control, to raise revenue for environmental protection, etc.
- Energy production as part of an integrated agricultural management system, e.g. to supply another cash crop to small farms
- Biopower as part of an integrated environmental strategy, e.g. to control potentially toxic waste from animal production, for erosion control, habitat preservation, etc.
- Other.

The environmental consequences of energy crop production will depend heavily on the practices at individual plantations.

G. Photovoltaics and heavy metal

A final environmental consideration concerns the composition of photovoltaic modules. Two advanced PV technologies rely on semiconductor materials that incorporate heavy metals rather than silicon: cadmium telluride (CdTe) cells and copper indium diselenide (CIS) cells accounted for 0.8% and 0.1% of the global market in 1998, respectively.[116] While these metals are toxic, the quantities involved are small; a CdTe module of one square meter may contain 6 grams of cadmium, compared with 2.5 grams in a nickel cadmium penlight battery. Release of cadmium and selenium to the environment through their use in PV technology usually occurs through resource mining, refining, module use, and module decommissioning, and can be minimized through appropriate module fabrication procedures, construction techniques, and recycling programs. One source estimates base-case emissions of cadmium from the total life cycle of CdTe modules at 0.5 g/GWh, and of selenium from CIS modules at 8.9 g/GWh.[117] By comparison, another source estimates emissions of cadmium in the flue gas and solid waste (and not including mining and refining) from average current coal plants at 13.9 g/kWh, and emissions of selenium at 420 g/GWh.[118]

PART V. RADIATION[119]

A. RADIOACTIVITY

This section considers releases to the environment of radiation from nuclear power generation. It does not fully discuss the possibility of catastrophic accidents, although that remains a threat with low probability and potentially disastrous consequences.[120] Nor does it fully discuss decommissioning nuclear plants, although the environmental legacy of that process remains unclear.[121]

Radioactive materials such as uranium naturally degrade into lighter "daughter" elements, which in turn degrade, culminating in stable elements. This process is called fission. When bombarded by neutrons, atoms of one rare type of uranium—uranium-235—release neutrons that go on to split other uranium atoms in a chain reaction. Nuclear reactors exploit the heat given off by this process to boil water for a steam turbine.

Once ingested through air, food, or water or through cuts and abrasions, living organisms may incorporate radioactive elements into their tissues. For instance, tritium mimics normal hydrogen in water; strontium-90 and radium-226 behave like calcium and collect in bones; cesium-137 resembles potassium and accumulates in the muscles; and so on.[122] Radioactive substances harm living organisms by emitting alpha particles, beta particles, and gamma radiation, which ionize the molecules they strike by knocking off a negatively charged electron. Ionization can break chemical bonds and thereby damage living cells, particularly through damage to DNA molecules, which encode genetic information. Damage to the DNA of sperm or egg cells can result in damage to future generations.[123]

Current nuclear regulations assume no threshold for danger from radiation. That is, even very small amounts of radiation are assumed to have the potential to harm humans. The danger is also presumed to grow in a linear fashion, so that more radiation presents a correspondingly larger threat. Research continues on the validity of these assumptions.[124]

Radiation varies in strength. For instance, while casual exposure to the gamma rays emitted by some radionuclides cause severe harm, the alpha rays emitted by uranium outside the body pose little threat to human health. When inhaled or ingested, however, uranium's emissions alter cells' reproductive processes, increasing the risk of lung and bone cancer. Animal studies indicate that radiation from uranium may affect the developing fetus, and can increase the risk of leukemia and soft tissue cancers. Research also suggests that radiation may induce "genomic instability."[125] That is, radiation in very low doses may trigger cell and chromosome damage that manifests only after cells undergo several normal divisions. Finally, some radioactive elements also prove chemically toxic. For instance, uranium at high concentrations can damage internal organs, particularly the kidneys.

In general, nuclear power accounts for a very small fraction of the radiation experienced by the U.S. population—less than 1.6% of total artificial radiation, and less than 0.3% of all radiation.[126] One source estimates that New York's six nuclear power plants cause between 0.403 and 1.467 statistical cancer deaths per year, and a comparable number of survivable cancers.[127] Reckoned very roughly, this equates to between 8.3 and 30.2 annual statistical cancer deaths nationally, plus a comparable number of survivable cancers. However, individuals in contact with various segments of the nuclear fuel cycle may have much higher exposure with correspondingly higher effects: the same source notes that nuclear workers bear 99.9% of the risk of fatal cancer from normal nuclear operations.[128]

B. HIGH-LEVEL RADIOACTIVE WASTE

As nuclear fuel ages, it loses its capacity to sustain an efficient nuclear reaction. Each year, a nuclear facility removes about a third of its highly irradiated ("spent") fuel rods to on-site cooling pools. These assemblies contain uranium, plutonium, and fission products such as strontium and cesium. Since regulators limit the pools' capacity, the rods must eventually be placed in steel or concrete containers, known as dry casks. The assemblies remain thermally hot and highly radioactive; a person standing one yard from an unshielded spent fuel assembly could receive a lethal dose of radiation (about 500 rems) in under three minutes. A 30-second exposure (85 rems) would significantly increase the risk of cancer or genetic damage.[129]

Spent fuel accounts for the majority of U.S. high-level nuclear waste. (Nuclear weapons facilities also contribute to the total.) As of 1997, about 70 power plants across the nation stored 35,000 metric tons of spent fuel. Increasing by about 2,000 metric tons per year, total high-level waste will reach at least 60,000 metric tons by 2010, and 80,000 metric tons by 2020.[130]

In theory, onsite storage waste represents only a temporary solution to high-level radioactive waste. The Nuclear Waste Policy Act of 1982 orders the U.S. Department of Energy (DOE) to select a geologic repository for high-level waste. Amendments in 1987 limited possible sites to Nevada's Yucca Mountain. DOE plans to begin storing waste in 2010. Under current law, the repository could host up to 70,000 metric tons of waste, including 63,000 metric tons from civilian reactors.[131]

