Arthur H. Rosenfeld with Deborah Poskanzer

A Graph Is Worth a Thousand Gigawatt-Hours

How California Came to Lead the United States in Energy Efficiency

Innovations Case Narrative:
The California Effect

Humans burn fossil fuels to provide energy for our needs, including heat, light, transportation, refrigeration, and industrial processes. Our continued dependence on combustion produces carbon dioxide, contributing to the increasing concentrations of greenhouse gases (GHGs) in the earth's atmosphere. Although energy efficiency alone will not likely be enough to reverse this trend, currently it is by far the fastest, cleanest, and cheapest energy resource available.

This article will discuss how my colleagues and I have promoted energy efficiency over the last 40 years. Our efforts have involved thousands of people from many different areas of expertise. The work has proceeded in several areas:

- Investigating the science and engineering of energy end-use
- Assessing the potential and theoretical opportunities for energy efficiency
- Developing analytic and economic models to quantify opportunities
- Researching and developing new equipment and processes to bring these opportunities to fruition

---

Arthur H. Rosenfeld is a member of the California Energy Commission, where he presides over the Research, Development and Demonstration Committee, the Dynamic Pricing Committee, and the Energy Efficiency Committee. Rosenfeld was the founder of the Center for Building Science at Lawrence Berkeley National Laboratory (LBNL), which he led until 1994. Rosenfeld is a recipient of the Szilard Award for Physics in the Public Interest, the Carnot Award for Energy Efficiency from the U.S. Department of Energy, and the Enrico Fermi Award, the oldest and one of the most prestigious science and technology awards given by the U.S. Government. Dr. Rosenfeld is also the cofounder of the American Council for an Energy Efficient Economy (ACEEE), the University of California's Institute for Energy Efficiency (CIEE), and the Washington-based Center for Energy and Climate Solutions (CECS).

- Participating in the development of California and later federal standards for energy performance in buildings and appliances
- Ensuring that market incentives were aligned with policies
- Designing clear and convincing graphics to convey opportunities and results to all stakeholders

Here I tell the story of how we developed and combined these efforts by developing a conceptual framework, calculating costs and benefits, and deploying our findings in a way that would achieve maximum persuasive impact. During this time I have served in various capacities: as a physics professor at the University of California, a researcher at Lawrence Berkeley National Lab (LBNL), an advisor at the federal Department of Energy, and most recently a Commissioner on the California Energy Commission.[1]

Technological innovation has been and will continue to be an important component of efficiency improvement. However, legislative, regulatory, and market innovations have also been a critical and challenging part of our effort. Our work covers a broad range of interconnected efforts; the ability to coordinate and align the work in all these sectors is at the core of my definition of "innovative."

Technological innovation has been and will continue to be an important component of efficiency improvement. However, legislative, regulatory, and market innovations have also been a critical and challenging part of our effort. Our work covers a broad range of interconnected efforts; the ability to coordinate and align the work in all these sectors is at the core of my definition of "innovative."

This article is built around a collection of favorite graphs that my colleagues and I have used over the years to support the campaign for efficiency. I begin with two graphs that illustrate general concepts of energy efficiency and energy intensity in order to illustrate the amazing savings available from improvements in energy use. Next, a series of figures chronicle how we used and continue to use technical and economic data to substantiate our arguments for an effective energy efficiency policy. I have chosen several examples of innovation that have contributed substantially to efficiency improvements over the long term: refrigerators, electronic lighting ballasts, computer applications that simulate building energy performance, and valuation methods for conserved energy. These cases are not necessarily the most recent—some are based on research performed many decades ago—but each one illustrates the complex web of challenges in engineering, economics, and policy that is typical of the efficiency field, and each one continues to bear fruit.

The cases discussed in this article all originated in my home state of California before they went on to influence energy efficiency strategy at the national or global level. California has been, and remains, the main arena for my efforts, and after four decades of innovation we are a leader in energy efficiency. The gap between our lower per-capita electricity use and national consumption has been dubbed the "California Effect." How much of this effect can be credited to our efficiency efforts, as opposed to advantages in climate and industrial mix, is a point of debate. I give my own analysis here, and the article that follows, by Ralph Cavanagh, also discusses the issue.

