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THE ART OF ENERGY EFFICIENCY: Protecting the Environment with Better Technology

Arthur H. Rosenfeld
Senior Advisor, EE-40, US DoE, Washington, DC 20585; e-mail: AHRosenfeld@LBL.gov

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■ **Abstract** After a first career as Professor of Physics, University of California at Berkeley, working in experimental particle physics at Lawrence Berkeley National Laboratory (LBNL), I was prompted by the 1973 Organization of Petroleum Exporting Countries (OPEC) oil embargo to switch to improving energy end-use efficiency, particularly in buildings. I cofounded and directed the Energy Efficient Buildings program at LBNL, which later became the Center for Building Science. At the Center we developed high-frequency solid-state ballasts for fluorescent lamps, low-emissivity and selective windows, and the DOE-2 computer program for the energy analysis and design of buildings. The ballasts in turn stimulated Philips lighting to produce compact fluorescent lamps. When they achieve their expected market share, energy savings from products started or developed at the Center for Building Sciences are projected to save American consumers $30 billion/year, net of the cost of the better buildings and products. In terms of pollution control, this is equivalent to displacing approximately 100 million cars. We did the analysis on which the California and later the U.S. appliance standards are based, and we also worked on indoor air quality and discovered how radon is sucked into homes. We worked closely with the California utilities to develop programs in "Demand Side Management" and "Integrated Utility Planning." I also worked in California and New England on utility "collaboratives" under which we changed their profit rules to favor investment in customer energy efficiency (and sharing the savings with the customer) over selling raw electricity. I cofounded a successful nonprofit, the American Council for an Energy-Efficient Economy, and a University of California research unit, the California Institute for Energy Efficiency, and I served on the steering Committee of Pacific Gas and Electric's ACT^2 project, in which we cost-effectively cut the energy use of six sites by one half. Starting in l994, my third career has been as Senior Advisor to the U.S. Department of Energy Assistant Secretary for Energy Efficiency and Renewable Energy.

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1944–1975: FROM PHYSICS TO ENERGY EFFICIENCY

Particle Physics

This is my story of how I came to switch in mid-career from doing experimental particle physics to developing efficient uses of energy and what I've learned along the way. It's also a story of why many of my colleagues made the same switch, ultimately providing a surprisingly large segment of the leadership in the new, politicized field of conservation/energy efficiency.

I briefly cover my 19-year career in elementary particle physics, which began at the University of Chicago, where Enrico Fermi signed my thesis on Pion production in the UC cyclotron in 1954 (1a, 1b) and ended with the Oil Producing and Exporting Countries (OPEC) oil embargo in l973.

I received my Bachelor of Science degree in physics at age 18, in l944. After serving 2 years in the U.S. Navy at the end of World War II, I entered graduate school at the University of Chicago and achieved a record that got me accepted by Enrico Fermi as one of his students. My first taste of publication success was as a coauthor of a widely read and translated textbook, *Nuclear Physics* by Fermi, Orear, Rosenfeld, and Schluter (1c). Shortly before Fermi's death in l954, Professor Luis Alvarez, at the University of California at Berkeley (UC Berkeley), had started building a series of hydrogen bubble chambers to detect particles produced in the new Bevatron at the Radiation Laboratory [now Lawrence Berkeley National Laboratory (LBNL)] overlooking the Berkeley campus. The opportunities at Berkeley seemed endless. Fermi wrote me a wonderful recommendation as his "second most promising graduate student" (he coyly declined to identify his first) and soon, with my bride Roz, I moved to Berkeley as an assistant professor, teaching and helping Luis organize his growing research group.

The bubble chambers worked wonderfully well. Our data analysis hardware and computer programs (my primary responsibility) kept up with a flood of photographs. Soon we were discovering most of the particles and resonant states that led Murray Gell-Mann to propose a sort of periodic table of elementary particles—SU3, the "eightfold way"—and to predict quarks.

By 1969 we had identified a dozen new particles, and Luis was awarded the Nobel Prize in Physics. Luis was the first to acknowledge that his prize was the result of a group effort, and he took eight of us, with spouses or partners, to Stockholm for the celebrations. But Luis strongly preferred individual research and invention and had grown tired of managing a group of 200 physicists, scanners, data analysts, and engineers, so he used the opportunity of the Nobel Prize to switch to astrophysics. So by October 17, 1973, I was serving as chairman of Group A (the old Alvarez group) when OPEC embargoed oil sales to the West.

The Oil Embargo

When the first gasoline shortage struck, I knew only two facts about energy use: (*a*) the developed countries are expected to burn up half the world's oil in my generation (it seemed rather selfish); and (*b*) European energy "intensities" [per capita, or per dollar of gross domestic product (GDP)] were only about half of ours, yet they had a comparable standard of living. I had learned this from the time I spent at the Centre Européen pour la Recherche Nucléaire (CERN) in Switzerland and at other European accelerator laboratories, where I observed that my colleagues did not freeze in the dark. They did, however, drive smaller cars and turn off lights in unoccupied rooms and buildings.

I noted that if we Americans used energy as efficiently as do the Europeans or Japanese, we would have been *exporting* oil in 1973, so OPEC would have posed little threat to the U.S. economy. I quickly discovered that many of my physicist friends had independently concluded that it would be more profitable to attack our own wasteful energy use than to attack OPEC.

One small incident strengthened my hunch that it would be easy to save energy. At the office, late one Friday night in November 1973, I knew I'd have to wait in a half-hour line on Saturday to buy gasoline. I compared that with the equivalent gallons used by my office over the 60-h weekend. My too-brightly-lit (1 kW!) office burned the equivalent of 5 gal/weekend of natural gas back at the power plant. I was one of only a few on my 20-office floor who ever switched off the lights in our offices and perhaps in the hall, but on the way to my car that evening, I decided to switch off the lights in the other 19 offices. The problem was to find the switches. A few were only hidden behind books. The challenge was finding the rest that were hidden by file cabinets, bookcases, and posters. After 20 min of uncovering light switches (and saving 100 gal for the weekend), I decided that UC Berkeley and its Radiation Laboratory should do something about conservation.

In December 1973, I had the first of my thousands of contacts with the local utility, Pacific Gas and Electric (PG&E). PG&E had purchased a large ad in the *San Francisco Chronicle*, with the following message:

> "Don't mess with the Thermostat. You'll use more gas heating your house in the morning than you'll save overnight."

Shocked by this unscientific claim, I called PG&E's research manager Stan Blois, and asked him if he kept his coffee hot on the stove all night, to avoid having to reheat it in the morning. Blois quickly agreed that the ad showed dismal incompetence; and he must have responded quickly, because it never reappeared. But the incident raised some nagging concerns about the motivations and competence of utilities.

Princeton Summer Study

In January 1974, at the Annual Meeting of the American Physical Society in New York, Professor Sam Berman of Stanford University and I ran into my former

Berkeley colleague Robert Socolow, who had by then joined the Princeton Center for Energy and Environmental Studies. Rob reminded us that the American Physical Society had foreseen the need for a summer study on efficient use of energy and was looking for leaders. We decided on the spot to volunteer to organize a 1-month study in the summer of l974, if we could work that fast. Along with Marc Ross of the University of Michigan, we easily found financing from the National Science Foundation and the Federal Energy Agency, which was the predecessor to the Energy R&D Administration (ERDA), which ultimately became the present Department of Energy (DoE). We promptly invited participants and "briefers"—experts in buildings, industry, transportation, and utilities. Life was simpler then—and spurred on by an atmosphere of crisis—we managed in five months to move from an idea in New York to our first meeting at Princeton.

Once convened, it took us only a few days to understand why we in the United States used so much energy; oil and gas were as cheap as dirt or water, and so they were treated like dirt or water. (Even today, gasoline is only one-third the price of milk). I realized that, because the Europeans and Japanese had no domestic gas or oil, the cost of imported fuels naturally entered into their considerations of balance of trade, national security, and tax policy. Abroad, energy efficiency was a respectable form of engineering. Whereas Americans largely purchased by least "first cost," Europeans understood and operated under the concept of "life cycle cost."

By the end of the first week, we realized that we were discovering (or had blundered into) a huge oil and gas field buried in our cities (buildings), factories, and roads (cars), which could be "extracted" at pennies per gallon of gasoline equivalent.

We began to write a book *Efficient Use of Energy* (2), which for many years was the best seller of the American Institute of Physics. In it we pointed out that fluorescent lamps were l5% more efficient if powered at frequencies much higher than 60 Hz directly from the power lines. (This led later to the development at LBNL of solid-state, high-frequency ballasts, or power supplies, for fluorescent lamps.) Sam Berman, David Claridge, and Seth Silverstein wrote a whole chapter on the design and use of advanced windows. They pointed out that the heat leaking out of windows in U.S. buildings every winter, if averaged over a full year, corresponds to the energy content of 1—2 million barrels of oil per day (Mbod), which was the same as the oil flow projected via the trans-Alaska pipeline from the new Prudhoe Bay Field. They then described how, in 1968, three Russians had already coated a thin film of low-emissivity (low-E) semiconductor material on to the inside surface of double-glazed windows, thus virtually stopping radiation transfer and doubling their thermal resistance. Applied to U.S. windows, this would save half of Prudhoe Bay's daily production.

In 1974, the U.S. car fleet averaged 14 miles/gal [mpg (16.7 liter/100 km)], but we learned enough about auto economics to estimate that a "least-cost" (life cycle optimized) six-passenger car should get ~35 mpg (7 liter/100 km). [By 1999 standards, this seems modest, because the year 2002 goal of the Partnership for a New Generation Vehicle is 80 mpg (www.uscar.org/pngv/index.htm)].

During that month in Princeton, many of us became aware that our new knowledge would soon change our lives. We returned home to edit the book for publication in Spring 1975. In Washington, Congressman Richard Ottinger of New York, Chair of the House Subcommittee on Energy and Power, decided not to wait for the American Institute of Physics version, so he had it reproduced as a committee print. Five years later Ottinger would help us again in a bolder way, when the Reagan transition team sidetracked the 1980 Solar Energy Research Institute (SERI) Solar/Conservation study.

1974–1985: EARLY GAINS

Energy-Efficient Buildings

I returned to Berkeley and to experiments at Stanford's Linear Accelerator Center, but at least two forces were pushing me to work (at least temporarily, I thought) on energy efficiency.

First, the California Energy Commission (CEC) was created in 1974, with authority, among other things, to approve or deny site applications for new power plants, to write energy performance standards for new buildings, and to sponsor research and development (R&D). At the time, as shown in Figure 1, installed power was running $\sim$30 GW and growing about 6% per year. This required building two huge power plants every year, typically 1-GW and nuclear or fossil fueled. More than half of that new electricity (i.e. more than one plant per year) would be used to supply new homes and buildings, many of them heated by electric resistance and by lights in commercial buildings. (Such lighting systems, in l974, were designed to burn 24 h/day all winter). I began thinking about the economic tradeoff between constructing a new $2-billion power plant and designing more efficient buildings.

Second, in the fall of 1974 I gave some talks on our Princeton study, both on campus and at LBNL, and immediately discovered that there were graduate students eager to do research in efficient use of energy.

I should note that, about 1971, the same concerns that had led the California State Legislature to plan the Energy Commission had led UC Berkeley to create an interdisciplinary graduate program, the Energy and Resources Group (ERG), and to attract a young physicist, John Holdren,[1] as our first Professor of Energy and Resources. Under his inspired leadership, ERG hired a five-person core faculty, attracted scores of associated faculty from other departments, and admitted some of the best students in the world. I served as vice-chair for many years, taught a course on "Efficient Use of Energy," and was able to place many ERG students in

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[1] Shortly after I left Berkeley for DoE in l994, Holdren accepted a distinguished chair at Harvard's Kennedy School of Government, and soon was appointed vice-chair of President Clinton's Council of Advisors on Science and Technology.

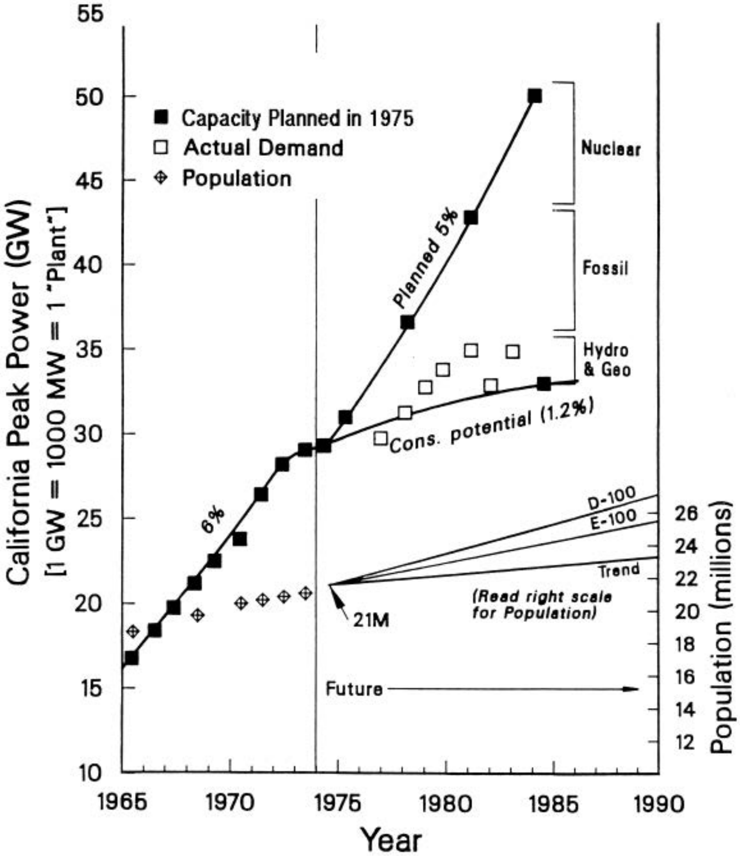

Figure 1 California peak power, historic (1965–1974) and projected (1975–1984) by utilities (5% annual growth), by Goldstein & Rosenfeld [1.2% (39)], and actual (2%). Although the ordinate is labeled "Peak Power," it is really capacity, derived from peak gigawatts × 1.06 to provide a 10% reserve margin and 4% downward correction for coincident demand. Source: Goldstein & Rosenfeld (4).

research projects at LBNL. Thus the successes of ERG and of LBNL programs in energy and environment are inextricably and synergistically intertwined.

During the fall of 1974, Berman and I, in our frequent talks while editing our parts of the Princeton study, decided to sponsor a 1975 summer study on energy-efficient buildings, at the UC Berkeley School of Architecture. Here we learned much more about lighting, windows, and heating, ventilation, and air-conditioning (HVAC) equipment. In those days, compared with today, the building thermal efficiency was worse by nearly a factor of two, and, in addition, chillers (machines that provide cold refrigerant for air conditioning) were oversized by ~50%.

The CEC's draft "Title 24" residential building standard proposed to limit window area to 15% of wall area, without distinguishing among north, south, east, and west. Indeed I don't think the standard even mentioned the sun! I contacted the CEC and discovered why they thought that windows wasted heat in winter and "coolth" in summer. The CEC staff had a choice of only two public-domain computer programs, the "Post Office " program, which was user hostile (although a few experts could use it successfully) and a newer program of the National Bureau of Standards, National Bureau of Standards (thermal) loads (NBSLD). They chose NBSLD, but unfortunately had run it in a "fixed-thermostat" mode that kept the conditioned space at 72°F (22°C) all year, thus calling for heat or cooling or both every day of the year. The indoor temperature was not permitted to float up (storing solar heat as it entered the house through windows or walls) or down (coasting on the stored heat). NBSLD's author, Tamami Kusuda, had written a "floating-temperature" option, but it was more complicated and still had bugs, and neither Tamami nor anybody at CEC could get it to work satisfactorily. No wonder the CEC concluded that windows wasted energy! I decided that California needed two programs for energy analysis in buildings: first and immediately, a simple program for the design of single-family dwellings and, second and later, a comprehensive program for the design of large buildings, with a floating-indoor-temperature option and the ability to simulate HVAC distribution systems.