In addition to fears that uninformed future generations might stumble on the repository, opponents of the Yucca Mountain plan note three environmental problems. First, experts disagree on the potential of leaks from the repository into the local water supply. Second, seismologists note that the area has experienced more than 600 seismic events above 2.5 on the Richter scale since 1976, raising the possibility of earthquake damage to containers.[132] Third, many communities worry about how the waste will reach Yucca Mountain. The State of Nevada, which opposes the proposal, calculates that transporting waste from its current locations during the repository's 25-year emplacement phase would require between 35,000 and 100,000 shipments crossing 43 states, affecting 109 cities.[133] The Congressional Research Service estimates a possible 154 truck and 18 rail accidents over 30 years, although the vast majority of those accidents would not release radiation.[134]

C. "Low-level" waste

While high-level waste and spent fuel are Federal responsibilities, states are required to develop disposal sites for so-called low-level waste; such sites received perhaps 325,000 cubic feet of material in 1997. Utilities produced about two-thirds of the total by volume, but 85% of the total radioactivity in question.[135] (Other sources include defense facilities, hospitals, and labs.) This material includes radioactive corrosion products that adhere to the interior of the reactor vessel, ion-exchange resins, irradiated parts and equipment, and matter trapped by filters. As electric companies decommission retired nuclear plants, the volume of low-level waste may grow substantially.[136] State and federal documents indicate that every low-level nuclear waste dump ever used—a total of six—has leaked, as indicated by the presence of tritium or other radionuclides in groundwater, vegetation, and elsewhere.[137]

> ***Every low-level nuclear waste dump ever used—a total of six—has leaked.***

The term "low-level" may mislead. Although this material in general contains less radioactivity and decays more rapidly than high-level waste, the two classes can contain the same radionuclides. In fact, some types of low-level waste can be more radioactive than some types of high-level waste.[138] Unshielded low-level waste can deliver a lethal dose of radioactivity in as little as 30 seconds.[139]

D. Routine releases from normal operations

Nuclear reactors release low levels of radioactivity as part of normal operations. Volatile fission products including tritium and noble gases may escape through the fuel rods' metal cladding; operators may also vent gas to control temperature, humidity, and radioactivity inside the plant. Plants monitor these radioactive emissions and store them in decay tanks before releasing them. Water released to the environment may contain tritium, cobalt, cesium, or other radionuclides. Radiation from these sources are a small fraction of background radiation, but the isotopes can be detected.[140]

E. Radiation and coal plants

Some analysts suggest that coal-fired power plants expose nearby residents to higher radiation doses than nuclear plants meeting U.S. government regulations.[141] Among the other trace elements listed in Table 3, coal contains between <1 and 10 parts per million (ppm) of uranium, and between <2.5 and 25 ppm of thorium, as well as radioactive potassium-40. Only 1% of the original radioactive material escapes as airborne matter. Rather, these heavy, radioactive metals concentrate in the bottom ash, which is generally stored onsite by utilities, buried in landfills, or sold for purposes such as cement making. One source estimates that in 1982, U.S. coal-fired plants released 801 tons of uranium (including 11,371 pounds of fissionable uranium-235) and 1,971 tons of thorium.[142] Although the risk to human health from a given coal plant's radioactive emissions may be small, this unnoticed source of radioactivity may over time represent a significant source of background radiation.

PART VI. LIFE-CYCLE ANALYSIS

An accurate comparison of the land, water, air, and climactic impacts of various electricity generation options requires "life cycle" analyses, which examine the effects of producing and transporting fuel, building and subsequently decommissioning facilities, generating power, and treating and disposing of waste. For ease of comparison, some studies translate these diverse impacts into dollars, in keeping with past regulatory practices of attempting to identify the least-cost resource strategy.[143] Such comparisons are controversial and, to some readers, unsatisfying, since many human health and environmental effects have no clear dollar cost.

Several studies tackle a more modest task—although still a dauntingly complex one—by comparing the air or climate impacts of energy choices on a full life-cycle basis.[144] (See Table 7.) Such a study might include the following major categories:

- *Coal:* Energy for mining; methane released from coal beds; energy to transport coal; energy to build plants; combustion emissions; energy to run desulfurization equipment and dispose of waste.

- *Oil:* Energy to drill, transport, and refine petroleum; methane released by drilling; CO_2 from flared gas; energy to build plant; combustion emissions; energy to operate desulfurization equipment and dispose of waste.

TABLE SEVEN. LIFE-CYCLE EMISSIONS FROM SELECTED GENERATING TECHNOLOGIES
GRAMS EMITTED PER KILOWATT-HOUR OF OUTPUT (G/KWH)

Technology / Emission	Coal[A]		Biomass[B]	PV[C]		Wind[D]	Geothermal[E]	Nuclear[F]
	Average current system	New source performance standard	Gasification combined-cycle	Grid-tied rooftop PV	Stand-alone rooftop PV w. battery		Flashed steam *(Reservoir emissions only!)*	Light water reactor
Particulates	9.21	9.78	0.04	Unk.	Unk.	Unk.	0	0.09
SO_2	6.70	2.53	0.30	Unk.	Unk.	Unk.	0.03	0.16
NO_X	16.1	14.6	0.69	Unk.	Unk.	Unk.	0	0.11
Carbon monoxide	1.3	1.5	0.08	Unk.	Unk.	Unk.	0	0.01
Non-CH_4 hydrocarbons	1.0	1.3	0.60	Unk.	Unk.	Unk.	0	Unk.
CO_2 from mining or cultivation	9	8	28	NA	NA	NA	0	Unk.
CO_2 from transportation	17	16	6	NA	NA	NA	0	Unk.
CO_2 from power generation	996	917	12	0	0	0	45-81	Unk.
Total CO_2	1,022	941	46	Unk.	Unk.	Unk.	45-81	36.6
Methane	4.4	5.2	0.005	Unk.	Unk.	Unk.	0.09-0.75	0.12
Total CO_2 equivalent[G]	1,114	1,050	46	60-150	280-410	7-74	47-97	39.1

[a] Data from Pamela Spath, Margaret Mann, and Dawn Kerr, *Life Cycle Assessment of Coal-fired Power Production*, NREL/TP-570-25119 (Golden, CO: NREL, 1999), tables 29 and 32, viewed 1 February 2000 at <www.eren.doe.gov/biopower/library/coal_life_cycle.html>.