In conclusion, I will describe an exciting new policy development that represents the culmination of many years of multi-pronged, interdisciplinary groundwork. In September 2008, the California Public Utilities Commission (CPUC) released California's Long-Term Energy Efficiency Strategic Plan, which was followed in September 2009 by the announcement of a $3.1 billion budget for the first three-year stage of implementation.[2] The Strategic Plan is a crucial component of the state's effort to roll back GHG emissions to 1990 levels by the year 2020. Achieving this goal, as set forth in the landmark Global Warming Solutions Act of 2006 (Assembly Bill 32), will bring California into near-compliance with the Kyoto Protocols. More importantly, the plan's detailed and entirely feasible program of increased energy savings, paired with job creation, provides a much-needed road map for a nationwide "green economy" stimulus.

ENERGY EFFICIENCY: CONCEPTS AND DEFINITIONS

Energy efficiency is defined as the amount of useful output derived from primary energy input. We encounter the idea of end-use efficiency every day when we calculate how many miles per gallon our cars achieve, or how much our electricity use drops when we replace an old refrigerator with a better one. Obviously, the greater the efficiency of our equipment, the less fuel we need and the lower our impact on climate change. The goal of energy efficiency is to use technical and process improvements to our appliances, buildings, and vehicles to deliver the same, or comparably satisfactory, levels of performance for less primary energy input.

To track the macroeconomic significance of efficiency gains we can index the *energy intensity* of an economy. Energy intensity is defined as the amount of primary energy needed to produce a unit of gross domestic product (GDP): lower energy intensity indicates a more energy-efficient economy. The good news is that in general, energy intensity improves through normal technological progress. This is intuitively obvious when we think about the efficacy of cooking over a wood fire compared to a modern range. Or to be more quantitative, lighting has progressed

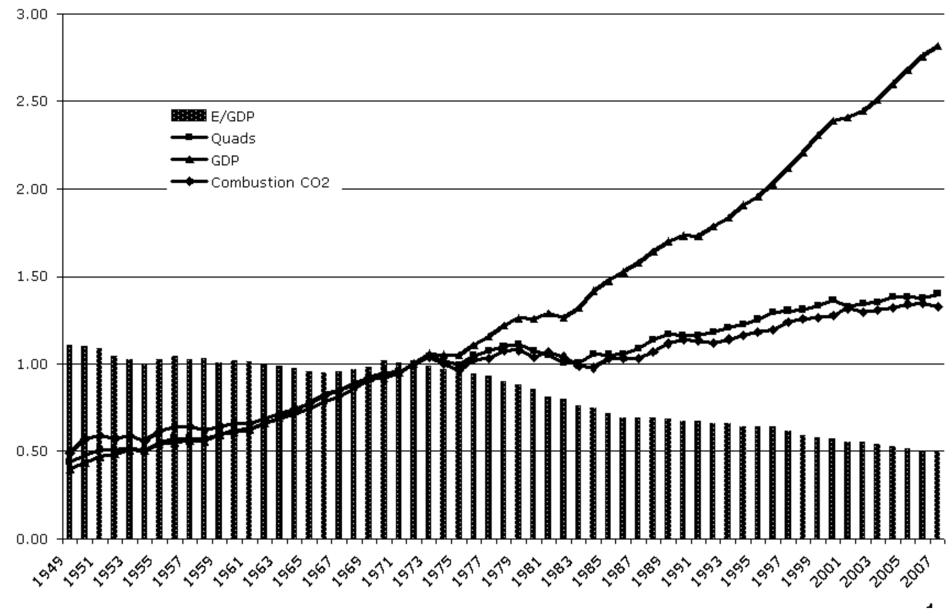

Figure 1. Index of U.S. Energy Use, GDP, Energy Intensity, and CO_2, with 1972 = 1.

from candles producing one lumen for every six watts of candle wax burned, to incandescent electric bulbs producing 17 lumens with each watt of electric input, to fluorescent lighting that produces 100 lumens per watt.

Figure 1 displays various energy and economic data for the U.S., indexed to a 1972 baseline.[3] These data include: Quads (10^15 Btus) of primary energy; Gross Domestic Product (in constant dollars); CO_2 emissions; and Energy Intensity (energy divided by GDP). In the high-growth decades following World War II, primary energy use, gross domestic product, and CO_2 emissions from combustion increased nearly in lockstep. Between 1949 and 1973, energy intensity barely changed, as seen from the unvarying height of the columns depicting energy intensity (E/GDP). In the years preceding the first OPEC oil embargo, the American consumer had not just scarce but diminishing motivation to reduce energy usage. The average retail price of electricity hovered below 2 cents/kWh through the late 1960s and early 1970s; in fact, the real price (in fixed 2000 dollars) actually declined.