Architecture professor Ed Dean and I promptly wrote a thermal simulator for a house and named it Two-Zone, because it distinguished between the north and south halves of the house. We easily convinced the CEC to drop their proposed cap on window area for non-north windows, as long as the building provided enough thermally accessible mass (e.g. uncarpeted tile floor or water-filled benches) to store solar heat (3). We didn't know the words "passive solar architecture" and so didn't realize that we had inadvertently written this concept into Title 24.

In 1976, the CEC temporarily adopted Two-Zone for calculating the residential standard. They also put up the first $200,000 to develop "Cal-ERDA," to be matched by support from ERDA (the predecessor to DoE), which also wanted a public-domain computer tool to design energy-efficient buildings. Cal-ERDA started as a collaboration of three national labs—LBNL, Argonne, and Los Alamos.

Version 1.0 was completed in about 2 years and delivered to the CEC for T-24 calculation. The then-new DoE took over Cal-ERDA at LBNL, under the name of DOE-1, to support planned national-building-performance standards. The DoE has supported DOE-1 and later DOE-2 ever since, and the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) soon chose DOE-2 as the tool for calculating and updating its "Standard 90" series of building performance standards, which has been adopted by most states. Today DOE-2 is used to design $\sim$15% of all new commercial space to beat existing standards by $>$20% and save more money.

Standards in general and building standards in particular have been the most successful and profitable ways for society to save energy and money. New building

HVAC energy intensity (i.e. energy use per square foot for heating and cooling) dropped to ∼50% between 1975 and 1985 (excluding the growth of computers and other "plug" loads). When I left California in l994, the CEC estimated that efficient buildings, those built under Title 24, were saving $1.5 billion annually, $0.5 billion in natural gas and $1 billion in electricity, which is the annual output of 2.5 huge 1-GW power plants. Since 1994, of course, the initial $1.5 billion/year has grown every year, as new buildings appear. Because other states have adopted building standards over a period of years, it would be tedious to calculate expanding this $1.5 billion/year to cover the whole United States, with eightfold the population of California, but I estimate that annual U.S. savings are roughly $10 billion.

What was the contribution of the DOE-2 group to this estimated annual $10-billion savings? I believe that the fortunate combination of our collaboration with CEC/T-24 and our provision of a credible, public-domain tool advanced the adoption of standards throughout the United States by 1–3 years, for a societal saving in energy bills of $10 billion–$30 billion.

DOE-2, now led by Fred Winkelmann, went on to become the tool of choice for the design of both real buildings and their performance standards in the United States. It has since been adopted in Canada and some Asian nations.

Goldstein-Rosenfeld's Controversial Low-Electricity Scenario

In 1975, the new CEC was still trying to set its priorities—how to balance supplying more energy against extracting more "service" from available energy. This debate was colored and politicized by a proposed ballot initiative, Proposition 15, to halt the construction of nuclear power plants. My new graduate student, Dave Goldstein [now Senior Scientist and codirector of Energy Programs at the National Resources Defense Council (NRDC)] and I did our first serious study of the potential for slowing electricity growth with cost-effective standards for buildings and appliances, and we came to the remarkable conclusion that our annual growth rate could drop from 5% (projected by the utilities) to 1.2% (4). We were invited by Assemblyman Charles Warren to testify on December 8, 1975, at which time we showed Figure 1 and discussed the engineering economic analysis behind it (5). Note that Figure 1 questions the need not only for ∼10 GW of *nuclear* power, but also ∼10 GW more power from *fossil* fuel.

The utilities were shocked by our estimates of potential savings. PG&E called LBNL's then-director Andy Sessler to complain that physicists were unqualified to project electricity-demand scenarios and to suggest that I be fired. Because my wife and my colleagues, including Sessler, had been telling me that I was overqualified to work on energy efficiency, I found the PG&E complaint somewhat comforting. To add to the heat, the Atomic Energy Commission's San Francisco Operations Office found an obscure rule, never before observed, that prohibited us from distributing copies of our report without their approval, which would not be forthcoming. They agreed to drop the ban a few months later, when the Operations

Office was caught printing tens of thousands of pronuclear brochures for the Stop Proposition 15 campaign.

California did indeed start to conserve electricity with two steps: Federal "Energy Guide" labels appeared on appliances (and mpg labels on cars), and the California Appliance Standards and Building Standards (Title 24) went into effect in l977. Title 24 forbade the installation of electric resistance heating for either space or water unless (as is seldom the case) it is cost effective over the full life of the building.

Actual peak demand is shown in Figure 1. Annual growth did in fact drop to 2.2%, much closer to our potential than to the utility forecasts. We were slowly being vindicated, and the hostility of PG&E was replaced with the first steps in a long productive collaboration, leading up to the 1989 ACT^2 project discussed in a later section ("California Pioneers Energy Efficiency"). Because nuclear power was proving to be surprisingly expensive, proposed nuclear plants were abandoned. Next followed the cancellation of new traditional thermal plants. The decline of nuclear power is well known, but the reader may be surprised that no application to site any large central power plant (nuclear, coal, or gas) has been filed in California since l974. Of course, demand has continued to grow at 2%/year, but that new power has come from small independent producers and cogenerators, from renewables (hydroelectric, geothermal, and wind resources), and from sources outside the state. But it is improved efficiency that has been the largest single generator of new electric services for California's growing economy.

The Energy Analysis Program at Lawrence Berkeley National Laboratory—Building and Appliance Standards

Although all of us in the new Energy Efficient Buildings or EEB program were paid by DoE to develop technology or study building-related topics, we were also interested in energy policy and analysis, and we collaborated with an existing small but official Energy Analysis Program under Will Siri. Early in 1978, while I was on sabbatical introducing DOE-2 in Paris, Siri hired a chemist, Mark Levine, who soon energized the program, eventually became its leader, and expanded it 10-fold. My life has been pleasantly entwined with Levine's ever since.

In his first year at LBNL, Levine teamed up with David Goldstein to lead the analysis of building energy performance standards for new residential buildings. The analysis soon resulted in the largest application of the DOE-2 program ever undertaken. We ran thousands of cases to evaluate the effects of energy efficiency measures on different types of houses in different locations throughout the nation. This massive analytical effort challenged the computer code, which needed to be modified in several important ways to account for such factors as window management, different strategies for insulation in basements, whole-house fans, and different types of thermal mass.

We were highly successful in identifying and documenting the economic and energy impacts of energy efficiency measures for houses and the cost-effective levels of such measures in different house types and locations throughout the nation. We were much less successful in helping DoE in its legislative efforts. Both Mark Levine and I testified on building energy performance standards for congressional committees (6), explaining their logic and likely economic benefits. However, the regulations prepared by DoE were—under the legislation at the time—submitted to the Senate, where they were defeated by one vote.

Congress has left new building energy standards to the states, except for federal buildings. But this has made little difference. Most states have adopted standards derived from ASHRAE's voluntary standards (which are based on DOE-2 simulations), and most of the energy efficiency measures that we recommended in 1981—multiple glazings for windows in cold climates, reduced air infiltration, increased insulation in roofs, walls, and foundations, and more efficient furnaces—have gone from rarities to common practice.

Windows and Lighting

By 1976 DoE had been formed and, like the CEC, was debating its priorities, focused mainly on energy supply. But it did have a small Office of Conservation and Solar Energy, and we found support for Sam Berman to develop both high-frequency ballasts for fluorescent lamps and "heat mirror" windows. Despite the risk that DoE's support might be unreliable, Berman courageously resigned his tenured professorship at Stanford University and moved to LBNL. Soon we also attracted Steven Selkowitz, a physicist-turned-architect, to lead the work on windows.

The years 1976–1985 were notable for the EEB Program at LBNL. Berman's group developed high-frequency ballasts, piloted them tediously through Underwriters' Laboratories, and arranged an invaluable field test, hosted by PG&E in its San Francisco skyscraper, which demonstrated electricity savings of $\sim$30%. This attracted the interest of lamp manufacturers, particularly Philips, who reasoned correctly that, if large electronic ballasts were effective for traditional tubular fluorescent lamps, Philips could miniaturize the ballasts and produce very efficient compact fluorescent lamps (CFLs) to replace incandescent lamps. Thus there soon appeared 16-watt CFLs that radiated as much light as a 70-W incandescent light and would burn for 10,000 h instead of 750 h.

Selkowitz' group developed "heat mirror" windows that, although transparent to visible light, kept invisible heat from leaking out and would save the gas-equivalent of half of Prudhoe Bay's daily oil production. This class of window is now called "low-E" because the more descriptive name "Heat Mirror" was quickly copyrighted by Southwall, one of our partner companies. Later, low-E variants were designed for commercial buildings or buildings in hot climates, where cooling is more important than heating. They exploit the fact that only half of solar heat is visible; the other half is "near-infrared" radiation. These advanced windows are termed "selective" because, although they are transparent to visible light and so *look* just like traditional windows, they *reflect* the near infrared. They keep out as much heat as the familiar reflective “solar control” glazing used on all office towers, yet the light transmitted through the clear windows permits occupants to use the daylight near the windows and to turn off the artificial light (this is called “harvesting” daylight).

Improving Indoor Air Quality

At the new DoE, we found support not only for Berman, but also for Craig Hollowell, an air quality chemist who wanted to shift his attention from outdoor to indoor air. We spend 90% of our time indoors, and the Ventilation and Indoor Air Quality (VIAQ) group soon was to show that indoor air is several times more polluted than outdoor air. An indoor-air study was an essential prerequisite to DoE’s program to save energy by sealing homes against drafts and reducing the air change rate in commercial buildings.

Hollowell and colleagues, who had been working on traditional outdoor air pollutants—mainly the products of combustion—had already decided to use their equipment to check indoor pollution in homes around Berkeley. They found that concentrations of nitrogen oxides and of course carbon monoxide were often substantially higher indoors than outdoors, indicating cracks in the heating systems or poor (or nonexistent) venting of other combustion appliances (7).

With the new funding from DOE, Hollowell undertook by 1979 to form a broad program on “building ventilation and indoor air quality,” to understand how to avoid any deterioration of indoor air quality that might be associated with changes of ventilation rates to reduce energy use. The practical requirement for accomplishing this became the main theme of the program—that is, to understand the concentrations and factors controlling them, for three main classes of pollutant: (*a*) combustion products, such as the oxides of carbon and nitrogen already mentioned; (*b*) chemicals of various kinds, arising from furnishings, cleaners, and other household products; and (*c*) radon and its decay products, arising naturally from the earth and from building material such as concrete and brick.

Paradoxically, the broadest and most important conclusion of the program’s work of the first several years was that, for each of these pollutant classes, indoor concentrations—for example, in homes—varied over extremely large ranges even in ordinary structures (for radon, easily a factor of a thousand from low concentrations to very high), and there was rather little correlation with ventilation rate or with the implementation of energy-conserving measures. The main determinant of indoor concentrations—what we had to learn to control—was the “source term,” the rate at which the pollutant of interest entered the indoor air.

Unfortunately in 1982, during these exciting discoveries, Craig died suddenly of a heart attack. Fortunately he had assembled a world-class team including Dave Grimsrud, Tony Nero, and Rich Sextro, who were able to continue despite this severe loss.

A major challenge for them was radon, a radioactive, chemically inert decay product of uranium. Radon is found in soil gas and gets sucked into buildings, particularly in winter. Indoors, radon decays into other radioactive nuclei, which are inhaled by occupants, stick in their lungs, decay by alpha-particle emission, damage lung tissue, and increase the risk of cancer, particularly for smokers (8).

Even before Hollowell's death, it was very clear that—energy efficiency aside—indoor radon would pose a special problem for the scientific and regulatory communities, because even a typical concentration posed an estimated lifetime risk of lung cancer (extrapolated from the observed risk among miners) of perhaps 0.1% for nonsmokers and perhaps 1% for smokers. Even the 0.1% is far above the risk limits used for control of pollutants (and for radiation exposures of the public) in other circumstances. And some people were receiving radon exposures (and putative risks) far higher, in the range where elevated lung cancer rates have been observed among miners. There are $\sim$100,000 lung cancer deaths annually in the United States, and the radon contribution is $\sim$10,000.

The LBNL indoor radon group (led by Tony Nero) discovered—based on long-term continuous data acquisition in homes—that a surprising amount of radon entered homes because it was sucked in from the ground by a "stack" or "chimney" effect, that is, by small pressure differences across the building shell generated by temperature differences (between the indoors and outdoors), by winds, and sometimes by combustion appliances that depressurize the house (9). These are the same pressures that cause infiltration of air across the building shell, causing a significant part of the heating load, but in this case the issue is the small amount of radioactive soil gas that is drawn from the ground underneath the house and that carries radon generated in the ground.

With this understanding it quickly became cost effective to find and fix homes with dangerous levels of radon and to build precautions into new homes in high-radon regions so that radon cannot be sucked in (10–12).

Going After Appliances

In 1976 California Governor Jerry Brown was looking for a way to disapprove Sundesert, the only still pending application for a 1-GW nuclear power plant. The Title 24 standard for buildings was an accepted idea, but somehow standards for appliances seemed more like a federal responsibility, so appliance standards were still controversial. David Goldstein and I then discovered that there was absolutely no correlation between refrigerator retail price and efficiency, although we controlled for every feature we could imagine. Figure 2 (13) shows 22 refrigerators, 11 with a life cycle cost of $>$\$1700 (averaging $\sim$\$1900) and 11 more below the \$1700 line (averaging $\sim$\$1550). Both sets of 11 had the same distribution of purchase prices. So if standards eliminated the least efficient half of the units, the consumer would notice no change in *purchase* prices, but would save some \$350 over the 16-year appliance service life. (Of course as standards began to motivate the design of even more efficient units, savings opportunities would grow). I pointed out to Governor Brown that California refrigerators were already using the output of five Sundeserts, and that even minimal standards would avoid the

(a)

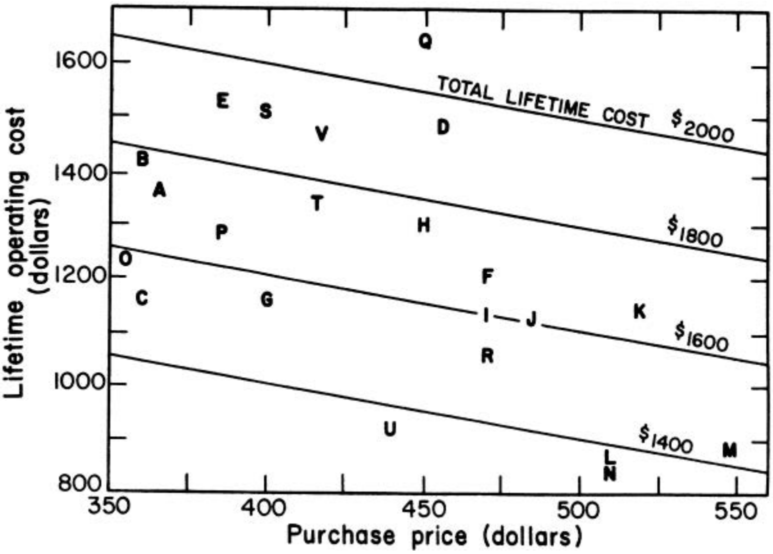

Figure 2 Scatter plot and cost data on 22 1976 refrigerators. The scatter plot (and Table on page 47) show little correlation between purchase price and efficiency. Source: Goldstein & Rosenfeld (13).

need for 1.5 Sundeserts, at no additional consumer cost. Brown promptly called Energy Commissioner Gene Varanini, who corroborated our claim.

After that, standards for new refrigerators and freezers were developed quickly and put into effect in l977, and they quickly contributed to the drama illustrated in Figure 3. (14). I say "contributed" because the striking discontinuity in slope at 1974 (from an annual energy use *growth* of 7%/year to a *drop* of 5%/year) actually results from the introduction of two policies (Federal appliance efficiency labels in l975 and California standards in l977) and a new technology (blown-in foam insulation.) Figure 3 shows that the California standards were tightened in 1980 and 1987, followed by federal standards for 1990, 1993, and 2001. In the 27 years between the 1974 peak annual usage of 1800 kWh and the 2001 federal standard of 450 kWh, we will have seen energy use drop to one quarter, making no correction for the 10% growth of average volume from 18 ft^3 to 20 ft^3. This corresponds to a remarkable compound annual efficiency gain of 5.1%. It is impossible to disentangle the contribution of standards and of accelerated improvement in technology, but clearly the combination has served society very well.