[b] Data from Margaret Mann and Pamela Spath, *Life Cycle Assessment of a Biomass Gasification Combined-Cycle System*, NREL/TP-430-23076 (Golden, CO: NREL, 1997), figures 9, 10 and 14, and pp. 41 and 46, viewed 1 February at <www.eren.doe.gov/biopower/library/life_cycle.html>. Note that the figure for total CO_2 includes only the quantity not absorbed during the biomass growth cycle, which amounts to 5% of the total figure of 890 g/kWh.

[c] Figures refer to complete rooftop systems incorporating multi-crystalline silicon modules: one for grid-connected use, and one for stand-alone, battery-augmented applications. Data from E.A. Alsema, "Energy Requirements and CO_2 Mitigation Potential of PV Systems," presented at *PV and the Environment 1998* in Keystone, CO (23–24 July 1998), viewed 19 July 1999 at <www.chem.uu.nl/nws/www/publica/98054.htm>.

[d] Wind ranges from studies surveyed in J.F. van de Vate, "Comparative Assessment of Full-Energy-Chain Associated Emissions of Green-house Gases from Different Energy Sources: A Tentative Analysis," *Renewable Energy* 5 (1994), pp. 2359–61, esp. figure 1.

[e] SO_2 data from Marshall Reed and Joel Renner, "Environmental Compatibility of Geothermal Energy" in Frances Sterrett (ed.), *Alternative Fuels and the Environment* (Boca Raton, FL: Lewis Publishers, 1994), p. 25. CO_2 and methane range from K.K Bloomfield and J.N. Moore, "Production of Greenhouse Gases from Geothermal Plants," *Geothermal Resource Council Transactions* 23 (17–20 October 1999), tables 1 and 2, and from Marshall Reed, U.S. DOE, personal communication, 7 February 2000. All geothermal estimates include only emissions from geothermal reservoirs. Life-cycle analyses would reveal impacts higher than those included here for the sake of comparison. Note that binary geothermal plants have no reservoir emissions at all.

- *Natural gas:* Energy to drill, pipe, and refine natural gas; methane escaping from pipelines; energy to build plant; combustion emissions.

- *Geothermal:* Energy to build plant and pipe system; emissions from reservoir, if any.

- *Wind:* Energy to build wind farm.

- *PVs:* Energy to fabricate silicon (or remelt semiconductor scrap) and manufacture PV equipment; energy to manufacture batteries, if used.

- *Fuel cells:* Energy to fabricate fuel cell; energy to produce hydrogen fuel; carbon released by the removal of hydrogen from natural gas, gasoline or other hydrocarbon feedstocks.

- *Biomass:* N_2O from producing fertilizer, if any; energy to cultivate biomass, if any; energy to collect and transport biomass; energy to build the facility; combustion emissions; energy to dispose of waste; "negative" emissions from CO_2 absorbed during biomass growth cycle. May also include "negative" emissions from avoiding combustion and rotting of fuel.

- *Nuclear:* Energy to mine, concentrate, convert, enrich, transport, and (outside the United States) reprocess uranium; energy to build and operate reactor; energy to transport and store radioactive waste.

- *Hydropower:* Energy to clear land; net emissions from permanently lost CO_2-absorbing biomass; energy to build dam; CO_2 and methane from rotting biomass in reservoir.

It is also possible to include the energy required to decommission power plants or recycle equipment. The type of energy used to accomplish these tasks will affect the level of emissions, as will the absolute quantity of steel, cement, aluminum, etc. Note that cement production itself emits CO_2, and that aluminum production releases carbon tetrafluoride, a potent greenhouse gas.[145]

Life-cycle analysis reveals interesting issues. For example, a report by the National Renewable Energy Laboratory on a hypothetical combined-cycle biomass gasification plant reckons that growing and transporting biomass, and building biopower facilities, requires about 5% of the energy produced by the cycle.[146] (The report also notes that soils vary in their capacity to accumulate carbon. Certain high-capacity soils may turn biopower from a modest source of CO_2 into a carbon-absorbing "sink.") The report calculates life-cycle emissions for this plant at 46 grams of CO_2 equivalent per kWh, plus the other pollutants described in Table 7.[147]

A separate NREL report analyzes the life-cycle impacts of hypothetical coal-burning facilities. As expected, combustion represents the largest source of CO_2. Perhaps unexpectedly, the majority of noncombustion CO_2 in current plants results from producing, transporting, and using limestone to absorb conventional pollutants from flue gas. Most of the SO_2 and NO_X comes from the power plant, while mining operations release most of the methane. For current coal systems, most of the particulate pollution comes from the production of limestone—ironically, particulate pollution from these operations exceeds the federal air standards set for coal plants. The report figures life-cycle greenhouse emissions of 1,114 g/CO_2 equivalent per kWh for current coal systems, and 1,050 g/CO_2 equivalent for systems capable of meeting the EPA's New Source Performance Standards for conventional pollutants.[148] The plants also produce the pollutants described in Table 7.

Life-cycle emissions from noncombustion generation options, such as nuclear, wind, and geothermal power, are generally far lower than combustion options, as described in Table 7, although greenhouse emissions from biopower are also quite low. For example, a 1993 study for the Swiss Department of Energy posits a life-cycle greenhouse impact for nuclear power of 39.1 grams of CO_2 equivalent per kilowatt-hour.[149] Other studies of nuclear power range between 8 and 54 g/kWh,[150] although it is not always obvious what each study considers. (The Swiss study excludes plant decommissioning and radioactive waste storage.) PV systems have much lower life-cycle emissions than combustion options, but are the highest of the noncombustion options, particularly those PV systems including a battery.