Beginning in 1973, however, the rising price of oil changed the U.S. perspective on energy, spurring California and then other states to adopt energy efficiency standards for buildings and appliances. After 1973, as Figure 1 shows, the GDP and energy consumption kept increasing, but the gap between the rates of increase widened dramatically: energy use grew much more slowly than the GDP, and energy intensity improved rapidly. Many factors contributed to these changes, including the increasing cost of energy and the implementation of federal Corporate

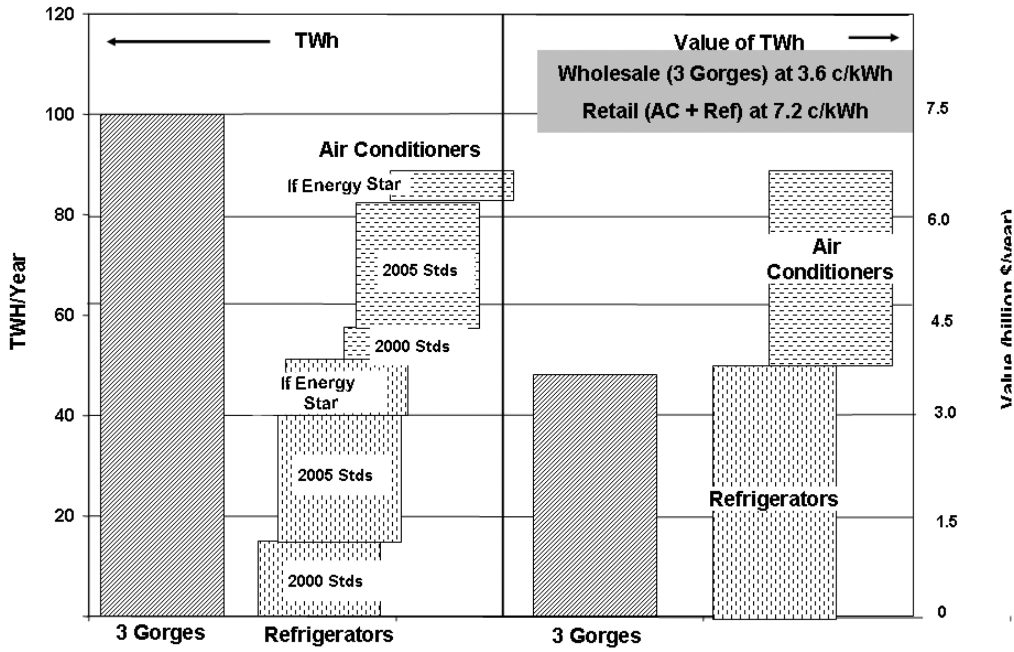

Figure 2. Comparison of Three Gorges Dam in China to Refrigerator and AC Efficiency Improvements.

Average Fuel Economy (CAFE) standards in the transportation sector. We also note that even as energy intensity was improving, U.S. energy use and emissions were increasing though at nowhere near the rate of the 1950s and 1960s.

A central concept of energy efficiency is that it can be measured as a source of energy. Every unit of energy we avoid using thanks to a more efficient device has its equivalent in a unit of fossil fuel that need not be prospected and combusted, or on a macro scale, a power plant that need not be built. Fleshing out the bare concept of avoided use with sound methodology and data has been a core part of our work. Figure 2 shows an especially dramatic example that reaches far beyond California.[4] The Three Gorges Dam in China is the largest hydroelectric power station in the world, completed in 2008 at a cost of $30 billion. The left side of Figure 2 shows the amount of energy the dam can generate, compared to the amount of electricity that will be avoided once all the refrigerators and air conditioners in China meet current Chinese appliance performance standards for, respectively 2000, 2005, or the U.S. Energy Star label. The right side of the graph compares the dollar value of generation and saved or avoided electricity. We spotlight China because the Chinese example points to the amazing opportunities for energy efficiency. The quantity of energy that will be saved or avoided when refrigerators and air conditioners meet more stringent performance standards in China will nearly equal the output from the nation's largest hydroelectric power station. And the "value" of the electricity saved will be nearly double that of the power station.

Energy efficiency is *one* weapon in the arsenal against over-dependence on GHG-emitting fossil fuels. I believe efficiency is the *best* weapon: cheapest, safest, and most immediately achievable. The technological barriers to efficiency improvements are negligible. Efficiency is truly the low-hanging fruit of the alternative energy scene. I now turn to the story of how, beginning in the early 1970s, we worked across many different fields to convince others that significant gains in efficiency could, in fact, become a reality.