The right vertical (macro) scale of Figure 3 is in units of "Sundeserts" (or typical 1-GW–baseload power plants running an average of 5000 h/year), not just for the 12 million refrigerators and freezers in California in l976, but for 150 million now running in the whole United States. By the time the 2001 standards take effect, we will have avoided needing 40 1-GW plants, selling 200 billion kWh to homes

(b)

SYMBOL	BRAND	PRICE	REF VOL	FZ VOL	TOT VOL	ENERGY USE kWh/MONTH	ANN. OPER. COST	LIFECYCLE COST	DEFROST
A	COLDSPOT 7655110	$365.	10.92	4.25	15.17	161.	$68.	$1717.	A
B	COLDSPOT 7657110	360.	12.30	4.77	17.07	169.	71.	1780.	A
C	COLDSPOT 7657010	360.	12.40	4.60	17.00	136.	57.	1502.	A
D	COLDSPOT 7657411	455.	12.31	4.75	17.06	175.	74.	1925.	A
E	COLDSPOT 7657210	385.	12.31	4.75	17.06	182.	76.	1914.	A
F	FRIGIDAIRE FPS-170TA	470.	12.26	4.75	17.01	144.	60.	1680.	A
G	GENERAL ELECTRIC TBF16VR	400.	11.28	4.30	15.58	139.	58.	1568.	A
H	GENERAL ELECTRIC TBF18ER	450.	12.92	4.65	17.57	155.	65.	1752.	A
I	GIBSON RT17F3	470.	12.40	4.60	17.00	136.	57.	1612.	A
J	KELVINATOR TSK170KN	488.	12.40	4.60	17.00	136.	57.	1630.	A
K	KELVINATOR TSK170KN	520.	12.40	4.60	17.00	136.	57.	1662.	A
L	PHILCO COLD GUARD RD 1667	510.	11.99	3.62	15.61	103.	43.	1375.	A
M	PHILCO COLD GUARD RD17G8	550.	12.37	4.65	17.02	104.	44.	1424.	A
N	PHILCO COLD GUARD RD17G7	510.	12.40	4.65	17.05	101.	42.	1358.	A
O	SIGNATURE UFO-1525-00	355.	10.44	4.74	15.18	146.	61.	1581.	A
P	SIGNATURE UFO-1715-20	385.	12.28	4.74	17.02	153.	64.	1670.	A
Q	SIGNATURE UFO-1625-00	450.	10.46	6.05	16.51	196.	82.	2096.	A
R	WESTINGHOUSE RT170R	470.	12.45	4.65	17.10	127	53.	1537.	A
S	WHIRLPOOL EAT17NK	400.	12.31	4.75	17.06	175.	74.	1870.	A
T	WHIRLPOOL EAT15PK	415.	10.86	4.19	15.05	160.	67.	1759.	A
U	WHIRLPOOL EAT171HK	440.	12.31	4.75	17.06	110.	46.	1364.	A
V	WHIRLPOOL EAT17PM	418.	12.46	4.75	17.21	175.	74.	1888.	A

M = MANUAL DEFROST, REFRIGERATOR AND FREEZER
P = AUTOMATIC DEFROST REFRIGERATOR, MANUAL DEFROST FREEZER
A = AUTOMATIC DEFROST, REFRIGERATOR AND FREEZER

NOTE: LIFECYCLE COST ASSUMES 20 YEAR LIFE.
ELECTRICITY IS ASSUMED TO COST 3.5 CENTS PER KW-HR AND FUEL INFLATION RATE (IN CONSTANT DOLLARS) CANCELS INTEREST RATE

Figure 2 (*Continued*)

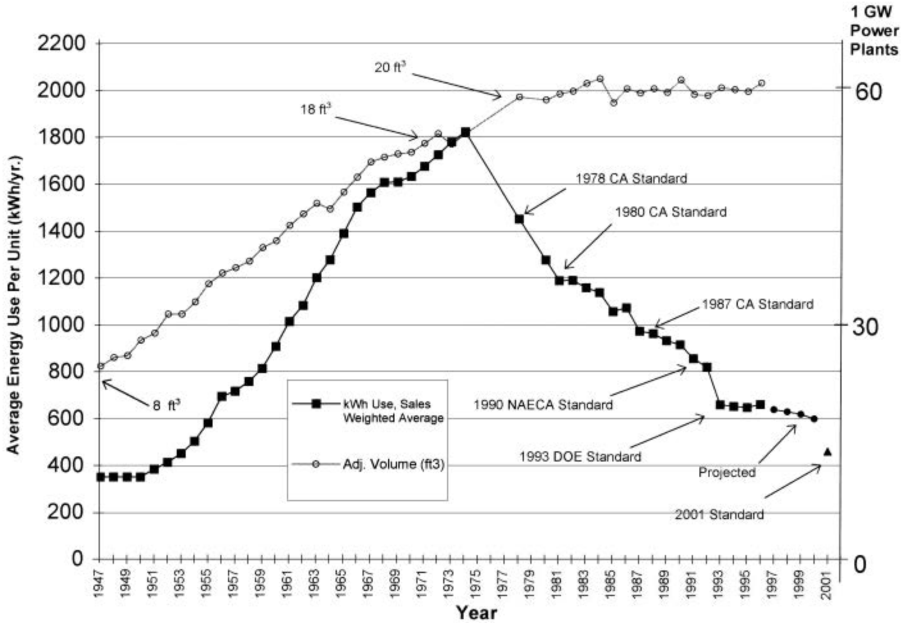

Figure 3 Electricity use by new U.S. refrigerators, 1947–2001. The *heavy line with dark squares* is the sales-weighted average annual kWh use of new refrigerators, unadjusted for increasing volume. The volume growth, from 8 cubic feet to 20, is the *lighter line with open circles*. The right-hand scale shows the number of large (1 GW) base-load (5000 hours/year) power plants required to power 150 million refrigerators + freezers, each with the kWh use on the left scale. The difference between 1974 (1800 kWh) and 2001 (450 kWh) is 1350 KwH. The eventual saving from 1350 kWh/year × 150 million units is 200 TWh/year, equivalent to 50 avoided 1 GW plants. At 8 cents/kWh, the avoided annual cost is $16 billion.

for total savings of $16 billion. The actual net savings to homeowners is only $10 billion–$11 billion, because we have to correct for the premium cost of the better refrigerators[2]. This cost premium cancels one-fifth to one-third of the savings, leaving a net of $10 billion–$13 billion/year.

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[2] The cost premium is usually related to the annual saving in terms of Simple Payback Time (SPT). Thus the original 1977 California standards (illustrated in Figure 3) saved about 500 kWh/year, worth $80/year, but there was a retail cost premium of about $80, so we say that the SPT was 1 year. But as equipment improves and electricity use drops, we find diminishing returns, so that going from the 1993 federal standard to that for 2001 saves only 200 kWh/year, worth $15/year, and the cost premium is again about $80, for an SPT of about 5 years. Averaged over the current (1982–1988) generation of refrigerators (which have a service life of ~16 years), the SPT is about 3 years. In summary, to save $1/year, we have to pay an annualized premium cost of $0.33. This estimate is conservative, because the actual cost of refrigerators has declined steadily in real dollars, with no visible spikes

Although I take up this point again in Table 1, *I want to compare the $16 billion annual electricity savings from just refrigerators with the entire $17 billion wholesale ("bus-bar") value of all U.S. nuclear electricity today*. The point I want to make here for end-use efficiency (versus additional central power plants) is that an efficient appliance saves electricity at your meter, priced at $0.08/kWh, whereas 1 kWh of new wholesale supply is worth only $0.02–$0.03 at the bus-bar. Thus even if electricity from some future wonderful new central power plant is "too cheap to meter," it still must be transmitted, distributed, and managed, for $0.05–$0.06/kWh.

CO_2-Avoided and 32 Million Equivalent Cars

Although I also take up CO_2 and cars when we get to Table 1, I point out here that a 1-GW power plant running the typical 5000 h/year emits annually CO_2 containing 0.8 million tons of carbon (MtC), equivalent to the emission from 0.8 million cars (at 25 mpg and 12,000 miles/year). So our 40 avoided plants correspond to avoiding 32 million cars.

In 1979, Mark Levine convinced DoE to engage LBNL to analyze planned federal appliance efficiency standards. I strongly supported this effort, but was somewhat less directly involved in it initially than I was in building energy performance standards. I hoped at the time that the appliance standards would become an important legacy of our activities, as it indeed did. But we were severely tested in this effort, first by the Reagan Administration's efforts to kill the standards by administrative means and later by the industry's lobbying of the 1992 Congress, led by Newt Gingrich. I strongly supported keeping this effort alive, and am thankful to this day for the critical role that Howard Geller and David Goldstein played in dealing with DoE and Congress in the face of much opposition in the early 1980s and again in the early 1990s. The extraordinary annual economic benefits of existing federal appliance standards—about $8 billion in l999, growing to $18 billion in 2015, and the avoidance in 1999 of 20 GW of power plant construction (14)—owes a great deal to the perseverance and leadership of Mark Levine and the analysis team of Jim McMahon, Isaac Turiel, and other key LBNL staff members.

Before moving on to discuss some national issues, I want to point out our good luck that the LBNL EEB program was located in the visionary state of California.

Pre-oil embargo concerns about nuclear electricity had created the CEC and helped elect Governor Jerry Brown, whose antinuclear policies kept the state from building too many power plants. This in turn created an incentive for energy efficiency that was lacking in most states. The majority of states had overestimated demand and built excess power plants, forcing them to sell their electricity to pay off their debt.

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near the years that new standards took effect. The estimate of 40 1-GW power plants is also conservative, because it assumes that refrigerator efficiency would have leveled off suddenly in l974, whereas conventional wisdom was that it would continue to grow 6% per year.

Before the October 17, 1973, embargo, the creation of the CEC had actually been vetoed by then-Governor Ronald Reagan, who reversed his position in light of the embargo and agreed to form the CEC. The CEC quickly implemented standards and services that convinced Californians that efficiency was a smart idea. In turn, LBNL and many UC Berkeley graduate students helped the CEC and the California utilities with technology and analysis. We at LBNL even trained PG&E's first residential auditors, their "house doctors." Synergistically, our morale and reputation were fueled by these mutually successful interactions.

1979–1986: PLAYING POLITICS

Forming the American Council for an Energy Efficient Economy

When Jimmy Carter was elected president in 1976, we hoped that he would emphasize efficient use of energy, but he didn't "get it," at least not at first. He did support solar tax credits, even if solar energy was not ready for prime time, but he offered little besides sweaters for "conservation." In 1979 he proposed an $88 billion "Energy Bank" to promote 2 Mbod of synthetic fuel and alternative gas, at an estimated cost of $38/barrel (bbl), wholesale. By the time this fuel was delivered to the consumer in the form of heating gas or gasoline, it would have cost >$50/bbl. This was in stark contrast with our estimates that the United States could save 9–12 Mbod (fivefold more) in buildings and cars alone, at ~$10/bbl (fivefold less). Efficiency advocates were simply too invisible to be noticed. That was when seven of us (15) decided to form a new, nonprofit think tank, the American Council for an Energy Efficient Economy, (ACEEE). In our frustration with a Democratic president, we did not foresee that, after the 1980 Ronald Reagan landslide election, we would be battling an even less-energy-sympathetic Republican administration for the following eight years.

ACEEE leadership was centered in Berkeley and Princeton, but we soon opened a Washington, DC, office. Robert Williams of Princeton and I served as Chairman and President, respectively, for the first 10 years, with notable leadership coming also from Carl Blumstein of UC Berkeley and Robert Socolow of Princeton. One of Williams' great contributions was to attract a graduate of Socolow's Center for Energy and Environmental Studies, Howard Geller, as ACEEE Director. Under Geller, ACEEE has become extraordinarily influential with officials at DoE, members of Congress, and other energy and environmental groups.

ACEEE conducts in-depth technical and policy assessments; advises governments and utilities; works collaboratively with businesses, standards agencies, and appliance manufacturers; publishes books, conference proceedings, and reports; organizes conferences and workshops, and informs consumers. ACEEE has an annual budget of $1.5 million–$2.0 million and, over the last 10 years, has sold $1.5 million worth of books, consumer guides, and reports. It is not a membership organization, but has an active mailing list of 25,000. I recommend their web site, http://aceee.org. I return to Geller and ACEEE shortly, when I discuss the "Alternative Conservation Budget."

SERI STUDY: "A NEW PROSPERITY—A SUSTAINABLE ENERGY FUTURE"

In 1979 Congressman Richard Ottinger, the champion of energy efficiency and renewable energy (who had preprinted the Princeton study in 1975) asked John Sawhill, Deputy Secretary of Energy under President Carter, to undertake the first in-depth solar/conservation study. Sawhill provided $1 million, and Director of the Solar Energy Research Institute Denis Hayes asked his deputy, Henry Kelly, a Harvard-trained physicist on leave from the Congressional Office of Technology Assessment, to lead the study along with Carl Gawell. They split the work into the standard four sectors: buildings, industry, transportation, and utilities, and asked me to lead the buildings study, as well as help steer the overall study. I in turn relied on help from David Goldstein and Alan Meier at LBNL and Jeffrey Harris, an economist/city planner at the CEC (now at LBNL's Washington, DC, office).

We were half through this work when President Reagan was elected in l980. There followed an exciting sequence of near-death moments for the study (under the 1980 Reagan transition team) and resurrection (under Ottinger). The skirmishing between November 1980 and March 1981 is summarized below.

The buildings chapter of the study contains 175 pages of conservation/solar-supply curves, which show that the United States was planning to build ~35-GW more electrical capacity than needed. This can be compared with the 250 GW then supplying buildings. The industry chapter estimates forthcoming efficiency gains that would "unload" another 15 GW, compared with 150 GW then supplying industry.

So our message to the U.S. utility industry was, "Be wary before you invest prematurely in 50 GW of new plants (at $1 billion–$2 billion each), the need for which is many years off." We had come to this conclusion by November 1980, when Ronald Reagan was elected. His transition team was horrified by our draft report, and they threatened each of us that we would be fired if we even sent drafts out for review. For emphasis they fired Denis Hayes, after which Henry Kelly promptly resigned, returned to the Office of Technology Assessment, and strategized with Ottinger.

Ottinger held a hearing on the report, in which DoE representatives testified that our analysis was flawed. Ottinger then reproduced our report as a committee print, which brought it into the public domain. Brick House Press then published it (16). By about 1985 it became evident that the capacity of U.S. power plants built too early was indeed at least 50 GW. These plants remain a problem to this day. Their output tends to be uncompetitive in a deregulated generation market, and their expense, called stranded assets, is a serious problem in utility restructuring.

Testifying to Preserve Conservation and Renewable Energy

Reagan took office in January 1981, and he soon produced a DoE budget that "zeroed out" the Office of Conservation and Renewable Energy. Committees of the Democratic House of Representatives were ready to hold hearings to protect conservation, but who would be allowed to testify? DoE officials obviously could not contradict the administration, and DoE dissuaded testimony by staff of its National Laboratories. I was not on the DoE payroll, although I directed the Center for Building Science at LBNL, so I could testify as a professor of physics. And three courageous scientists at Oak Ridge National Laboratory chose to testify whenever invited. They were Roger Carlsmith, William Fulkerson, and Eric Hirst. There may have been others, but these are the three I ran into frequently.