Fuel cells illustrate the importance of life-cycle analysis. This technology combines hydrogen and airborne oxygen in a chemical reaction yielding water, heat and electricity. Fuel cells entail no combustion; the cells themselves release no conventional pollutants, and few or no greenhouse gases.

However, the systems' life-cycle impact depends on the source of the hydrogen and the efficiency of the cell. In the short term, most stationary fuel cells are expected to incorporate a fuel processor able to extract hydrogen from natural gas. In such a system, the processor would emit moderate levels of CO_2, as well as low levels of NO_X and volatile organic compounds. For example, one study of phosphoric acid fuel cells fed by natural gas estimates efficiencies of 36%, CO_2 emissions at 1000 lb/MWh, and NO_X emissions at 0.02-0.03 lb/MWh. Exploitation of these cells' waste heat for productive purposes can raise overall efficiency to about 60%, lowering CO_2 emissions to about 660 lb/MWh.[151] In the future, fuel cells may run on hydrogen derived from sustainable biomass or biofuels, or from water split into hydrogen and oxygen by renewably-generated power. The life-cycle greenhouse profile of such systems would include primarily the energy necessary to manufacture the components.

PART VII. CONCLUSION: A CLEAR SOLUTION TO A COMPLEX PROBLEM

The environmental imperative for renewable energy remains as clear and as simple as ever:

- All energy use affects the environment.
- For any given resource, technology choices and management practices alter environmental consequences.
- Renewable energy technologies are, in the vast majority of cases, preferable to conventional technologies.
- Most conventional energy technologies are ultimately unsustainable.

Furthermore, the costs of large-scale clean energy development might prove surprisingly modest, and there may in fact be financial benefits:

- Analysis by REPP suggests that deploying 3,000 MW of wind in Texas would add about 75¢ to the average family's monthly electric bill. A national wind program that installed 10,000 MW over 10 years would generate $7 billion in direct economic activity.[152]
- Research undertaken by the American Council for an Energy-Efficient Economy suggests that a set of 10 policy measures targeting both energy efficiency and cleaner generation could lower U.S. carbon emissions in 2020 to 45% of business-as-usual levels.[153] Measures addressing power generation account for 22% of that total. Meanwhile, SO_2 would fall to 23% of business-as-usual levels, NO_X to 72%, and particulates to 71%. Consumers would save $500 billion through 2020 through increased efficiency.
- A collaborative study by five organizations suggests that by 2010, an "innovation path" could cut electric sector NO_X emissions by 48%, SO_2 emissions by 77%, direct particulates emissions by 38%, and CO_2 emissions by 27% below 1990 levels.[154] Through higher efficiency, the innovation path would bring net savings of $530 per American household, and cumulative savings of more than $1 trillion by 2010.

Achieving these results will require new combinations of public policy and market growth to support clean energy. The role of environmental information amidst that mix will change. As in the past, the evidence of damage surveyed in this report will provide data for legislative and regulatory proceedings intended to devise appropriate public policy. But it also must be used to condition the consumer market for environmentally sound power.

In fact, sound, voter-supported environmental policy and vibrant, consumer-supported clean energy markets require the same precondition: a committed public constituency. The primary barrier to the growth of such a constituency is a lack of public awareness. Most people do not know much about the extent and causes of environmental degradation, its effect on their lives, or the options we have for reducing it.

The opportunities for green marketing opened by restructuring of the electric sector may provide our best hope to enlighten the public. The amount of renewable energy capacity installed in response to green power markets is so far modest, although the total may grow in years to come. Potentially more important, we look to the substantial ability of the private sector to stimulate demand. Simply put, if the advertising industry can sell tail fins on Cadillacs, it should be able to sell Americans clean power for the sake of their children and grandchildren. We believe that the a healthy green power market will benefit from and in turn reinforce the campaign for sound environmental policy.

As noted at the start of this survey, an environmentally sound future will require us to live green, vote green, and buy green. Relying exclusively on voluntary markets would indeed be a risky strategy, and they may never pan out in any case. But let's be honest about the nature of our dilemma: as the foregoing litany indicates, the regulatory status quo has failed to protect us adequately. The environmental imperative for renewable energy remains with us; we require new tools to address it.[155]

1 Because this report compares options for electric power generation, it excludes the environmental impacts of power transmission and distribution. Most noticeably, these include land occupied and defoliated for transmission lines. More controversially, the electromagnetic fields surrounding high-voltage transmission lines may present a health hazard. (See Susan Kaplan, "Health Effects of Electromagnetic Fields: The State of the Science and Government Response," The Electricity Journal, January/February 2000, pp. 25-33.) Inclusion of the environmental impacts of transmission would reveal the advantage of smaller technologies (e.g., energy efficiency measures, fuel cells, microturbines, small wind turbines, and photovoltaic panels) that can be installed where customers use energy.

2 For a comprehensive landmark effort, see Richard Ottinger et al., Pace University Center for Environmental Studies, Environmental Costs of Electricity (New York: Oceana Publications, Inc., 1991).

3 U.S. Environmental Protection Agency (EPA), 1997 National Air Quality: Status and Trends" Nitrogen Dioxide (Washington, DC: December 1998), viewed 21 January 2000 at <www.epa.gov/oar/aqtrnd97/brochure/no2.html>. While the Clean Air Act's Acid Rain Program has modestly driven down nitrogen oxide (NOX) rates, power generation has soared, driving up emissions. Note also that carbon dioxide emissions have risen steadily. Since carbon dioxide (CO_2) is not generally considered a toxin, as are the criteria pollutants, and is not regulated as one, Part III treats it as a separate issue.

4 EPA, Latest Findings on National Air Quality: 1997 Status and Trends, EPA-454/F-98-009 (Washington, DC: December 1998).

5 Almost 15 million Americans have asthma, and 5,000 Americans die of asthma annually. National Center for Health Statistics, viewed 6 March 2000 at <www.cdc.gov/nchs/fastats/pdf/10199t59.pdf>.