"INVENTING" ENERGY EFFICIENCY

The price spikes of the 1973 OPEC embargo drew nationwide attention to energy end-use, but in rapidly-growing California, already sensitized to environmental issues such as smog and water shortages, the problem caused particular concern. I can't claim any great personal prescience: at the time of the crisis, my data set on energy consumption consisted of exactly two points, both gleaned from my European colleagues. First, European cars got an average of 27 miles per gallon, compared to our average of 14 mpg. Furthermore, Western Europeans used on average half as much energy per capita as their American counterparts, but I knew that they weren't "freezing in the dark" (the typical phrase used at the time by anti-conservation naysayers). I had stumbled upon the idea that per-capita energy use could be reduced without deprivation.

My learning curve spiked in 1974 when I served as a co-leader of a month-long workshop on energy efficiency, convened by the American Physical Society (APS) at Princeton University. Our first realization, which soon became a slogan for the field, was "what's cheap as dirt gets treated like dirt." In the world's other advanced economies, a higher dependence on expensive imported fuels made energy costs a critical factor in long-range economic strategy (on tax policy, balance of trade, and national security). Consumer psychology was also affected by higher energy prices: whereas Americans made their purchasing decisions largely on first cost (sticker price), the Europeans and Japanese were more likely to incorporate life-cycle cost (sticker price plus future operating costs) into their decisions. The soaring price of energy had a silver lining as a teachable moment: people could now realize that adopting better efficiency practices would be equivalent to discovering huge domestic oil and gas fields, which could be extracted at pennies per gallon of gasoline equivalent.

The APS summer study was organized as a mixture of briefings by practitioners from commercial sectors where energy consumption was a salient concern (construction, manufacturing, transportation, utilities, etc.), and analytic sessions led by physicists and chemists to discuss the state of research. Our overriding concern was to focus on efficiency improvements achievable with current technology, rather than on theoretically elegant but impractical research. We published our findings and recommendations in *Efficient Use of Energy*, for many years the best-seller of the American Institute of Physics.[5]

The volume set the tone for much of the energy efficiency work to follow, with its mixture of pure and directed research, its incorporation of social and economic factors into the engineering analysis, and its emphasis on feasibility. We were also aware that we had to illustrate our findings with concrete examples that would convey the importance of efficiency to a non-expert public (and government). For example, one-third of *Efficient Use of Energy* was devoted to discussion of recent advances in window technology, such as thin films of low-emissivity (low-E) semiconductor material; when applied to the inside surface of double-glazed windows, they doubled the thermal resistance.

Like much of the volume, this section was highly technical and inaccessible to the lay reader, and yet it contained highly practical implications that we wanted to convey to the public. It was written just as the last environmental objections to the Trans-Alaska Pipeline were overruled in favor of construction. The section's authors calculated that low-E windows, installed nationwide, would save the equivalent of half the oil produced in the Prudhoe Bay oilfields. In combination with other modest efficiency measures, these windows could have eliminated the need for the pipeline; it was this simple memorable fact, rather than the painstaking calculations, that became the public angle for the book.

STATE AND SCIENCE IN CALIFORNIA

Returning to California after the APS Efficiency Study, I took what was intended as a temporary leave from particle physics in order to teach, conduct research, and proselytize about energy efficiency. It seemed logical to focus on buildings and appliances rather than the transportation sector, since the latter was already under the oversight of the Department of Transportation, whereas work on the former was virtually *tabula rasa*. After a few years, it was clear that my sabbatical from physics had turned into a permanent defection. Worse yet, I coaxed a number of other scientists away from traditional career paths in physics or chemistry in favor of the risks of an upstart field. Colleagues including Sam Berman, Will Siri, Mark Levine, and Steve Selkowitz joined me in the process of redirecting our skills from basic research to the mixture of science, economics, and policy that efficiency work entailed. My most promising physics graduate students, David Goldstein and Ashok Gadgil, also joined us.

I do not wish to suggest that California was the only locus of innovation in energy efficiency. Colleagues in other parts of the country made the same career shift and did important early work, including Marc Ross at the University of Michigan and Rob Socolow at Princeton. The critical difference was that we were graced with optimal conditions for our ventures. Lawrence Berkeley National Laboratory (LBNL) had recently come under the fresh leadership of Andrew Sessler, who signaled the lab's intention to engage with society's most pressing problems by creating a new Energy and Environment Division as his first act as director in 1973. The division was a natural host for my Energy Efficient Buildings

Program (later known as the Center for Building Science), and sheltered it from much of the instability and administrative strife faced by similar programs at other institutions. At the same time, the University of California at Berkeley launched a doctoral program in Energy and Resources under the visionary leadership of John Holdren. Because this unique program created a talent pool with the necessary interdisciplinary skill set in policy, economics, and science, we were able to take on more ambitious projects than other institutions.