My division director at LBNL was cautious, so we agreed that, whenever I flew to Washington to testify, I would take vacation and pay my own expenses. Fortunately, that spring People's Express airline offered $198 round trips from Oakland to Baltimore, and I made half a dozen trips. I always insisted on being allowed to use an overhead projector to show transparencies loaded with data on energy efficiency success stories, much like Figures 1–3 of this paper. And of course I showed high-frequency ballasts, CFLs, low-E windows, and other technologies developed by our sister national laboratories. There were no serious repercussions. DoE called my laboratory director once to complain that I was in Washington again, but he explained that I had been formally invited to testify, and he felt that was my duty. Bill Fulkerson was admonished once by the DoE Assistant Secretary for Conservation and Renewable Energy, but Bill also had been officially invited, and the Assistant Secretary backed down.

When the dust settled after a frantic spring and summer, the conservation budget was down to about one-third of the previous Carter budget, but it was not zero. We had demonstrated, with the help of a Democratic House and the goodwill of a Republican Senate, that it was possible to stand up to the Reagan cuts and retain the best of worthy programs. The director of LBNL grew bolder, creating an Office of Planning and Development to communicate our cause to Congress. He also approved payment for my expenses when I was invited to testify, although, through l988, I continued to identify myself only as "Professor of Physics."

OPEC Collapses and the "Alternative Conservation Budget"

In late 1985 the OPEC cartel collapsed, causing oil prices to crash from $50/bbl to $25/bbl (in 1998 dollars). My view was that efficiency gains had made a significant contribution to reducing the demand that fed OPEC's near monopoly. Ronald Reagan and Margaret Thatcher proclaimed that the energy crisis was over, and the Reagan administration again moved to eliminate DoE's Office of Conservation and Renewable Energy.

After considerable discussion with our colleagues, Howard Geller (Director of ACEEE) and I decided that the best response was to craft an alternative budget for fiscal year (FY) 1987 (FY 87) and to distribute it to conservation supporters in Congress. We met with colleagues from environmental groups and congressional staff to craft a complete budget request for conservation. We conducted informal interviews with the DoE Deputy Assistant Secretaries for Buildings, Industry, and Transportation, and we received recommendations for changes. We printed a budget in the traditional government format, but labeled it "Alternative Conservation Budget, submitted by the Energy Conservation Coalition," and distributed it to friendly Congressmen, particularly those on the appropriations committees. It must have helped, because the FY 87 Conservation appropriation was only a little less than for FY 86. This strategy worked so well we decided to follow it throughout Reagan's administration. Indeed the budget remained stable and increased after George Bush was elected in 1988.

American Physical Society's Award for Physics in the Public Interest

On April 26, 1986, I received the American Physical Society's Leo Szilard Award for Physics in the Public Interest. I was particularly pleased for two reasons. First, previous recipients included many great physicists, Richard Garwin, Hans Bethe, and Andrei Sakharov among them. My LBNL colleague Tony Nero was to receive it in 1989. Second, I had known Szilard at Chicago and had helped him to organize the Council for a Livable World.

I wrote an activist acceptance speech, detailing the improvements in efficiency that helped defeat OPEC, including the benefits of efficiency even when prices were low, and the need to change utility rules to make it more profitable for utilities to sell efficiency than to sell electricity. With a few phone calls I got some reporters to the prespeech dinner, but while there one of them got an urgent phone call about an accident at the nuclear power station at Chernobyl, near Kiev. That totally ended my press coverage. But perhaps Chernobyl illustrated the environmental costs of both nuclear and coal-based electricity and hence made an indirect case for efficient use of electricity.

1982: SUCCESS STORIES

Compiling the Economic Benefits of New, Efficient Products

I had realized in 1981 that for at least the next 4 years I would be testifying regularly, so Jeff Harris, Mark Levine, and I began to prepare and update detailed tables on the economic successes of projects at the DoE national laboratories. The best documentation is in the 1987 *Annual Review of Energy* (17), but because this is an autobiography about developments with which I have been closely associated, I reproduce instead Table 1, a shorter version of the main table in the *Annual Review of Energy*, Vol. 12, which focuses on LBNL and was updated to l994 for presentation at my Carnot prize award in January l994 (which I discuss shortly).

TABLE 1 Economics of Three New Energy Efficiency Technologies and Appliance Standards. (A 1994 update of Tables 1 & 4 of Ref. 17)

	Research & Development				**Standards**
	High frequency ballasts vs core coil ballasts	**Compact fluorescent lamps (1) vs incadescents**	**Low-E (R-4) windows vs. double glazed windows per small window (10 ft^2)**	**Total**	**Refrigerators and freezers ‘76 base case vs ‘92 CA Stds.**
1. Unit cost premium(2)					
a. Wholesale	$8	$5	$10		$100
b. Retail	($12)	($10)	($20)		($170)
2. Characteristics					
a. % energy saved	33%	75%	50%		60%
b. Useful life(3)	10 years	3 years	20 years		20 years
c. Simple payback time (SPT)(4)	0.8 year	0.5 year	2.9 years		1.3 year
3. Unit lifetime savings					
a. Gross energy	1330 kWh	440 kWh	10 MBtu		20,720 kWh
b. Gross $(5)	$100	$33	$70		$1550
c. Net $ [3b−1a]	$92	$28	$60(6)		$1450
d. Gross equivalent gallons(7)	106	35	69		1660
e. Miles in 25 mpg car	2660	880	1720		41,440
4. Savings 1985–1993					
a. 1993 sales	25 M	42 M	20 M		6 M
b. Sales 1985 through 1993	54 M	147 M	96 M		50 M
c. Cum. net savings [4b × 3c]	$5.0 B	$4.1 B	$5.8 B	$15B/8yr	$73 B

5. Savings at saturation(8)					
a. U.S. units	600 M	750 M	1400 M		125 M
b. U.S. annual sales	60 M	250 M	70 M		6 M
c. Annual energy savings [5b × 3a]	80 BkWh	110 BkWh	0.3 Mbod		130 BkWh
d. Annual net $ savings [5b × 3c](9)	$6 B	$7 B	$4 B	$17 B/yr	$9 B
e. Equivalent power plants(10)	16 “plants”	22 “plants”		38	26 “plants”
f. Equivalent offshore platforms(10)	45 “platforms”	60 “platforms”	35 “platforms”	140	70 “platforms”
g. Autos offset(11)	16 M	22 M	12 M	50 M	26 M
6. Project benefits					
a. Advance in commercialization	5 years	5 years	5 years		5 years
b. Net project savings [6a × 5d]	$28 B	$35 B	$21 B	$84 B	$45 B
7. Cost of DOE for R&D	$3M	$0(12)	$3M	$6M	$2M
8. Benefits/R&D cost [6b/7]	9,000:1		7000:1	14,000:1	23,000:1

From: “The Role of Federal Research and Development in Advancing Energy Efficiency,” Statement of Arthur H. Rosenfeld before James H. Scheuer, Chairman, Subcommittee on Environment, Committee on Science, Space, and Technology, U.S. House of Representatives, April 1991. Available from Center for Building Science, LBL, (510) 486–4834.

(1) Calculations for CFLs based on one 16-watt CFL replacing thirteen 60-watt incandescents burning about 3300 hours/year, assuming that a CFL costs $9 wholesale, or $5 more than the wholesale cost of thirteen incandescents. For retail we take a lamp cost of $18.

(2) Unit cost premium is the difference between one unit of the more efficient product (e.g. one high-frequency ballast) and one unit of the existing product (e.g. one core-coil ballast).

(3) Useful life is the assumed calendar life of the product (as opposed to operating life such as burning hours for a lamp) under normal operating conditions. A commercial use is assumed for CFLs, but labor savings are not included.

(4) SPT is the number of years required to recoup the initial incremental investment in an energy-efficient measure through the resulting reduction in energy bills.

(5) Assuming price of 7.5¢/kWh for commercial sector electricity and a retail natural gas price of $7/MBtu (70¢/therm).

(6) For hot weather applications where low-E windows substantially reduce cooling loads, air conditioners in new buildings can be down-sized, saving more than the initial cost of the low-E window.

(7) Assuming marginal electricity comes from oil or gas at 11,600 BTU/kWh, thermally equivalent to 0.08 gallons of gasoline.

(8) Saturation is 100% of the market for all products excepts CFLs. It is unrealistic to assume that CFLs will replace infrequently used incandescents; thus, we have defined market saturation for CFLs as 50% of current energy used by incandescents.

(9) Net annual savings are in 1990 dollars, uncorrected for growth in building stock, changes in real energy costs, or discounted future values. See Ref. 17, Table 1. Note that we attribute energy saved by the product over its useful life to the year it gets sold.

(10) One 1000 MW baseload power plant supplying about 5 BkWh/year $= 57 \times 10^{12}$ Btu $= 0.1\times$ Alaskan Arctic National Wildlife Refuge (ANWR). One offshore oil platform $= 10,000$ bod. To convert “plants” burning natural gas to “platforms”: 1 “plant” $= 27,000$ bod $= 2.7$ “platforms.” ANWR, at 0.3 Mbod, is equivalent to about 30 “platforms.”

(11) 1 automobile (400 gallons/year) generates 1 tonne carbon per year. Thus electricity and gas savings can be converted to “autos offset” (1000 MW power plant is equivalent to 1 M autos).

(12) Descended from high-frequency ballasts (only DOE assistance was in testing).

I would prefer to use a later version because the savings estimates have doubled, and there are indeed excellent, but lengthy, later versions by Evan Mills[3], but they no longer fit on one page. Instead I shall discuss Table 1 and then explain why the annual net savings have grown from $17 billion to $30 billion.

The columns of Table 1 correspond to three technologies and one appliance standard. High-frequency ballasts for fluorescent lamps and low-E windows were developed in the EEB program at LBNL. CFLs were certainly not developed in EEB, but as I mentioned earlier, we know that our development of high-frequency ballasts advanced the decision of Philips and others to produce CFLs. I have included the first of the standards we developed (i.e. for refrigerators), which has shown dramatic energy savings. LBNL does only the engineering economic analysis for appliance standards; the R&D is done entirely by the manufacturers, with some assistance from Oak Ridge National Laboratory.

Rows 1 through 3c of Table 1 show the economics for a single unit (e.g. a ballast, a CFL, or a small window). Note the short SPTs in row 2c: <1 year for a better ballast or a CFL, 1.3 years for a l992 refrigerator compared with a 1974 model shown in Figure 3, and so on.

Because of the threat of greenhouse warming, we must contemplate a world in which the use of fossil fuel is constrained. If we save a gallon of gas today, perhaps our children will have it to burn when they need it. So row 3d shows equivalent gallons saved, and 3e shows the energy service "stockpiled," for example, miles driven in the family car at 25 mpg. Thus consider a refrigerator that conforms to the l992 standard of 650 kWh/year as compared with 1800 kWh/year back in 1974. Over the 16-year life of the refrigerator, that difference saves 1600 equivalent gallons—enough to run the family car for 3.5 years (i.e. to drive 41,000 miles).

Comparison of rows 4a and 5b shows that the three technologies already have significant market shares (typically 30% and growing), so they will likely saturate the market (row 5b) unless they lose out to some even more efficient competitor. So the net annual savings at saturation, row 5d, is plausible: $17 billion from the three technologies advanced by LBNL and tens of billions of dollars from many different standards.

When the savings are electrical, row 5c uses units of billions of kilowatt-hours (BkWh), but BkWh are unfamiliar to most readers, so we note that the average large plant (1 GW, like Chernobyl, Three Mile Island, or a big coal-burning plant) sells $\sim$5 BkWh/year. We use this fact to convert a drab 190 BkWh saved by ballasts and CFLs to the total annual output of 38 huge power plants.

When the savings are natural gas, row 5c uses equivalent Mbod. Thus, compared with traditional double-glazing in homes, low-E windows will save 0.3 Mbod. Although 0.3 Mbod equals the anticipated yield of gas from the Arctic National Wildlife Refuge, it doesn't relate to anything as familiar as cars. So on row 5g we

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[3] Mills, who succeeded me at the Center for Building Sciences when I left for DoE in 1994, has written "From the Lab to the Marketplace," a valuable 42-page amplification of the ideas above (18).

show that the 0.3 Mbod of natural gas saved corresponds to a steady supply of fuel sufficient to run 12 million cars!

Finally we can add *fuel* conserved at electric power plants to *gas* saved by low-E windows to get a total for all three technology columns of Table 1. This totals an impressive 50 million cars (one-third of U.S. cars), and also corresponds to 50 MtC in avoided CO_2. To comply with the Kyoto greenhouse gas protocol, the United States must conserve domestically ∼400 MtC/year, so 50 MtC is a 12% step.

DOE-2 to Beat Current Standards, and Cool Communities In 1995, LBNL polled architecture/engineering firms about their use of DOE-2, not just to comply with standards, but to exceed them. The poll showed that 15% of new commercial space is designed with DOE-2 and that its users typically beat applicable standards by 22%. Improved practices in just 15% of new space today soon become standard practice. So we assume that, by 2010 or 2020, half of U.S. commercial space will have been designed or retrofitted to save 20% in energy use. This gives an overall savings of 10% of the annual commercial building energy bill of $105 billion, i.e. $10 billion/year. This poll and savings estimate came after Table 1 was prepared. Nor does Table 1 include a predicted $4 billion/year to come from reduced air conditioning in "Cool Communities," in which buildings have white roofs, shade trees, and lighter colored pavement (see the later section dealing with "Cooling Summer Heat Islands").

Thus, my updated 1990 estimate for the net annual savings from these five LBNL-initiated technologies or tools is not $17 billion but $30 billion. And there are more recent successes in the pipeline, such as Mark Modera's AeroSeal to seal leaks in ducts ($3 billion/year) and Helmut Feustel's nonturbulent fume hoods for chemistry laboratories ($0.5 billion/year). (These two successes are discussed below in the section entitled, "Putting It All Together at LBNL.")

For drama, I like to compare the annual $30 billion efficiency savings, initiated by a single center at LBNL, with the smaller $13-billion–$20-billion wholesale value of all electricity produced by all U.S. nuclear power plants.[4] Everyone has heard of nuclear power, and most view it as a national asset. Few have heard of LBNL's Center for Building Science or would consider it a comparable asset. This is an enduring and difficult problem. It's human nature to be proud of a large visible investment, like a power plant or even an array of photovoltaic (PV) cells, and to ignore many small purchases, usually invisible, like ballasts, lamps, windows, and

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[4] In 1997 sales of nuclear electricity were 666 BkWh, and "bus-bar" (wholesale) prices averaged $0.02–$0.03/kWh. For the first 6 summer 1998 months of operation of the California Power Exchange, the average market clearing price was $0.025/kWh. Because nuclear plants cannot reduce their output to follow load, they must sell at night when the price is very low. Hence their average price on the California PX would be <$0.025/kWh. A $0.025 bus-bar price is only one-fifth of the 1998 PG&E residential rate (Tier 1 = $0.116, Tier 2 = $0.132). By 2000, these rates should drop about $0.02 as "stranded assets" are paid off, but residential prices will still run about $0.10/kWh. So there will be an ∼4:1 cost advantage to shedding 1 kWh at the meter as opposed to supplying the kWh to the bus-bar.

refrigerators. That makes it hard to convince most people that, for any given year in the foreseeable future, it will be cheaper and cleaner to improve efficiency by a few percent than to increase supply by the same amount. Give a congressman the choice of funding energy supply or energy efficiency, and he will go for supply almost every time.

Benefit/Cost Ratio of Department of Energy-Funded Research and Development

In row 6 of Table 1, we translate the savings of Table 1 into the language of benefit/cost—specifically the *societal* benefit achieved for a certain *government* cost.

My view is that science grows and technology improves inexorably and that, if there had been no OPEC and no DoE, eventually somewhere (probably abroad) somebody would have developed each of the technologies of Table 1 and a computer program like DOE-2. However, LBNL clearly advanced the commercialization of these technologies and tools by at least a year. In Table 1, line 6a, I actually estimated 5 years. We can then calculate the remarkable benefits and benefit/cost ratios in row 8 for each column of Table 1. But these amazing numbers immediately raise the question “But what about the failures?”

So now we switch to the “portfolio” approach to benefit/cost analysis for all R&D at LBNL. Specifically, we calculate the benefit by assuming that projects initiated at LBNL have brought about the happy day when our society is saving $17 billion/year in energy 5 years earlier than might otherwise have happened, for a total benefit of $84 billion over 5 years. Let me add a small fraction of the later successes and round off this net benefit to $100 billion.