6 As natural gas contains no nitrogen, gas-fueled facilities generate all their NO_X thermally. Fuel-bound nitrogen accounts for 50 to 60% of oil-fired plants'NOX emissions, and 70 to 90% of coal plants' NO_X. However, only 50-60% of the nitrogen in oil, and 10-20% of that in coal, actually forms NO_X. Low combustion temperatures and high moisture content in wood limit NO_X emissions from wood-fired plants. Personal communications to author from Conrad Schneider, Clean Air Task Force (3 February 2000) and Rui Afonso, Energy & Environmental Strategies (4 February 2000).

7 One landmark epidemiological study tracked the health of 8,000 people in six cities over 14-16 years. Compensating for the subjects' age and smoking habits, researchers found that residents of Steubenville, OH, the most polluted city, had a 26% higher mortality rate than those of Portage, WI, the least polluted city. Douglas Dockery et al., "An Association Between Air Pollution and Mortality in Six U.S. Cities," New England Journal of Medicine, 9 December 1993, pp. 1753-59. Another important study linked pollution levels in 151 U.S. cities to data from the American Cancer Society; tracking over a half-million subjects, the research team calculated that residents of the most polluted city had a 17% higher mortality risk than residents of the least polluted city. C. Arden Pope III et al., "Particulate Air Pollution as a Predictor of Mortality in a Prospective Study of U.S. Adults," American Journal of Respiratory Critical Care Medicine 151 (1995), pp. 669-74. Based on these and other studies, the Natural Resources Defense Council (NRDC) calculates that approximately 64,000 Americans die annually from heart and lung disease attributable to particulate air pollution. Deborah Shprentz et al., Breath Taking: Premature Mortality Due to Particulate Air Pollution in 239 American Cities (New York: NRDC, 1996).

8 Joel Schwartz et al., "Episodes of High Coarse Particle Concentrations Are Not Associated with Increased Mortality," Environmental Health Perspectives, 5 May 1999, viewed 29 January 2000 at <ehpnet1.niehs.nih.gov/docs/1999/107p339-342schwartz/abstract.html>.

9 J. Thurston et al., "Respiratory Hospital Admissions and Summertime Haze Pollution in Toronto, Canada: Consideration of the Role of Acid Aerosols," Environmental Research 65 (1994), pp. 271-90.

10 P. Weisel et al., "Relationship Between Summertime Ambient Ozone Levels and Emergency Department Visits for Asthma in Central New Jersey," Environmental Health Perspectives 103, sup. 2 (1995), pp. 97-102, and;

11 P. Kinney and H. Ozkaynak, "Associations of Daily Mortality and Air Pollution in Los Angeles County," Environmental Research 54 (1991), pp. 99-120.99-120; EPA, op. cit. note 5, pp. 1, 7.

12 Institute for Energy and Environmental Research, Uranium: Its Uses and Hazards, viewed 19 November 1999 at <www.ieer.org/fctsheet/uranium.html>.

13 Martha Keating, Laid to Waste: The Dirty Secret of Combustion Waste from America's Power Plants (Denver, CO: Citizens Coal Council et al., 2000), p. 9, viewed 9 March 2000 at <www.cleanair.net/laidtowaste.htm>.

14 National Center for Health Statistics, viewed 6 March 2000 at <www.cdc.gov/nchs/fastats/pdf/10199t59.pdf>.

15 Stacey Davis, Mercury Emissions from Coal-fired Power Plants (Washington, DC: Center for Clean Air Policy, 1998), pp. 15-16. The ratio of ionic to elemental Hg in flue gas varies widely from source to source, and techniques for estimating the relationship remain controversial. Davis cites ratios ranging from 38:63 to 79:21.

16 U.S. EPA, Latest Findings on National Air Quality: 1997 Status and Trends, EPA-454/F-98-009 (December 1998), pp. 1, 7.

17 EPA, Mercury Study Report to Congress: Overview, EPA-452/R-97-0003 (Washington, DC: December 1997), viewed 18 January 2000 at <www.epa.gov/ttnuatw1/112nmerc/mercury.html>. See also Felice Stadler, Turn Up the Heat on Dirty Power: Why Power Plants Must Reduce Their Mercury Pollution (Washington, DC: Clean Air Network, 1998).

18 Davis, op. cit. note 15, p. 10. Davis notes that "most scientists are reluctant to say that mercury at present levels in the environment is causing adverse effects to humans or wildlife. However, there is a statistical relationship between current levels of mercury in the environment and subtle population-based neurological and developmental effects in people and reproductive deficiencies in animals residing in some of the communities that have been critically evaluated to date." Ibid., p. 13.

19 Analysts use two principal units to describe emissions from energy-generating technologies. The first relates emissions to the heat content of fuel fed into the plant, e.g. pounds of NO_X emitted per million Btu, or lb/mmBtu. The second describes emissions in terms of the electrical energy produced by the plant, e.g. grams of NO_X emitted per kilowatt-hour, or g/kWh. The two measures are related by the plant's "heat rate," usually expressed as Btu/kWh. Heat rates for coal plants range between 10,000 and 12,000 Btu/kWh. More efficient gas turbines need less heat from fuel to produce equivalent electricity, so their heat rates generally range from 7,000 to 9,000 Btu/kWh. (Thus, a very rough rule of thumb: lb/MWh = lb/mmBtu x 10.) This survey seeks to use consistent

units, avoiding translation in cases where the appropriate heat rate is not obvious, so as to avoid introducing errors.

20 Energy & Environmental Research Center, A Comprehensive Assessment of Toxic Emissions from Coal-fired Plants: Phase I Results from the U.S. Department of Energy Study (Grand Forks, ND: University of North Dakota, 1996), table ES-1.

21 EPA, Acid Rain Program, 1998 Emissions Scorecard, viewed 24 January 2000 at <www.epa.gov/acidrain/score98/text98.pdf>. See also <www.epa.gov/acidrain/overview.html> and <www.epa.gov/acidrain/sources.html>, viewed 24 January 2000.

22 Lars Hedin and Gene Likens, "Atmospheric Dust and Acid Rain," Scientific American, December 1996, pp. 88-92; William Stevens, "The Forest that Stopped Growing: Trail Traced to Acid Rain," The New York Times, 16 April 1996, p. C4. In October 1998, EPA, referring to Section 110 of the Clean Air Act, promulgated a plan to cap NO_X emissions in 22 eastern states and the District of Columbia. Several states along with utility and business groups have filed lawsuits challenging this, and a federal court has ruled that Congress violated the constitution in the CAA by delegating too much authority to EPA. EPA continues to move ahead with the plan. Carl Levesque, "EPA Hopes NO_X Rules Not Dead Yet," Public Utilities Fortnightly, 1 February 2000, pp. 14-15.

23 Much of the following draws on Peter Vitousek et al., "Human Alteration of the Global Nitrogen Cycle: Causes and Consequences," Issues in Ecology, Spring 1997, available at <www.sdsc.edu/~esa/issues.htm>.

24 A metric ton equals 1,000 kilograms, or approximately 2,200 pounds. Some sources, following European usage, refer to a metric ton as a "tonne." Others use the metric measure "teragram" to denote one million metric tons.

25 EPA, Where is the Air Pollution Coming From? viewed 13 March 2000 at <www.epa.gov/owowwtr1/oceans/airdep/air5.html>, and Environmental Effects of Acid Rain, viewed 18 January 2000 at <www.epa.gov/acidrain/effects/envben.html>. Nationally, other nitrogen sources include the application of manufactured nitrogen-based fertilizer, and cultivation of soy, peas, alfalfa, and other plants that derive most of their nitrogen from the atmosphere rather than stocks of previously fixed nitrogen in the soil.

26 Ecological Society of America, Atmospheric Nitrogen Deposition to Coastal Watersheds: Workshop Report, held at University of Rhode Island Coastal Institute, 2-4 June 1997.

27 Danielle Droitsch, Clearing the Air: Protecting a National Jewel (Washington, DC: National Parks and Conservation Association, 1999).

28 Commission for Environmental Cooperation, Continental Pollutant Pathways: An Agenda for Cooperation to Address Long-Range Transport of Air Pollution in North America (Montreal: 1997), p. 6; viewed 31 January 2000 at <www.cec.org/english/resources/publications/index.cfm>.

29 Richard Monastersky, "Asian Pollution Drifts Over North America," Science News Online, 12 December 1998, viewed 29 January 2000 at <sciencenews.org/sn_arc98/12_12_98/fob5.htm>.

30 See, for example, Paul Miller, Northeast States for Coordinated Air Use Management, "Lifting the Veil of Smog: Why a Regional Ozone Strategy is Needed in the Eastern United States," article appearing in EM, April 1999, viewed 7 February 2000 at <www.nescaum.org/pdf/transport.pdf>.

31 Kurt Waltzer, Ozone Valley" Ozone Alley: Smog Pollution in the Ohio River Valley: What Can Be Done (Columbus, OH: Ohio Environmental Council, 2000), figures 1 and 2, viewed 1 March 2000 at <www.theoec.org/ovalley/Ohio%20Report-1.pdf>.

32 For instance, project developers in New England have about 25,000 MW of combined-cycle gas plants somewhere in the permitting process" a quantity roughly equivalent to the existing system's peak capacity. Although some of those plants will never be built, 9,000 MW of the total are either under construction or have recently come on line, per David Marshall, Conservation Law Foundation, personal communication, 15 March 2000.

33 For the moment, however, diesel engines provide the huge majority of America's distributed generation. Collectively, these units may release about as much NO_X as the state of Georgia, which ranks fourteenth in the nation. Virinder Singh, Replacing Diesel Engines with Renewable Energy, draft REPP report, Washington, DC, 23 February 2000.

34 Currently, states must ensure that a new power plant in an area meeting federal air standards uses "best available control technology" to limit pollution; a facility in an area failing to meet federal requirements must match "lowest achievable emission rate." States interpret these phrases differently, but the standard for best available NO_X control technology is selective catalytic reduction, achieving 0.15 pounds of per million Btu (lb/mmBtu) of energy. The standard for sulfur dioxide (SO_2) is scrubbers achieving 0.3 lb/mmBtu. Old coal plants routinely emit over 0.5 lb/mmBtu of NO_X, and as much as 6.0 lb/mmBtu of SO_2. John Coequyt and Rebecca Stanfield, Up In Smoke: Congress' Failure to Control Emissions from Coal Power Plants (Washington, DC: U.S. PIRG Education Fund and the Environmental Working Group, 1999), p. 9.

35 Coequyt and Stanfield, op. cit. note 31, p. 1.

36 Northeast States for Coordinated Air Use Management, Air Pollution Impacts of Increased Deregulation in the Electric Power Industry: An Initial Analysis (15 January 1998), pp. 7-8, viewed 5 February 2000 at <www.nescaum.org/pdf/dereg.pdf>.

37 Geoffrey Rothwell, "The Risk of Early Retirement of U.S. Nuclear Power Plants under Electricity Deregulation and Carbon Dioxide Emission Reductions," presented to Center for Clean Air Policy Restructuring Dialogue in Washington, DC, November 1999.

38 The portfolio standards should enable the installation of 3,800 new renewable megawatts (MW) by 2010, and support the operation of 3,600 existing MW. The state funds now amount to $1.7 billion, and by 2010 could finance the installation of 1,000 new MW, in addition to supporting 4,100 existing MW. Ryan Wiser et al., "Emerging Markets for Renewable Energy: The Role of State Policies During Restructuring," Electricity Journal, January/February 2000, pp. 13-24.