The cost to the federal government of the entire LBNL program (successes plus failures) was ∼$10 million annually for each of the 20 years before 1994, or $0.2 billion total. The benefit/cost ratio is then $100 billion/$0.2 billion or 500/1. If the reader is more conservative and prefers to think of advancing technology by only 1 year, we still get 100/1. I conclude that Congress and DoE underinvest in the profitable R&D that has been carried out at our national laboratories.

1982–1993: PUTTING IT ALL TOGETHER AT LAWRENCE BERKELEY NATIONAL LABORATORY

Conservation Supply Curves

Back in 1977, Roger Sant, my friend who invented the phrase “least-cost energy services,” and who founded Applied Energy Services, suggested that the best metric for an energy efficiency investment was the “cost of conserved energy” (CCE) or the “cost of conserved electricity,” or, in these days of global warming, the “cost of conserved carbon.”

At LBNL we promptly took up CCE for all of our analyses. This led to “conservation supply curves,” which are now in general use (19). Two of my ERG graduate students, Alan Meier and Janice Wright, developed conservation supply curves in their theses, and, in 1983, we finally got around to writing a book about them (20). If you want to pick up only one interesting analytic idea about the economics of energy efficiency, I recommend Box 1 and our book. Or you can go to the Internet. The National Academy of Sciences study, *Policy Implications of Greenhouse Warming* (21), is on the web and has an appendix on CCE and conservation supply curves. Amory Lovins uses CCE in many papers and books, for example, Von Weizsacker & Lovins (22, 23).

Box 1: Cost of Conserved Energy and Supply Curves of Conserved Energy

In the mid 1970s, many researchers proposed substituting risky or expensive energy supplies with affordable conservation. One of the drawbacks in these discussions was their inability to easily compare both the economics and the scale of conservation with new energy supplies. Energy conservation is typically a diffuse resource and results in reducing costs, whereas new energy supplies tend to be huge, lumpy, and expensive. The solution was a new investment metric, "the cost of conserved energy," and bookkeeping techniques to create the "supply curve of conserved energy."

Most conservation measures require an initial investment that, in turn, creates a stream of energy savings for the lifetime of the measure. The *cost of conserved energy* (CCE) is calculated by dividing the annualized payment by the annual energy savings. Thus

$$\text{CCE} = [\text{annualized investment cost}]/[\text{annual energy savings}].$$

The annualized cost corresponds to equal ("levelized") repayment, including interest, of the investment, with the payments extending over its useful life. The energy savings can be electricity (measured in kW) or gas (measured in MBtu), or even CO_2 (MtC). For example, if the measure saves electricity, then the CCE will be in units of $/kWh. A measure is cost effective if its CCE is less than the price of the energy that it displaces. This permits easy comparison of the costs of supplying energy, such as from a new power plant, a new oil field, or even a wind farm. Furthermore, the cost of conserved energy is "portable"; that is, it does not depend on local prices of the displaced energy. By contrast, the price of displaced electricity may vary from a few cents per kilowatt hour in Oregon to $0.15/kWh in New York or $0.25/kWh in Japan.

Conservation steps can be "stacked," cheapest first, in order of increasing CCE to form a staircase called a "supply curve of conserved energy." Each step on the supply curve represents a conservation measure, whose width is its energy savings and height is its CCE. A "micro" conservation supply curve displays the cumulative impact of efficiency improvements to a single refrigerator, house, or cement factory. A "macro" curve then addresses the problems of aggregation. In the macro case, each step represents the measure applied to millions of refrigerators, houses, or autos. Certain energy and cost bookkeeping rules were outlined by Meier et al (20) to ensure consistency and to avoid double-counting and to understand the energy and cost consequences of implementing measures out of order. The resulting supply curves of conserved energy provide a simple way to compare new energy supply technologies with the contribution of millions of individual energy-saving actions. Most of the conservation supply curves of the late 1970s and early 1980s demonstrated huge reserves of conserved energy at CCEs of $<$\$0.05/kWh. Many curves turned up sharply at higher CCEs giving the false impression that conservation was a limited resource. In fact this inflection was not a consequence of diminished conservation, but simply reflected the failure of anyone to investigate and market cost-effective energy-saving measures above \$0.06/kWh.

Figure 4 is adapted from Figure 3–14 of Meier et al (20). It is a “macro” curve showing the CCE for six cost-effective residential lighting steps plotted against the electricity saved in California for each step (measured in gigawatt hours per year). One can see at a glance that two more steps (7 and 8) are not economic.

Dollars Saved The annual dollars saved by, say, step 2 (“fluorescent kitchen lighting”) are of course the area between step 2 and the “price” line, that is, a savings of \$0.05/kWh × 600 GWh = \$30 million. Thus the total societal annual saving for the first six steps is just to the entire shaded area between the steps and the price line, in this case ∼\$60 million.

Downsizing The Hvac System Figure 4 is too simple to illustrate an interesting issue in plotting conservation supply curves. Consider a step representing the choice of roof color (white vs traditional) for each 1000 ft^2 of roof (or reroof) for a home in Los Angeles. One thousand ft^2 shingle roof ordered in white will cost \$15 extra (once every 20 years), but it will stay cooler in midafternoon. Using Burbank weather, the DoE-2 program shows that each summer it will save about 500 kWh in air conditioning. One might say, wrongly, that it’s CCE was a small positive quantity, ∼\$0.003/kWh, which is much less than the price of the avoided electricity, so, although a cool roof is a wise investment, it’s still an investment with a small positive first cost. That’s wrong, or at least it’s the least interesting issue, because we have so far forgotten that the cool roof reduces peak cooling load by ∼0.2 kW and thus permits the homeowner to downsize the chiller by ∼0.2 kW of electricity, corresponding to 0.2 “tons” of air-conditioning capacity. This then saves ∼\$120 on the first cost of the air conditioner (or the next air conditioner if we are replacing an existing roof). Thus the correct (combined) CCE is not +\$0.003/kWh, but is negative at −\$0.02/kWh. Thus,

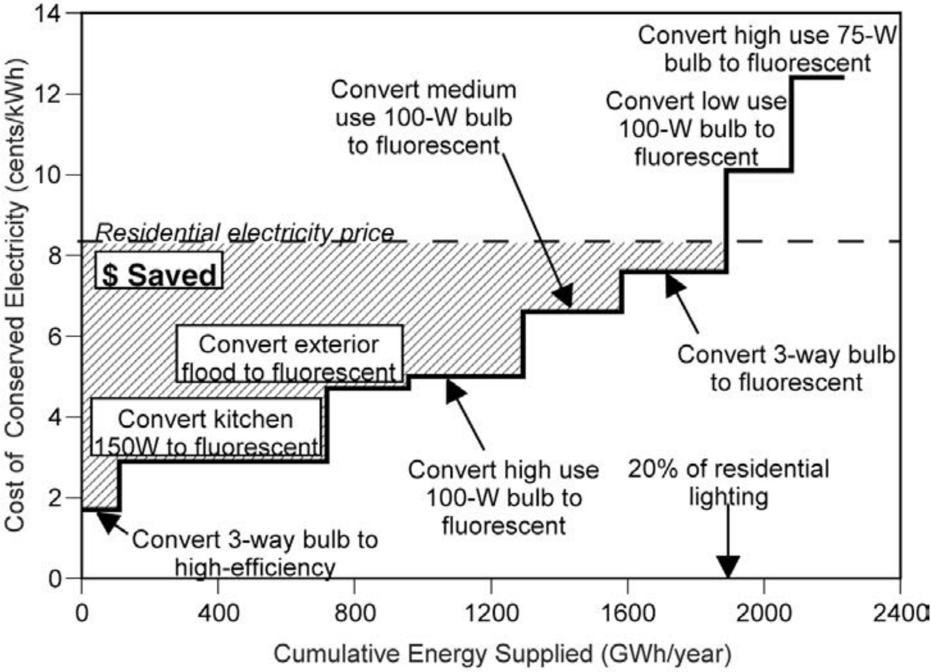

Figure 4 Macro supply curve of conserved residential lighting in California. Although the last cost-effective step costs 7.6 cents/kWh, the average CCE is only 4.8 c/kWh. This is adapted from Figures 3–12 of Meier et al (20).

in the words of Amory Lovins, this is not just a free lunch, but one they prepay you to eat. Lovins prefers to describe this as a two-step process, first one with a positive CCE ("select white color") and then a second step with a negative CCE ("downsize air conditioner"). He calls this "tunneling through the cost barrier" and ending up saving money. It doesn't matter whether we talk about one combined step or two linked steps; it does matter that we account for downsizing HVAC, which many inexperienced analysts fail to do. Perhaps we can fix DOE-2 and it successor to do this accounting automatically.

Forming the Center for Building Science

I insert this brief section mainly to explain why I change names for the LBNL Buildings Program.

By 1985, despite budgetary problems in Washington, the EEB Program had grown to half the size of our whole division, which also contained Mark Levine's Energy Analysis Program and, among others, a solar program. So we formed the Center for Building Science (CBS) with four programs: windows and lighting, indoor environment, energy analysis, and building systems. As director, my job was to coordinate research among the programs and to represent them to the outside world, including Washington, DC, and the UC campus.

Forming the California Institute for Energy Efficiency

Before the oil price crash of l985, EEB/CBS had a synergistic relation with the California utilities. They advised us on R&D priorities, we developed technologies, and they marketed them through Demand Side Management (DSM) programs to improve customers' use of energy. But with the collapse of OPEC, it appeared that DoE's support would dwindle to "generic, long-range, high-risk research," and we foresaw that the utilities would have to pay for our previously free services. With my long-time colleagues Carl Blumstein of the UC Energy Institute, Don Grether, deputy director of our Applied Science Division at LBNL, and Jeff Harris and Mark Levine, we proposed a new UC California Institute for Energy Efficiency (CIEE), funded by a utility contribution of 1/5000th of their revenues, which would provide $5 million/year. The utilities were skeptical, but the California Public Utilities Commission decided that a rate increase of 1/5000 was a good public investment, and we finally formed CIEE in l988. I headed it during the search for the director, James Cole, who has since led CIEE to sponsor multimillion dollar, multiyear projects spanning several institutions (e.g. intercampus institutions and often LBNL) on the scale of successful national laboratory or industrial R&D projects.

One of CIEE's success stories was to support Mark Modera of LBNL, who studied leaks from air ducts running through unconditioned spaces in the attics, crawlspaces, and basements of homes. He showed that on average about one-fourth of the hot or cold air leaked out, doing no good, and in fact doing some harm. (Blowing cold air out of a duct in the *attic* creates a partial vacuum in the *house*, which sucks in warm outside air.) To be more specific, a 4-kW air-conditioning unit with typical dust losses typically delivered only 3 kW of cooling. Multiplied by 20 million centrally air-conditioned homes (and including a "coincidence factor"), that's a waste of 10 GW, corresponding to ~$1 million/h on a hot afternoon, $1 billion for a whole summer, and about $2 billion more in excess heating fuel in a winter. With CIEE help, Modera developed the aerosol technique, described below, which quickly seals all leaks up to the size of a dime. This has led to a new private company, Aeroseal, Inc. (http://www.aeroseal.com). Next, CIEE is attacking duct leaks in commercial buildings.

Modera's idea was to pressurize ductwork with a fog of small sealant particles. By temporarily blocking off the registers and the HVAC equipment, he forces the air to leave the ducts only via the leaks. But there it has to make sharp turns, which the heavy suspended particles cannot follow; so they crash into the sides of the leak, and stick there.

He carefully adjusts the particle size—too heavy and they settle out, too light and they can follow the air out of the leak. The particles must also solidify before they reach the leak; this helps them bridge a gap quickly (24).

Another CIEE success involves the hoods used to contain and remove fumes from research laboratories and high-technology manufacturing facilities. Annually, each unit typically exhausts \$500–\$1000 worth of heated or cooled indoor air. Helmut Feustel of LBNL invented the idea below to safely reduce the exhaust rate to one-fourth, saving \$375–\$750 per new unit (and there are about a million fume hoods in the United States). The cost premium for a new hood is $\sim$\$1000, but the building air conditioner can be downsized and that saves $>$\$1000, so the net first cost is negative. CIEE and DoE supported Feustel to build, test, and optimize a prototype. Now LBNL is looking for a licensee.

Feustel's idea stems from an earlier observation by his colleague Ashok Gadgil that, when air rushes past the body of a worker at a fume hood (or a spray booth), it forms a turbulent eddy just downstream of his body, that is, between the worker and the work. This turbulent eddy tends to blow fumes back out of the hood opening, so the hood air intake has to be speeded up to compensate. Feustel's simple solution was to introduce less air, but smoothly, from inside the hood. The air to be exhausted can then be reduced to one quarter, and only $\sim$10% of that is drawn from outside the hood, past the worker, so turbulence, if any, is reduced to 1/40 (25).

Urban Heat Islands and Cool Communities

Back in 1985 my LBNL colleagues Hashem Akbari, Haider Taha, and I realized that hot, dark roofs and pavements were half of the cause of summer urban heat islands, which in turn increased the smog (ozone, O_3) in Los Angeles and many other large cities. We already disliked hot roofs because they raise air-conditioning demand by 20%, and we had long been trying to get building energy codes to give credit for cool roofs. Today, 14 years later, the U.S. Environmental Protection Agency (EPA) is indeed preparing to recommend cool surfaces and shade trees as preferred ozone compliance measures for many of the cities that will exceed the 1998 air quality standards.

Throughout the world, cities are summer heat islands. They are 3–10°F hotter than their surroundings, and as cities grow, they typically add 1°F each decade. A few percent of this heating is manmade (e.g. from cars or air conditioners), but overwhelmingly it comes from two roughly comparable sources: air blows over dark-colored roofs and pavements and warms by conduction, and trees, which cool the air by evaporation, are disappearing.

We started the Heat Islands Research Project at LBNL in 1985 to investigate a strategy for switching to cooler roofs and pavements and planting trees on the west side of buildings. We modeled individual buildings and showed air-conditioning savings of 20% from cooler roofs plus similar savings from shade trees. We confirmed these results on real buildings, using white paint and with trees in large containers. Next we modified the urban solar reflectivity in the Los Angeles meteorologic model, the cooling impacts for Los Angeles and found a summer 3 PM temperature reduction ΔT of 6°F. (To our surprise, the then current official Los Angeles meteorological model did not even address spacial dependence of solar reflectivity!) Finally we fed ΔT into the urban airshed smog model, which already took into account the steep temperature dependence of ozone formation. The airshed model estimated a reduction in population-weighted O_3 of $>10\%$!

This saving of electricity and avoidance of smog costs little. At the time of roof replacement, a new white roof costs little more than a dark one, but will last longer. Pavements can be cooled two different ways: retain asphalt as the binder, but use white aggregate that will show as the dark asphalt wears down to the light aggregate color, or "white top" with concrete, which is stronger and actually cheaper in the long run. In Los Angeles, trees shading a lawn actually save water because the trees, after a few years of watering, survive on natural ground water, whereas the cooler lawn requires less municipal water.

For Los Angeles, estimated annual savings are impressive—over half a billion dollars—from

1. Direct air-conditioning savings to the buildings with cooler roofs and shade trees: $100 million.
2. Indirect air-conditioning savings to all buildings because Los Angeles' temperature is $\leq 6°$F cooler: $70 million.
3. Health and lost work time saved because O_3 is reduced 12%: $360 million.

This 12% reduction in ozone is comparable with that achieved by switching to cleaner-burning gasoline, which costs drivers an extra $1 million daily. It is fivefold the reduction predicted for 10% electric cars. If we assume each one of a million electric cars costs an extra $5000 ($500/year for each car), then 10% electric cars will cost $500 million/year. These costs are expensive compared with the low costs for Cool Communities!

For a decade decision-makers in Los Angeles regarded Cool Communities as "too good to be true." This started changing about 1996 amid the following events and activities.