39 Developers have installed 37 MW of renewable power expressly to serve competitive markets, plus 74 MW to serve utility-run green pricing programs in monopoly markets. Lori Bird and Blair Swezey, Estimates of Renewable Energy Developed to Serve Green Power Markets, National Renewable Energy Laboratory (NREL) (Golden, CO: December 1999), viewed 19 January 2000 at <www.ere.doe.gov/greenpower/new_gp_cap.shtml>.

40 Research described in Raymond Costello, "Biomass Cofiring Offers Cleaner Future for Coal Plants," Power Engineering, 1 January 1999, viewed 31 January 2000 at <pe.pennwellnet.com>.

41 The U.N. Environment Programme and the World Meteorological Organisation established the Intergovernmental Panel on Climate Change (IPCC) in 1988 to assess evidence of climate change and formulate response strategies. Over 3,000 leading international scientists participate in the IPCC process. See IPCC, Second Assessment Report: Climate Change 1995, Summary for Policymakers: The Science of Climate Change, at <www.epa.gov/

oppeoee1/globalwarming/publications/reference/ipcc/science.html>.

42 Water vapor is the most important greenhouse gas. Although human activity does not directly emit climactically significant quantities of water vapor, rising temperatures increase evaporation, setting up a positive feedback loop for accelerating warming. Modeling such indirect effects represents a chief challenge of climate science.

43 Tom Wigley, The Science of Climate Change: Global and U.S. Perspectives (Washington, DC: Pew Center on Climate Change, 1999), p. 5, available at <www.pewclimate.org>.

44 "Technical Summary" in J.T. Houghton et al. (eds.), Climate Change 1995: The Science of Climate Change 1995 (Cambridge: Cambridge University Press, 1996), table 1.

45 The IPCC lists global warming potentials in D. Schimel et al., "Radiative Forcing of Climate Change," in Houghton et al., op. cit. note 44, table 2.9. Note that figures referring to carbon and CO_2 are not interchangeable; 3.67 grams of CO_2 contain 1 gram of carbon.

46 EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1997, EPA 236-R-99-003 (Washington, DC: April 1999), tables ES-1 and 2-3; viewed 18 January at <www.epa.gov/oppeoee1/globalwarming/publications/emissions/us1999/index.html>.

47 Because trees and other plants absorb CO_2 as they grow, land clearing and deforestation exacerbate the climate problem. In some developing countries, such land use trends account for very large fractions of national greenhouse gas inventories, as well as large absolute emissions. Loss of biomass may contribute 23% of net global CO_2 emissions. Michael Coda, "Land Use Change Outside the U.S.," presented to the National Energy Modeling System/Annual Energy Outlook Conference (Crystal City, VA) 21 March 2000.

48 U.S. Department of Energy (DOE), Energy Information Administration (EIA), Emissions of Greenhouse Gases in the United States: 1995, DOE/EIA-0573(95), p. 8. The United States probably contributes a smaller fraction of global methane and nitrous oxide emissions, and a larger fraction of halocarbons and sulfur hexafluoride.

49 Carbon emissions denote lower heating value, which does not include the energy of condensation in the water vapor contained in combustion products. See Nebojsa Nakicenovic, "Energy Primer," in Robert Watson et al. (eds.), Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses (Cambridge: Cambridge University Press, 1996), p. 80. See also Adam Serchuk and Robert Means, Natural Gas: Bridge to a Renewable Energy Future (College Park, MD: Renewable Energy Policy Project, 1996).

50 Some 2 billion people now lack full access to electricity. The Electric Power Research Institute (EPRI) estimates that raising electricity usage in developing countries to 1950-era U.S. levels would require construction of 10 million MW of additional generating capacity. EPRI, Electricity Technology Roadmap: 1999 Summary and Synthesis, C1-112677-V1 (July 1999), p. 68. For comparison, the world currently hosts 3.13 million MW of generating capacity. DOE, EIA, World Total Electricity Installed Capacity, January 1, 1980 - January 1, 1998, viewed 28 February 2000 at <www.eia.doe.gov/emeu/international/electric.html#Capacity>.

51 Conventional and unconventional natural gas account for 72 and 103 GtC of identified reserves, respectively, and 138 and 403 GtC of ultimately recoverable stocks, respectively. R. Watson et al., Technologies, Policies and Measures for Mitigating Climate Change: IPCC Technical Paper I (IPCC, 1996), table 9.

52 "Technical Summary" in Houghton et al., op. cit. note 44, table 5.

53 Schimel et al., op. cit. note 45.

54 EPA, op. cit. note 46, table ES-1. The percentages noted (and similar figures) may be deceptively precise, given the difficulty of the calculations they represent.

55 U.S. Department of State, Climate Action Report: 1997 Submission of the United States of America Under the United Nations Framework Convention on Climate Change, July 1997, p. 66.

56 Outside the United States, several petroleum-producing nations lack a natural gas infrastructure. They set afire—""flare"—"most of the gas escaping from petroleum wells. This constitutes a surprisingly large source of CO_2. The World Bank estimated that in 1990 the world, led by Nigeria, the Soviet Union, and Algeria, flared 107 billion cubic meters of gas, or 4% of total production. John Homer, Natural Gas in Developing Countries (Washington, DC: World Bank, 1993), table 2.9.

57 For the World Commission on Dams, see <www.dams.org>.

58 C. Galy-Lacaux et al., "Long-term Greenhouse Gas Emissions from Hydroelectric Reservoirs in Tropical Forest Regions," Global Biochemical Cycles, 2nd Quarter, 1999, p. 503. See also Fred Pearce, "Rotten Business," New Scientist, 28 August 1999. Preliminary research suggests slightly lower emissions, at 52 million metric tons of CO_2 equivalent, but stresses that Petit-Saut will nevertheless emit 2,600 grams of CO_2 equivalent per kilowatt-hour over its first 20 years of operation, more than double the emissions of a comparable coal-fired power plant. Stuart Gaffin and Deborah Moore, Environmental Defense, "Comment on 'Long-term Greenhouse Gas Emissions fro Hydroelectric Reservoirs in Tropical forest Regions' by Galy-Lacaux et al.," submitted to Global Biochemical Cycles.