- Southern California Edison, the Los Angeles basin's largest utility, independently verified the LBNL analysis.
- EPA plans to add cool surfaces and shade trees to its list of ozone control measures acceptable for State Implementation Plans for the 114 urban areas that will soon be out of compliance with ozone standards. Accordingly, California South Coast Air Quality Management District has added cool roofs and shade trees to its list of control measures.
- South Coast Air Quality Management District has gone even farther. Since 1994 it has operated a "cap-and-trade" smog offset market called RECLAIM (REgional CLean Air Incentive Market) which trades offset credits at about $1000/tonne of NO_x (precursor or feedstock of smog). Now South Coast Air Quality Management District has accepted the concept of direct reduction of smog (O_3) by temperature as equivalent to a reduction in NO_x.

- U.S. standards for new building energy efficiency, such as ashrae series 90, are being updated to credit the solar reflective properties of the roof.

So after a decade with little attention paid to cool roofs and shade trees by the air quality community, the persistence of the Berkeley group has borne fruit; the Cool Communities Program is recognized as sound environmental science.

The national savings to be realized are great. Because roofs are replaced only every 10–20 years and trees take 10 years to mature, the full savings from Cool Communities will be delayed until ∼2015. But by then we may be able to eliminate heat islands throughout the United States, save air-conditioning costs of $4 billion/year, and avoid annual CO_2 emissions of 7 MtC. U.S.-wide health gains have not yet been modeled, but we do have some sad but significant statistics. When Chicago suffered 700 heat-related deaths in l995, it turned out that most of the fatalities were frail, elderly people who lived on the top floors of badly ventilated apartment buildings with nonfunctioning air conditioning (the power failed) and with dark roofs. Cooler buildings, under white roofs, in cooler communities will also protect the elderly and infirm during heat storms and thus prevent tragedies like the Chicago heat storm.

For more details, see our paper in *MIT Technology Review* (26), which is also available on the Web (http://EETD.LBL.gov/Heatisland).

What about heat islands and ozone outside the United States? To outmatch Los Angeles and Phoenix, there are of course scores of hot, polluted megacities abroad. One of my goals is to help them introduce the use of cool pavements, shade trees, and cool roofs, particularly cool tiles, to reduce smog. A first step could be for DoE/EPA to invite city planners from abroad to study at LBNL and to work for some months on “cool community” projects in the United States.

When I moved to Washington, DC, in l994, my new boss, DoE Assistant Secretary Christine Ervin, and I agreed that I would continue as national spokesman for Cool Communities and start collaborations with Los Angeles, EPA, National Aeronautics and Space Administration, ASHRAE, and the roofing industry. As I have already noted above, we have indeed set up these collaborations. EPA now has a Heat Island Reduction Project, and cosponsors Energy Star Roofs with DoE. We have even cultivated and sponsored a Cool Roof Rating Council, an industry group that will test, rate, and label cool roofs. But we still excite far less interest than the President’s Million Solar Roofs initiative.

Solar Collectors on Hot Roofs—a Missed Opportunity

In 1997 the Administration, with the backing of the solar industry, introduced a “Million Solar Roofs” initiative to install solar systems (mainly domestic hot water and PVs) on buildings. To my great (but predicted) disappointment, it fails to address the most obvious “solar” option of switching roof color (an almost free measure at the time of the next roof replacement, which accordingly has little backing from manufacturers—cheap solutions are not popular).

Here is a brief comparison of cool roofs and PV for a 2000-ft^2 roof in Florida. Compared with a traditional roof, a cool roof will reduce daily air conditioning use by $\sim$10 kWh, worth about $1. (27–29). A typical PV installation is sized for 3–4 kW (peak) and, even if bought in quantity, costs $6–$8/W (peak), for a total of $20,000–$30,000. In area, the PV array covers only $\sim$10% of the roof, leaving plenty of space for the rest to be white. To simplify the economics, let us consider a smaller, 2-kW (peak) system installed on a traditional hot roof. It will supply $\sim$10 kWh each sunny day, all of which will go to offsetting the air- conditioning penalty for the hot roof. At $8/W (peak), the 2-kW (peak) system costs $16,000, whereas a new cool roof costs nothing extra. And a cool roof reduces ozone formation; a hot solar collector on a hot roof certainly does not. In other words it is dumb to put PV on a dark roof, and more generally it makes no economic sense to install any renewable-energy systems on an inefficient building.

PV is already economic for off-grid markets (i.e. not served by power companies) and should soon be cost-effective on-grid in Hawaii, which is blessed with sunshine and burdened with expensive, oil-fueled electricity. To delay greenhouse warming, we should accelerate PV development and deployment where it is cost effective. But elsewhere, PVs should be introduced on a level playing field, along with other renewable technologies that are already cost effective: cool roofs, wind power, domestic hot water, and transpired collectors (30).

1985–1989: CALIFORNIA PIONEERS ENERGY EFFICIENCY

National Association of Regulatory Utility Commissioners Energy Efficiency Task Force and California Collaborative

The National Association of Regulatory Utility Commissioners, chosen from all 50 states, saw the societal benefits of utility DSM programs, and they were aware of DSM's peril after the 1985 OPEC collapse. So they appointed my good friend and Chair of the National Association of Regulatory Utility Commissioners' Energy Conservation Committee, Nevada Public Service Commissioner Stephen Wiel (now at LBNL) to form a task force to recommend changes to utility profit rules to reward DSM investments. Wiel in turn invited the usual efficiency champions including Ralph Cavanagh of NRDC, Amory Lovins of Rocky Mountain Institute, Maine Commissioner David Moskovitz, and me.

Some utilities in the Pacific Northwest were already allowed to earn a 10% premium rate of return on efficiency investment, and at first this seemed like a natural recommendation. But I was concerned about basing rewards on the level of investment. Thus my work on cool roofs to reduce air-conditioning costs and smog showed that, when a roof needed replacing anyway, there was no significant investment needed to order the new roof in a cool color and to downsize the air conditioner. The cleverest measures to save energy are the ones that cost the least, but these are least likely to excite the profit motive of a utility, no matter how large a premium rate of return is allowed. Moskovitz and I easily convinced the group that a return-on-investment formula just favors large, dumb investments, whereas "shared savings" are economically efficient. This point of view would soon lead to the California Collaborative and to a Shared Savings program. Under Shared Savings, whenever a California utility saved a customer $1.00, it was permitted a tiny rate increase (less than 1%), allowing its stockholders to earn an extra $0.15 and leaving the customer quite content with $0.85 savings.

In l988 the task force wrote a historic statement (Box 2), adopted by Wiel and his committee and later endorsed by the National Association of Regulatory Utility Commissioners as a whole, calling for new profit rules, awarding the highest profits to those programs that cost the least.

Box 2: Statement of Position of the NARUC Energy Conservation Committee on Least-Cost Planning Profitability

A utility's least-cost plan for customers should be its most profitable plan. However, due to the fact that incremental energy sales increase profits, traditional rate-of-return calculations generally provide substantially lower earnings to utilities for demand-side resources than for supply-side resources. For that reason, profit motive generally encourages utilities to invest in supply-side resources even when demand-side alternatives are clearly identified in its resources plan as being the least-cost resource.

The loss of profits to utilities from relying more upon demand-side resources is a serious impediment to the implementation of least-cost planning. This obstacle to least-cost planning should be addressed. There are identified mechanisms for offsetting the profit-erosion problem.

Therefore, it is the position of the Energy Conservation Committee that state commissions:

1) should require their utilities to engage in least-cost planning;
2) should consider the loss of earnings potential connected with the use of demand-side resources; and
3) should adopt appropriate mechanisms to compensate a utility for earnings lost through the successful implementation of demand-side programs which are a part of a least-cost plan and seek to make the least-cost plan a utility's most profitable resource plan.

(Adopted unanimously by the Committee on Energy Conservation on July 26, 1988.)

This statement stimulated Collaborative Processes in California, New England, and some other states. The process brought together utilities, regulators, energy users, state agencies, environmental groups, and other stakeholders to draft detailed new profit rules. Under the auspices of the Conservation Law Foundation of New England, I testified in every state in New England, leading up to their Collaborative. Both California and New England Collaboratives took effect in 1990, and introduced Shared Savings. The same utilities that had championed growth as a manifest good now championed efficiency as even more profitable.

Parenthetically, I should point out here that Box 2 is dated July l988, the same year that the hot dry summer marked another historic energy-related development. This was the summer that the United States lost about 5% of its agriculture, as did Europe and China, and when recognition of the threat of global warming suddenly ignited, again bolstering the case for energy efficiency.

From 1990, the Shared Savings idea spread slowly across the United States, and DSM programs grew to about $3 billion/year. But the prospect of “restructuring,” which would introduce competition between power companies, caused utilities to reduce these programs by 1996. Fortunately the California legislature, well aware of the value of energy efficiency, passed AB 1890 in l996, imposing a “wires charge” of 2.5%, i.e. a “wire charge” of 2.5% on all electricity sold within the state for the next 4 years. The wires charge yields $540 million/year to fund public benefits programs—$240 million for DSM (with a modern emphasis on market transformation), $60 million for public-benefit R&D, $110 million for a renewable-energy portfolio, and $130 million for low-income programs. I continue to serve (with a bad attendance record) on the Technical Advisory Committee for the California Board for Energy Efficiency.

Shared Savings was a great idea for regulated utilities. Many countries still have private utilities (or are privatizing them) and will continue to regulate them as natural, noncompeting monopolies. I plan to continue to recommend Shared Savings to help these countries promote greater efficiency.

Advising the California Legislature on Energy/Environmental Regulation

In 1989–1990, I had the pleasure of being invited to sell my legislative ideas from the inside. California Senator Herschel Rosenthal, Chair of the Legislature’s Joint Committee on Energy Regulation and the Environment, sponsored Senate Concurrent Resolution-7, establishing an 18-month study of improving energy efficiency and air quality. Three academics or environmentalists were to collect facts and opinions and make recommendations. Dian Grueneich, a public-interest utilities lawyer and counsel for CIEE and I were chosen. Our third colleague later resigned when a conflict of interest arose.

We used interviews, questionnaires, workshops, and our own experience to draft 30 recommendations for a more efficient California. Joint Committee members merged most of them into half a dozen bills, all of which passed the Legislature. It was a rewarding and efficient way to enhance efficiency and air quality, and champions of these causes in other states might suggest the same approach (31).

Pacific Gas and Electric's ACT^2 Shows 50% Reduction in Energy Use

Another wonderful opportunity appeared in l989. At the kickoff hearing on the California Collaborative on July 20, both Amory Lovins and I claimed that it was cost effective to reduce most buildings' energy use by 50% and that California utilities should expand their DSM programs to capture this potential saving and earn 10%–20% of its value.

PG&E already had a strong efficiency program, but was now interested in testing its ability to maximize profits by halving the measured energy intensity of existing buildings and the projected intensity of new buildings built to barely satisfy, but seldom to beat, the Title-24 standard. Amory and Carl Weinberg, PG&E's Manager of R&D, proposed to the PG&E Board a $10-million demonstration of super-efficient buildings. The Board approved the formation of ACT^2 and appointed a steering committee of Ralph Cavanagh, Amory, Carl, and me[5]. We retrofitted or redesigned seven sites (residential and commercial, existing and new). At six of the seven sites, we easily saved 50%. In the last site, we saved only 45% (28).

To me, the most interesting outcome was not the official one, which was that an alert, motivated design team can save 50% of the energy with a reasonable payback time, but was how hard it was to find any competent design team and any competent "third party" to do the measurement and verification. In both cases the first design team and the first "commissioning" team were not up to the task, and we had to fire them and restart the selection process. The real lesson learned is that we need to motivate and train many more architects and commissioning agents to design and deliver efficient buildings.

Amory Lovins frequently calls ACT^2 the first whole-building project to demonstrate that conservation supply curves bend down again if savings are big enough to downsize, simplify, or eliminate the HVAC equipment (23, 33). I have already discussed this issue in Box 1.

Unfortunately, by the time we finished the last ACT^2 site, planning for utility restructuring had swept away PG&E's interest in profitable Shared Savings projects. Sadly, PG&E has dismantled its highly experienced ACT^2 team.

1993: WATER FOR DEVELOPING COUNTRIES

In spring 1993, as usual I taught Physics 180—Efficient Use of Energy, which involves student projects. Derek Yegian, a graduate student who had served in the Peace Corps and was interested in improving drinking water in poor countries,

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[5] The project was originally called A^2 for Amory and Art. I suspect that some senior PG&E officials thought that it would fail, and thus A^2 was a fine name. But it was a great success, and we changed the name to ACT^2 for "Advanced Consumer Technology Test for Maximum Energy Efficiency."

proposed solar thermal-water pasteurization. In the developing world, waterborne diseases such as cholera, typhoid fever, gastroenteritis, dysentery, and infectious hepatitis kill more than 400 children every *hour* and cause the loss of billions of hours of worker productivity each year. Municipal tap water is uncommon in many households, and two out of three people in the world must fetch water from outside their homes. Disinfecting water by boiling it over cookstoves stresses the biomass resource, deforests hillsides (leading to mud slides after storms), and increases the burden on those collecting the fuelwood, mostly women and children. Gathering wood occupies time that might be spent productively in other activities.

I hired Yegian at LBNL for the summer, and within a month, with the help of my Indian-born former graduate student and colleague at LBNL, Ashok Gadgil, Yegian greatly improved the design of existing solar pasteurizers and passed the plans on to Pax International, which provides them to developing countries. Yegian still had another 6 weeks to be creative.

Gadgil pointed out that in India and Southeast Asia water pollution is worst during the monsoon season when heavy rainfall washes raw sewage and other contaminants from the fields into the wells and surface water. And of course, there is little sun during the monsoon.

So we went on to show that we could use a 40-W ultraviolet germicidal lamp to purify 4 gal/min at a cost of a few cents per ton. In a modern city with a reliable water distribution system, one can purify with chlorine for \$0.01/ton, but that doesn't help villages or slums in developing countries. Gadgil, Yegian, and others developed a prototype device called UV Waterworks (UVWW). One 40-W unit will supply a village of 1000, and there are $>$300,000 electrified villages in India alone. Each UVWW unit daily disinfects 10 tons of water. During each year of a 10- to 15-year life serving a typical developing-nation community of 1,000 people, each unit will prevent the death of one child and the stunted growth of 10 children. Under aggravated conditions like epidemics, health benefits will be much larger. Because women are primarily responsible for collecting fuel wood, fetching water, and bearing and caring for children, the UV disinfection system can greatly improve women's quality of life by reducing their workloads as well as the number of children they lose to waterborne diseases. Each UVWW unit will avoid daily foraging for firewood by more than 100 women and children.

Each unit also avoids the daily release of 0.8–2 tons of carbon equivalent from combustion of wood or other biomass that would have been used to boil the water. I summarize a paper by Gadgil et al (34). Biomass-fueled cook stoves average only 12% efficiency, so to boil 1 kg of water; they generate CO_2 with a carbon equivalent of 0.12 kg. But the cookstoves also generate many products of incomplete combustion of which CH_4, NO_x, and CO have high global warming potentials, adding an additional equivalent carbon burden of 0.08 kg of C. Even if the biomass is sustainably harvested (no CO_2), the minimum daily additional carbon emission from incomplete combustion for 1000 people to boil 10 tons of water is 0.8 tC each day. Adding nonsustainable CO_2 brings the figure up to 2.0 tC/day or 730 tC/year (equivalent to the carbon emission from 730 cars). We find it remarkable that a device costing only a few hundred dollars, with a service life of $\sim$10 years, has the lifetime potential of saving 2500–7500 tonnes of carbon. In terms of deforested hillside, the life-time mass of avoided firewood is equivalent to more than 10,000 tons! After I left Berkeley, Ashok Gadgil and LBNL found Elwyn Ewald, a retired expert of Third World health with 20 years of development experience, who licensed LBNL's UVWW patent rights, formed WaterHealth International [www.waterhealth.com], and has put it in production. In December 1998, 25 UVWW units were serving 10,000 villagers in the Philippines, and, by the end of the century, the number of users worldwide should grow to between 100,000 and 200,000.

In 1996, UVWW received *Discover Magazine's* award for best environmental invention for the year, and a *Popular Science* award as one of the top 100 inventions of the year.

1993: FROM BERKELEY PROFESSOR TO DEPARTMENT OF ENERGY ADVISOR

Department of Energy's Carnot Award for Energy Conservation

In 1993 I received the pleasant news that I was to be the second LBNL recipient of the Carnot Award. DoE's Office of Energy Efficiency and Renewable Energy had created this prize, named after Sadi Carnot, the great French scientist who, in 1824, calculated the maximum theoretical efficiency of an engine, now known as its Carnot efficiency. This analysis in turn led to the formulation of the Second Law of Thermodynamics. Sam Berman had been the first recipient in 1988, and I received mine in January 1994. It was for this award and talk that I prepared Table 1.

When Clinton and Gore took office in l992, Washington became a less hostile, even inviting city. Many of my friends who had played the role of loyal opposition to the previous administration now were the administration. Thus Jack Gibbons, director of the Office of Technology Assessment was appointed Science Advisor to the President and Director of Office of Science and Technology Policy, and he took my old friend Henry Kelly with him to the White House. I began to catch a case of Potomac fever.

On my January 1994 Carnot Prize trip, I met Christine Ervin, then DoE's Assistant Secretary for Energy Efficiency and Renewable Energy, and we discussed my coming to DoE as her science advisor. At the time, UC was offering a very attractive retirement plan, and I had a list of projects I wanted to start at DoE, so I readily accepted. In June 1994 Roz and I rented out our Berkeley hillside home and moved to Alexandria, VA.

National Science and Technology Council Construction and Building Subcommittee

In the Clinton administration, much interagency planning and coordination occurs in councils, like the National Security Council, International Trade Council, Council of Economic Advisors, and including the National Science and Technology Council. My friend Henry Kelly was now partly responsible for the National Science and Technology Council, and had suggested that it form a subcommittee on Construction and Building (C&B). He further suggested as cochairs Richard Wright, Director of the Buildings and Fire Research Laboratory at the National Institute of Standards and Technology, and me. We hit it off wonderfully, partly because Richard was pleased to do most of the work and to host our secretariat at the National Institute of Standards and Technology, staffed by his associate director, Dr. Andrew Fowell.

I learned that construction is one of our two largest industries—health is the other (then comes transportation and then food). Our annual construction investment is nearly $1 trillion. Two-thirds of construction goes into buildings, new or remodeled. The construction industry spends only 0.5% of its revenues on R&D, although the U.S. average is 3% (35). I also learned that construction, which employs only 6% of our workforce, pays 33% of workers' compensation, with insurance premiums ranging from 7% to 100% of payroll. For each new home, the cost of workers' compensation averages $5000. Construction workers die or are injured on the job at 2.5-times the rate for all other industrial sectors. The best U.S. construction companies are as safe as those in Europe or Japan, but many are 5-fold–10-fold worse. Safety training for U.S. workers is sadly lacking.

We crafted seven ambitious goals for constructed facilities, to be demonstrated and ready for general use by 2003. Five of these goals involved 50% reductions in delivery time; in cost for operation, maintenance, energy, and water; in occupant-related illnesses and injuries; in waste and pollution; and in construction workers' illnesses and injuries. To these we added a 50% gain in durability and flexibility and a 30% gain in productivity and comfort. The last will be hardest to achieve and hardest to measure.

We then invited industry leaders to several workshops to comment on the goals and set R&D priorities. To our surprise industry leaders supported the ideas and have adopted them as National Construction Goals.

I personally have been most interested in the issues of indoor environment and air quality and their relation to both occupant health and productivity. We have started a Workplace Productivity and Health project and are planning a more ambitious Healthy Buildings initiative.

The C&B Subcommittee has started several valuable industry-government partnerships, of which the best known is PATH (Partnership for Advancing Technology in Housing). These projects are discussed in reference 35.

Better Financing for Commercial-Building Retrofitting—Monitoring and Verification Protocols and Data

Building energy retrofit yields on average a 20% return on investment, but with modern controls, monitoring, and better "commissioning," experienced contractors can reliably get 30%–50% returns. Even a 20% return on investment beats the stock market, and building investments are less *risky* than the stock market. But the data demonstrating all of this are scattered (and often proprietary), so Wall Street is only beginning to understand that energy retrofits of buildings are low-risk profit centers.

While still in Berkeley, I had decided that we needed a comprehensive public-domain collection of retrofit data to convince bankers to lower their interest rates. As soon as I got to DoE, I met Greg Kats, who had similar interests. But Greg had a Stanford MBA and actually understood finance. He was also experienced in energy efficiency policy and had worked with Amory Lovins at the Rocky Mountain Institute before joining DoE. Greg and I teamed up and started talking to lenders, who advised us of an unexpected prerequisite—a common national monitoring and verification protocol.

In 1994 >$1 billion of retrofit was financed by utilities or by energy service companies under performance contracts. These may take different forms. The capital may be provided by the host building or by the energy service companies. In either case the energy service companies perform the work and are repaid out of measured savings. Note that all performance contracts require that host and contractor agree on a protocol to establish the value of each year's savings.

What troubled our financial advisors was that many different protocols were sprouting like weeds. New Jersey had one, as did individual utilities and the EPA. Furthermore, ASHRAE had a project to write a detailed engineering protocol, but that would take several years. Our Wall Street friends asked us to coordinate these individual protocols and provide a national protocol. So Greg and I invited all of the parties above plus many other stakeholders to collaborate and produce the l996 North American Energy Measurement and Verification Protocol (36).

Subsequently Greg, as Director of Finance for Energy Efficiency and Renewable Energy, has spent about half of his time, and I have devoted ~10% of mine, in managing and expanding the protocol to cover water conservation, indoor environmental quality, and industry. We have worked to get it adopted in many states, and internationally by Canada, Mexico, the European Community, and for projects of the World Bank and sister development banks. Hence we have renamed it International Performance M&V Protocol (IPMVP). The Federal Energy Management Program for federal buildings has also adopted it.

The IPMVP has been translated into Chinese, Japanese, Korean, Spanish, Portuguese, Russian, Ukrainian, and Polish and is being adopted and applied at different rates in each country. It is being translated into another four of five languages this year. We have been told that a pending $40-million World Bank efficiency loan to Ukraine would probably not occur without the IPMVP, which provides confidence in better and more consistent savings performance and allows reduced transaction costs through the standardization it provides.

The good news is that risk as perceived by financiers and hence the risk premium on the interest rate is indeed dropping. This must be partly owing to bankers' increasing familiarity with retrofit, and partly to the existence of IPMVP; we cannot apportion the credit. But when we were first organizing the IPMVP a few years ago, the average interest rate premium above 30-years on Treasury bonds was 4–7%, and now it has dropped to $\sim$2%, for a gain of 2–5 percentage points.[6] Our growing benefit/cost database should help to shave off a little more.

Emissions Trading Under International Performance Monitoring and Verification Protocol

As the only international consensus approach to measuring and verifying efficiency upgrades, the IPMVP is expected to serve as a technical basis for emissions trading programs domestically and internationally. Domestically, for example, EPA is planning on using the IPMVP as a basis for determining emissions credits allocation in state implementation plans for NO_x compliance. Internationally, the Intergovernmental Panel on Climate Change, multilateral development banks, and other institutions expect to use the IPMVP to determine CO_2 offsets and achieve consistency between countries in determining CO_2 reduction from efficiency investments as part of an international climate change trading programs.

Our next goal is to decrease the energy use of new buildings and beat the relatively lax code requirements. The most cost-effective opportunity to save energy is during the design phase of a building, and today many new buildings have beaten code by 25%–35%, with annual return of investment of 25%–35%. Greg and I plan to collect data and case histories and work with public and private builders to encourage them to make small additional investments to achieve rewarding net savings. We will do this in collaboration with EPA's Energy Star Buildings program.

1995–PRESENT: GLOBAL CONCERNS

Energy-Efficient, Low-Carbon Technologies—The Five-Lab Study

My most productive and stimulating collaborator at DoE turned out to be Joe Romm, who worked his way up through several different jobs while I've been in

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[6] On a five-year loan, the five-year percentage cost of interest is about 2.5 × the annual interest rate. So, if the rate has dropped 4% (from 6% to 2%), the cost of the project has dropped 10%, which should significantly accelerate the rate of investment in retrofits. Of course the 2%–5% drop in interest rate does not apply to large successful energy service companies that have excellent credit ratings and low cost of capital.

Washington. Joe received a doctorate in physics from Massachusetts Institute of Technology in l987. He worked on national security issues until 1991 and with Amory Lovins at Rocky Mountain Institute until 1993. Amory recommended him to Hazel O'Leary, then Secretary of Energy, and her deputy, Bill White, who snapped him up as a special assistant. By 1995, Joe had become Principal Deputy to Christine Ervin, the Assistant Secretary for Energy Efficiency and Renewable Energy, who had hired me. (Christine resigned after Clinton's first term, and Joe went on to serve as Acting Assistant Secretary). Between 1992 and 1994, he also wrote an excellent book (37) and has now written a comprehensive sequel (38).

In the summer of 1996, <18 months before the United Nations conference on climate change, scheduled for Kyoto in November 1997, Joe, Christine, Eric Petersen[7] (now Director of Policy, Planning, and Budget for Energy Efficiency and Renewable Energy) and I began to talk quantitatively about CO_2 reduction. Among developed countries in 1996, discussion centered on returning to 1990 levels by 2010. In 1990 the United States emitted 1340 MtC from CO_2. For 2010, the Energy Information Agency's (EIA) "business as usual" CO_2 scenario projected 1740 MtC, so the analytic challenge was to estimate the cost (or gain) to save annually 400 MtC, which meant shaving 23% off the projected annual 1740 MtC in 2010, only 12 years away. This required increasing our CO_2 efficiency at an average annual rate of 2%. After the collapse of OPEC in late 1985, efficiency has been growing annually at a 1% rate, so adding 2% would raise the total rate to 3%. Most economists feared that this would be very expensive, and would threaten our economy.

In contrast, several engineering economic studies undertaken about 1990 (I had worked on two of them) found cost-effective carbon savings of 30%–50%, but they all had a 20- to 30-year time horizon, to allow for natural stock turnover (39). The 20- to 30-year implementation time is required by the long service life of energy-related products. Thus cars and appliances last 12 years; refrigerators, 16; airplanes and factories, 30; power plants, 40 years; buildings and urban sprawl, 100 years. These are very long times in the light of our self-imposed constraint of 2010.

There was one heartening empirical fact, which I had been pointing out for years. OPEC hit us with high prices from fall 1973 through fall 1985 (12 years), but during the first year or so confusion reigned over policy, so that new products did not really start adapting until late 1974, leaving us 11 years to respond to energy scarcity. The good news was that, between 1974 and 1985, auto fuel economy doubled (corresponding to an improvement of 7%/year). Many other products roughly doubled in efficiency; thus the average new refrigerator plotted in Figure 3 dropped its energy use to 58%. Space heating for new buildings dropped to 50%, corresponding to an efficiency gain of 100% or, again, 7%/year. Using overall data on energy vs GDP, I get a good fit to a rate of efficiency gain of 5% a year, averaged over all energy-consuming new products, for those energy-aware 11 years (40).

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[7] Petersen died of cancer, Aug. 25, 1999.

Given all of these considerations, the four of us at DoE realized that we just did not know how fast and at what cost (or reward) we could "get to Kyoto." We determined to find out quickly.

The expertise for a comprehensive low-energy, low-carbon study was mainly at DoE's national laboratories. We also realized that a lab study (as opposed to a DoE study) would, once completed, avoid tedious "concurrency sign-offs" at DoE. Christine put up \$500,000, and Joe picked five labs; Berkeley (Mark Levine) and Oak Ridge (Marilyn Brown) were coleaders, supported by Argonne, National Renewable Energy Lab, and Pacific Northwest National Lab (see 36a–41).

The efficiency analysis took shape by Christmas, but added up to only 230 MtC out of the 400 MtC required by 2010 to satisfy the Kyoto goal. But this efficiency gain would save billions of dollars annually (a net of \$43 billion in 2010), and enough natural gas to fuel one-fourth to one-third of our coal-fired power plants. So to find the remaining 170 MtC we focused on electric power plant conversion and on the gas-fired generation of combined heat and power for industry and buildings. By summer we estimated that we could "get to Kyoto" by combining the efficiency gains with a \$10 billion/year investment in low-carbon electric generation, saving $\sim$200 MtC/year from each. (Lowering carbon per kilowatt hour also includes extending the service life of nuclear plants, and accelerated investment in renewable energy sources.) To stimulate \$10 billion/year investment within the utility industry, we would need a carbon tax (or better, cap-and-trade permit price) of \$25–\$50/tC.

Note that the trading of carbon permits represents only an income transfer between companies, mainly within the utility and auto industries, and not a cost to society. Of course there is some real cost, for example to convert a power plant from coal to gas, or just to burn gas instead of coal, but the real cost is small compared with the transfer payments that induce the fuel switching. Our complete scenario (annual net efficiency savings less investment in lower carbon electric power) shows a tiny net economic gain of \$38 billion out of a year 2010 projected economy of \$10 trillion, or $<0.5\%$. We were happy to call this $(0 \pm 1)\%$ (41).

Zero cost or reward was welcome news at a time when the Administration's planning for Kyoto was mainly bad news. As I mentioned before, most economists feared that to comply with Kyoto would seriously threaten our economy, and the administration gets advice from thousands of economists. Its response was to plan to be noncommittal at Kyoto. It would argue that CO_2 production by the already-developed countries (known as the Annex I countries) would soon be overwhelmed by CO_2 from the developing countries, so we could not afford to cut our CO_2 (and hurt our economy) unless they also agreed to reduce their CO_2 growth. (My problem with this argument is that EIA predicts that, as far ahead as 2020, 55% of CO_2 will still come from Annex I countries, and of course the CO_2 stored in the atmosphere over the last 100 years is overwhelmingly from our developed countries. So I can understand the feeling of the developing world that it is we who should take the first steps.)

So the bad news was that two of the leading champions of energy efficiency and greenhouse gas reduction were quitting government service. Tim Wirth, then Undersecretary of State for Global Affairs, and Eileen Clausen, Assistant Secretary for Oceans and International Environmental and Scientific Affairs, were both preparing to leave government to move to foundation-supported positions.

With Christine's blessing, Joe Romm led the charge to convince the Administration that we could afford to cooperate at Kyoto. He worked tirelessly to convinced Energy Secretary Federico Peña, colleagues at the Office of Management and Budget and other agencies, and friends on Capitol Hill. On October 10, l997, in a speech at a White House Conference on Global Climate Change, President Clinton said, "I'm convinced that the people in my Energy Department labs are absolutely right." And Vice-President Gore did go to Kyoto, asserted real U.S. leadership, and salvaged a squabbling, foundering conference.

Of course this victory was only partial, because the present Congress is not ready to adopt the Kyoto Protocol.

I do not want to imply that the Five-Lab study convinced many economists, because it has been criticized by skeptics as close as the EIA, an agency housed at DoE, but independent of DoE. In October 1998, EIA released a study requested by the U.S. House of Representatives Committee on Science (42) in which they detailed their concerns in Section 7.

These concerns point up the gap between macroeconomists and physical scientists. The former tend to model the economy "top-down" (i.e. from the top, downwards), using as levers mainly energy prices and taxes, with little attention to individual technologies. The latter work "bottom-up" with simple spread sheets and conservation supply curves, organized by individual technologies.

The macroeconomic models work well for conditions close to business as usual, but in my opinion they run into trouble if they stray far from business as usual, mainly because they keep the rate of efficiency improvement for new products unrealistically frozen at $\sim$1%/year. The engineering economists (at least those making a road map from here to Kyoto) envision a different world, far from business as usual. In this world, some combination of science, natural disasters, and business and political leadership is foreseen to have created a sense of urgency to delay the risk of global warming. In this "greener" world, industry, business, and government would naturally take an interventionist, perhaps even energy-intrusive stand, reminiscent of the OPEC-dominated years 1974–1985. Then, with steady domestic leadership rather than unexpected OPEC price spikes, I believe we can achieve the remarkable 5%/year rates of technical progress of those years, without the disruptions. So, in conclusion, we haven't convinced many economists, but the White House listens both to economists and technologists, and the Five-Lab study gave Clinton and Gore the Kyoto road map they needed.