59 For instance, it may not be appropriate to include large tropical hydropower facilities in climate protection policy instruments such as the Kyoto Protocol's Clean Development Mechanism.

60 Schimel et al., op. cit. note 45.

61 EPA, op. cit. note 46, table ES-1.

62 Schimel et al., op. cit. note 45.

63 EPA, op. cit. note 46, table ES-1.

64 EPA, op. cit. note 46, p. 2-37.

65 Future Resources Associates, Inc., The Environmental Costs and Benefits of Biomass Energy Use in California, NREL/SR-430-22765 (Golden, CO: NREL, 1997), table 3. The biopower industries of other regions may exhibit different characteristics.

66 U. S. DOE, Annual Energy Outlook 2000, DOE/EIA-0383(2000), December 1999, table A17.

67 Marshall Reed, U.S. Department of Energy, personal communications, 9 and 10 February 2000.

68 Calculation from Karl Gawell, personal communication, 13 March 2000. Based on zinc production and energy consumed reported in U.S. Department of Commerce, 1992 Census of Mineral Industries: Copper Ores, Lead and Zinc Ores, Gold Ores and Silver Ores, MIC92-I-10B, tables 3a, 6a1 and 7b. Assumes emissions in Table 7. This calculation considers only electricity and excludes the distillate and gasoline used in zinc production.

69 Sulfate aerosols do not counteract the effect of greenhouse gases in a straightforward way. For one thing, while greenhouse gases trap heat constantly, sulfate particles only reflect sunlight during the day. For another, sulfates endure in the atmosphere a much

shorter time than greenhouse gases" and they return to ground as acid rain and particulate pollution.

70 Wigley, op. cit. note 43, p. 15, esp. figure 5. Wigley notes the difficulty of interpreting past solar variation from indirect evidence, and warns that the reconstructions remain "highly uncertain (p. 8)." See also D. Rind et al., "Simulated Time-Dependent Climate Response To Solar Radiative Forcing Since 1600," Journal of Geophysical Research, 1999, pp. 1973-90.

71 National Research Council (NRC), Reconciling Observations of Global Temperature Change (Washington, DC: 2000). See <www.nas.edu>. By contrast, the IPCC in 1995 found evidence of warming between 0.3 and 0.6° C; Houghton, op. cit. note 44, p. 4.

72 Ibid.

73 NOAA press release at <www.noaanews.noaa.gov/stories/s105.htm>, and annual NASA summary at <www.giss.nasa.gov/research/observe/surftemp/1998.html>, both viewed 13 January 1999. For World Meteorological Organization, see Joby Warrick, "Earth At Its Warmest In Past 12 Centuries; Scientist Says Data Suggest Human Causes," Washington Post, 8 December 1998, p. A3. While cooler, 1999 was still one of the warmest years in over a century of data.

74 W. Krabill et al., "Rapid Thinning of Parts of the Southern Greenland Ice Sheet," Science 283 (1999), pp. 1522-24.

75 Corals "bleach" when physiological stress disperses symbiotic algae. Prolonged bleaching kills the coral. C.D. Harvell et al., "Emerging Marine Diseases" Climate Links and Anthropogenic Factors," Science, 3 September 1999, pp. 1,505-10; A.E. Strong et al., "Ocean Hot Spots and Coral Reef Bleaching," Reef Encounters, January-July 1998, pp. 20-22.

76 Richard Alward et al., "Grassland Vegetation Changes and Nocturnal Global Warming," Science, 8 January 1999, pp. 229-31.

77 David Schneider, "The Rising Seas," Scientific American, March 1997, pp. 112-17.

78 Wigley, op. cit. note 43.

79 William Burns, The Possible Impacts of Climate Change on Pacific Island State Ecosystems (Oakland, CA: Pacific Institute for Studies in Development, Environment and Security, 1999), viewed 25 January at <www.pacinst.org>.

80 Wigley, op. cit. note 43, pp. 29-33.

81 Virginia Tolbert and Lynn Wright, "Environmental Enhancement of U.S. Biomass Crop Technologies: Research Results to Date," Biomass and Bioenergy, 1998, pp. 93-100.

82 EPRI and DOE, Renewable Energy Technology Characterizations, EPRI TR-109496 (December 1997), pp. 6-31. The land required by wind power may be less than commonly thought. Based on an authoritative wind atlas (D.L. Elliott et al., An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States, Battelle Pacific Northwest Laboratory, PNL-7789/UC-261 (August 1991)), another REPP study estimates that the 12 Midwestern states could meet 10% of their electricity needs with 27,700 wind turbines on 3,363 square kilometers of land, or just 0.35% of available and appropriate windy land in the region; Jamie Chapman et al., Expanding Wind Power: Can Americans Afford It? (Washington, DC: REPP, 1998), table 1.

83 Geoffrey Buckley, "The Environmental Transformation of an Appalachian Valley, 1850-1906," Geographical Review, April 1998, pp. 175-98.

84 Jeff Skousen, Paul Ziemkiewicz, and Christina Venable, "Evaluation of Tree Growth on Surface Mined Lands in Southern West Virginia," viewed 18 February 2000 at <www.wvu.edu/~agexten/landrec/evaltree.htm>.

85 The U.S. Department of the Interior's Office of Surface Mining first collated voluntary reports by states and tribes of land disturbed by coal mining in 1998. OSM, 1998 Annual Report, at <www.osmre.gov/anrep98.htm>. According to the most recent EIA data, those reporting entities accounted for only 60% of total U.S. coal production. Disturbed area for non-reporting states calculated roughly from their 1997 coal production as a fraction of U.S. total production. Result multiplied by 85%, the portion of U.S. coal production that supplies power plants. Data from www.eia.doe.gov/cneaf/coal/statepro/tables, www.eia.doe.gov/cneaf/coal/quarterly/html/t3p01p1.html and www.eia.doe.gov/cneaf/coal/quarterly/html/t37p01p1.html, all viewed 22 March 2000.

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