Fortunately DoE has recognized the value of the Five-Lab team and has transformed it into a relatively permanent "Clean Energy Future" study group tasked to formulate policies to help the United States make progress along the Five-Lab road map.

Delaying the Threat of Climate Change

I conclude with a few personal observations on global warming/climate change. Before 1988, my first motivation for improving energy efficiency was to save money; second, I wanted to save resources (e.g. oil, gas, and forests) for future generations.

Then came the hot dry summer of 1988, when the threat of greenhouse warming burst onto the scene and into the headlines. This not only reenergized the energy efficiency community, whose prominence was waning and whose budgets had been flat since the collapse of OPEC in l985, but it also slightly changed my priorities from "1. Money, 2. Resources, 3. Pollution," to "1. Money, 2. Pollution, 3. Resources." Restated in environmental language, my concerns are switching from "running out of sources" to "running out of sinks." Thus my heightened interest, discussed above under the Five-Lab study, in combined heat and power, in gas-fired and biomass cofired electric generation, life extension of nuclear plants, and appropriate renewable-energy resources.

Before 1988 my goal was simple—invest in efficiency so as to save as much money as possible. But for CO_2 reduction I have a two-phase strategy:

1. For the next decade, until we understand more precisely the threat of climate change, I think that the only politically realistic policy for the Unites States will be to stabilize emissions at today's levels (or better, to try for 1990 levels).
2. By 2010, the risk of climate change should be better understood and accepted and the cost somewhat quantified, and worldwide we'll probably have to plan on further reducing CO_2/GDP well below the 1990 Kyoto target.

How difficult is Goal 1, to stabilize CO_2 emissions? I cannot resist one last small table (Table 2), which hearkens back to the discussion, for the United States, of the Five-Lab Study, but adds data on developing countries.

Table 2 shows projected annual growths (not today—1999—with Asia and Russia in economic crisis, but EIA's estimate for the 25-year average (1995–2020) for the United States, China, developing countries, and the whole world. The top three rows display the primary outputs: GDP, E, and CO_2; the next two rows are just the derived intensities E/GDP and CO_2/GDP.

If the United States (shown in column A) is to maintain economic growth yet stabilize CO_2 emissions, row 3 shows that we need to reduce CO_2 by only an extra 1.2%/year, on top of the present 0.7%/year shown on line 3a, for a total annual drop of CO_2/GDP of 1.9%/year. Technically this should be easy. In the preceding section (on the Five-Lab Study), I pointed out that, in the energy-anxious 11 years 1975–1985, new energy-related U.S. products improved their efficiency ~5%/year. Energy and carbon showed almost identical growth rates, so if the external threat of OPEC moved us to gain 5%/year, broad internal recognition of the risk of climate change should be able to motivate us to accelerate from the present annual improvement of 0.7% to 1.9%.

TABLE 2 Projected annual percentage growth (1995–2020) of gross domestic product, primary energy, and CO_2 for the United States, China, developing countries[a], and the world.

Growth indicator	**A. United States**	**B. China**	**C. Developing countries**[a]	**D. World**
1 Gross domestic product, (GDP)	1.9	7.9	5.2	3.1
2 Primary energy (E)	1.0	4.2	3.8	2.3
3 CO_2	1.2	4.4	3.8	2.4
2a E/GDP	−0.9	−3.7	−1.4	−0.8
3a CO_2/GDP	−0.7	−3.5	−1.4	−0.7
2b E/GDP fit to new products during the "Efficiency Years" (1975–1985)[b] *Source: Rosenfeld, Bassett (40)	−5			−3[b]

[a] Developing countries are Asia (except Japan and Australia), Middle East, Africa, and South and Central America (except Mexico).

[b] Eastern Europe and the former Soviet Union did not respond to the OPEC price shock, so we exclude these countries from our world fit.

Source:DOE/EIA-0484(98)(43) *Intl En. Outlook's Report # is DOE/EIA-0484(98), and it is my autobio citation 43.

At the other extreme, consider the developing countries in column C, whose combined GDP is predicted to grow much faster than that of the United States. To maintain this growth but level off in CO_2, they must decrease their emissions and energy use by an additional annual 3.8%, on top of their present 1.4% (row 3b), for a total of 5.2%. This sounds difficult, except for two encouraging trends:

1. Developing countries have energy and carbon intensities roughly 2.4-fold higher than that of the industrialized countries, (see Figure 19 of reference 43), so the technical constraints will not soon be a problem. They could increase their intensities at the required 5.2% annually for 30 years before they reach the satisfactory intensities of Switzerland, France, Austria, or Greece today.
2. Regardless, the developing countries are still the minor part of the problem; despite their rapid growth, they will reach not reach 40% of the world's CO_2 emissions until 2005, or 50% till 2020. (Table A9 of reference 43). So after the industrial world starts to conserve CO_2, there is still a decade or so for this new urgency and the new technology it spawns to diffuse into the developing world.

Before we leave Table 2, I call attention to the China column (B). Chinese planners are committed to energy efficiency, not because of any great concern for CO_2, but simply because efficiency beats coal production as a stimulant to economic growth. This commitment has led to a remarkable gain in energy intensity, which is predicted to continue at an annual rate of 3.7%. My hope is that the rest of the developing world can achieve this goal.

CONCLUSION: FROM REVELATION THROUGH REVOLUTION

In conclusion, energy efficiency is an enduring challenge. Inefficient use of energy and hence waste of money and resources will merit our attention for the foreseeable future, and I believe the same can be said of the threat of climate change. Energy efficiency has been a rewarding discipline because it simultaneously saves money and protects the environment. I'm proud to be working in this field.

ACKNOWLEDGMENTS

As the reader will have observed, my greatest pleasure has been to work with leaders of energy efficiency for the last 25 years and to have been able to attract a few of the strongest to Lawrence Berkeley Lab. More friends than I have room to list have reviewed and improved this autobiography; I end with thanks to all of them.

LITERATURE CITED

1. Fermi E, Orear J, Rosenfeld AH, Schluter RA. 1949. *Nuclear Physics*. Chicago: Univ. Chicago Press
1a. Rosenfeld AH. 1954. Production of charged pions from hydrogen and carbon. *Phys. Rev.* 96:130
1b. Rosenfeld AH. 1954. Production of pions in nucleon-nucleon collisions at cyclotron energies. *Phys. Rev.* 96:139
2. Carnahan W, Ford KW, Prosperetti A, Rochlin GI, Rosenfeld AH, et al. 1975. *Efficient Use of Energy: Part I. A Physics Perspective*, ed. SM Berman, SD Silverstein, *Part III. Energy Conservation and Window Systems. AIP Conf. Proc. No. 25*. College Park, MD: Am. Inst. Phys. Updated by Hafemeister D, Kelly K, Levi B. 1986. *AIP Conf. Proc. No. 135*
3. Dean E, Rosenfeld AH. 1977. Modeling natural energy flow in houses. In *Efficient Use of Energy in Buildings, A Report of the 1975 Berkeley Summer Study, LBL 4411, EEB 77-2*, ed. E Dean, AH Rosenfeld, Chapter 3. Berkeley, CA: Lawrence Berkeley Natl. Lab.
4. Goldstein DB, Rosenfeld AH. 1976. *Projecting an Energy-Efficient California. LBL 3274//EEB 76-1*. Berkeley, CA: Lawrence Berkeley Natl. Lab.
5. Goldstein DB, Rosenfeld AH. 1975. *Conservation and Peak Power—Cost and Demand. LBL4438//EEB 76-2*. Berkeley, CA: Lawrence Berkeley Natl. Lab. Reproduced in 1988. *NATO Adv. Sci. Inst. Ser.*, Vol.

149. Dordrecht, The Netherlands: Elsevier/Kluwer

6. Rosenfeld AH, Levine MD. 1981. *Accelerating the Building Sector's Sluggish Response to Rising Energy Prices*. Testimony before the Interior Appropr. Comm., US House Represent., Washington, DC, April 8, *LBL 12739, EEB 81-2*
7. Traynor GW, Anthon DW, Hollowell CD. 1982. Technique for determining pollutant emissions from a gas-fired range. *Atmos. Environ.* 16:2979–87
8. Budnitz RJ, Berk JV, Hollowell CD, Nazaroff WE, Nero AV, Rosenfeld AH. 1979. Human disease from radon exposures: the impact of energy conservation in residential buildings. *Energy Build.* 2:209–15
9. Nazaroff WW, Feustel H, Nero AV, Revzan KL, Grimsrud DT, et al. 1985. Radon transport into a detached one-story house with a basement. *Atmos. Environ.* 19:31–46
10. Nero AV, Schwehr MB, Nazaroff WW, Revzan KL. 1986. Distribution of airborne radon-222 concentrations in U.S. homes. *Science* 234:992–97
11. Nero AV. 1988. Controlling indoor air pollution. *Sci. Am.* 258(May):42–48
12. Price PN. 1997. Predictions and maps of county mean indoor radon concentrations in the mid-Atlantic states. *Health Phys.* 72:893–906
13. Goldstein DB, Rosenfeld AH. 1977. Facts and fact sheets on home appliances. In *Energy Extension Services, Proc. 1976 Berkeley Workshop*. Berkeley, CA: Lawrence Berkeley Natl. Lab.
14. Geller H, Goldstein DB. 1999. Equipment efficiency standards: mitigating global climate change at a profit. Geller-Goldstein Szilard Lecture. *Phys. Soc.* 28(2):1–5.
15. Berman S, Fisher AC, Hollander JM, Rosenfeld AH, Ross MH, et al. 1979. *American Council for an Energy-Efficient Economy: Manifesto*. Unpublished
16. Rosenfeld AH. 1981. Buildings section. In *A New Prosperity: Building a Sustainable Energy Future, the SERI Solar/Conservation Study*, ed. H Kelly, pp. 11–175. Andover, MA: Brick House
17. Geller H, Harris JP, Levine MD, Rosenfeld AH. 1987. The role of federal research and development in advancing energy efficiency: a $50 billion contribution to the US economy. *Annu. Rev. Energy* 12:357–95
18. Mills E. 1995. *From the Lab to the Marketplace. LBL Publ. 758*. Berkeley, CA: Lawrence Berkeley Natl.Lab. http://EETD.LBL.gov/CBS/Lab2Mkt/Lab2Mkt.html
19. Meier A, Rosenfeld AH, Wright J. 1982. Supply curves of conserved energy for California's residential sector. *Energy* 7(4):347–58
20. Meier A, Wright J, Rosenfeld AH. 1983. *Supplying Energy Through Greater Efficiency: The Potential for Energy Conservation in California's Residential Sector*. Berkeley: Univ. Calif. Press
21. Natl. Acad. Sci. 1991. Conservation supply curves for buildings. In *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science*, Append. C, pp. 708–16. Washington, DC: Natl. Acad. Press. www.nap.edu/ readingroom, search for "warming"
22. Lovins AB, Lovins LH. 1991. Least-cost climatic stabilization. *Annu. Rev. Energy Environ.* 16:433–531
23. Von Weizaeker EU, Lovins AB, Lovins LH. 1997. *Factor Four: Doubling Wealth, Halving Resource Use*. London: Earthscan. Available in North America only from Rocky Mountain Inst. http://www.rmi.org
24. Modera MP, Dickerhoff D, Nilssen O, Duquette H, Geyselaers J. 1996. Residential field training: an aerosol-based technology for sealing ductwork. *Proc. ACEEE Summer Study* 1:169–75. *LBNL Rep. LBL-38 544*. Berkeley, CA: Lawrence Berkeley Natl. Lab.

25. Feustel H, Simionas R. 1996. *1995 Indoor Environment Program Annual Report*, p. 11. EEDT Div., *LBNL Rep. 38351*. Berkeley, CA: Lawrence Berkeley Natl. Lab.
26. Rosenfeld AH, Romm J, Akbari H, Lloyd A. 1997. Painting the town white—and green. *MIT Technol. Rev*. Feb/Mar: 54–59. http://www.EETD.LBL.gov/heatisland
27. Konopacki S, Parker D. 1998. Saving energy with reflective roofs. *Home Energy* 15(6):9
28. Parker D, Huang YJ, Konopacki SJ, Gartland LM, Sherwin JR, Gu L. 1998. Measured and simulated performance of reflective roofing systems in residential buildings. *ASHRAE Trans*. 108, Part 1. www.fsec.ucf.edu/∼bdac
29. Parker D, Durant S. 1998. *The Impact of PV on Energy-Efficient Housing*. FSEC-CR-1019-98. Cocoa, FL: Fla. Solar Energy Cent. See also www.fsec.ucf.edu, click on Million Solar Homes, PVRes
30. Kutcher CF. 1996. Transpired solar collector systems: a major advance in solar heating? *Energy Bus. Technol. Sourcebook. Proc. 19th World Energy Eng. Congr., Atlanta, GA*, Nov. 6–8, pp. 481–89. Atlanta: Assoc. Energy Eng.
31. Grueneich D, Rosenfeld AH, Modisette D. 1990. *Summary of Draft Recommendations for Legislative Action: Energy Efficiency as a Coordinated Environmental and Energy Strategy*. Submitted to Calif. Legis. Jt. Comm. Energy Regul. Environ., Sacramento, Sept. 12
32. Brohard G, Brown M, Cavanagh R, Lovins A, Rosenfeld A. l998. ACT2 Project: the final report. *Proc. 1998 Summer Study on Energy Efficiency in Buildings*, pp. 67–78. Washington, DC: Am. Counc. Energy-Effic. Econ.
33. Hawken P, Lovins AB, Lovins LH. 1999. *Natural Capitalism: Creating the Next Industrial Revolution*. New York: Little Brown. In Press
34. Gadgil A, Greene D, Rosenfeld AH. 1998. Energy-efficient drinking water disinfection for greenhouse gas mitigation. *Proc. 1998 Summer Study on Energy Efficiency in Buildings* 5:131–41. Washington, DC: Am. Counc. Energy-Effic. Econ.
35. Rosenfeld AH, Snell JE, Wright RN. 1999. *Construction and building—interagency program for technical advancement in construction and building*. Rep. Subcomm. Constr. Build., Comm. Technol., Natl. Sci. Technol. Counc. www.bfrl.nist.gov/info/cbtc/pubs.html
36. Bullock C, Kats G, Rosenfeld AH. 1996. *North American Energy Measurement and Verification Protocol. DOE/EE-0081*. Washington, DC: US Dep. Energy. www.IPMVP.org
37. Romm JJ. l994. *Lean and Clean Management—How to Increase Productivity by Reducing Pollution*. New York: Kodansha Am.
38. Romm J. 1999. *Cool Companies*. Covelo, CA: Island Press
39. Brown MA, Levine Md, Romm JP, Rosenfeld AH, Koomey JG. 1998. Engineering-economic studies of energy technologies to reduce greenhouse gas emissions: opportunities and challenges. *Annu. Rev. Energy Environ*. 23:287–385
40. Rosenfeld AH, Bassett D. 1999. *Annual energy efficiency improvement: 1% today, 5% from 1975–1985, what next?* Int'l Energy Agency Workshop Eng. Econ. Stud. Low-Carbon Technol., Washington, DC. ww.w.iea.org/workshop/engecon
41. Interlab. Work. Group. 1997. *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy Technologies by 2010 and Beyond. ORNL CON 444*. www.ornl.gov/ORNL/Energy_·Eff/labweb.htm
42. Energy Inf. Agency. 1998. *Impacts of the Kyoto Protocol on US Energy Markets and Economic Activity. SR/OIAF/98-03*. Washington, DC: US Dep. Energy
43. Energy Inf. Agency. 1998. *International Energy Outlook, 1998 with Projections through 2020. DOE/EIA-0484 (98)*. Washington, DC: US Dep. Energy