Finally, and most importantly, our California community of efficiency scientists formed just as the state's first efficiency legislation came into effect. A proposal to establish state oversight of energy supply and demand had been languishing on Governor Reagan's desk since 1973, opposed by utility companies, appliance manufacturers, and the building industry. However, in the atmosphere of crisis following the OPEC embargo, the governor was compelled to act, and the Warren-Alquist Act was signed into law in 1974. The Act established the California Energy Commission (CEC), which had the authority to approve or deny site applications for new power plants, to write energy performance standards for new buildings, to fund research and development, and to support investment in efficiency programs. Soon thereafter, the commission's mandate was expanded to include major appliances. The first generation of state appliance performance standards (Title 20) was published in 1976, followed in 1978 by a building standard (Title 24).[6]

The establishment of the CEC created a market for our research, which in turn made the commission effective. This fortunate convergence of policy requirements and scientific knowledge was a key factor behind California's leadership in energy efficiency. In the years before the commission's in-house research capability was developed, it relied upon local scientists for data, forecasts, testing protocols, and analytic tools. One example was the creation of a computer application to simulate the thermal performance of buildings. In early drafts of Title 24 (residential building standards), the commission proposed limiting window area to 15 percent of wall area, based on the (erroneous) belief that larger window areas would waste heat in winter or "coolth" in summer. No allowance was made for the compass orientation of the windows; indeed, I don't think the sun was even mentioned.

The staff had used a computer simulation that ran on a "fixed-thermostat" assumption, maintaining indoor temperature at 72° F (22° C) year round. Keeping to this exact mark required heating or cooling—or *both*—every day of the year! We saw the need for a simulation that allowed a "floating temperature" mode, permitting indoor temperature to rise slightly during the day, as solar heat entered and was stored in the building's mass, and then float down at night, as the house coasted on stored heat. Such a model could demonstrate that in many situations, expanded window area would actually lower energy demand, supporting the inclusion of passive solar methods in the state building code. Unfortunately, the existing public-domain programs were too awkward and bug-ridden to handle more complex and realistic thermal simulations. I immediately sat down with my colleague Ed Dean, a professor of architecture, to write a residential thermal simulator, which we dubbed Two-Zone because it distinguished between the north and south halves of the house. The CEC was soon convinced to drop the proposed limit on non-north-facing windows, and the concept of passive solar heating was included in Title 24, years before the term itself was in common use.[7]

Two-Zone became the progenitor of a generation of public-domain building performance simulators. When the federal Department of Energy (DOE) was formed in 1976, it funded further development of the software through a collaboration of the national labs at Berkeley, Argonne, and Los Alamos. Since that time, the program, known as DOE-2, has been an essential tool for evaluating energy use in complex systems. Although similar proprietary programs were also developed, the public availability of DOE-2 allowed extensive feedback, which fed the increasing sophistication of the model. While enabling tools such as DOE-2 do not in themselves save energy, without them it would not be possible to write appropriate state and federal buildings standards, or to establish high-profile certification programs such the Green Building Council's Leadership in Energy and Environmental Design (LEED).[8]

Improved HVAC (heating, ventilation ,and air-conditioning) performance in buildings has been one of the most profitable and uncontroversial ways for society to save energy and money.

Improved HVAC (heating, ventilation, and air-conditioning) performance in buildings has been one of the most profitable and uncontroversial ways for society to save energy and money. It would be tedious to calculate exactly how much of these savings can be attributed to the DOE-2 program, since standards were implemented gradually across the states, and some technical improvements occurred independently of implementation. My own guesstimate is that annual U.S. savings in buildings energy use (compared to pre-standards performance) are roughly $10 billion per year, and that the modest allocation of public funds to support the creation of a viable public-domain modeling tool advanced the adoption of standards by one to three years.[9]

THE POLITICS OF DEMAND FORECASTING

Another early task of the California Energy Commission was to determine an appropriate balance between increasing generation capacity through granting permits for new plants and extracting more "service" from the existing supply. Often as not, these decisions took place against a politically charged backdrop. Proposition 15, scheduled to go to California voters in March 1976, proposed to halt the construction of all nuclear power plants. My graduate student David

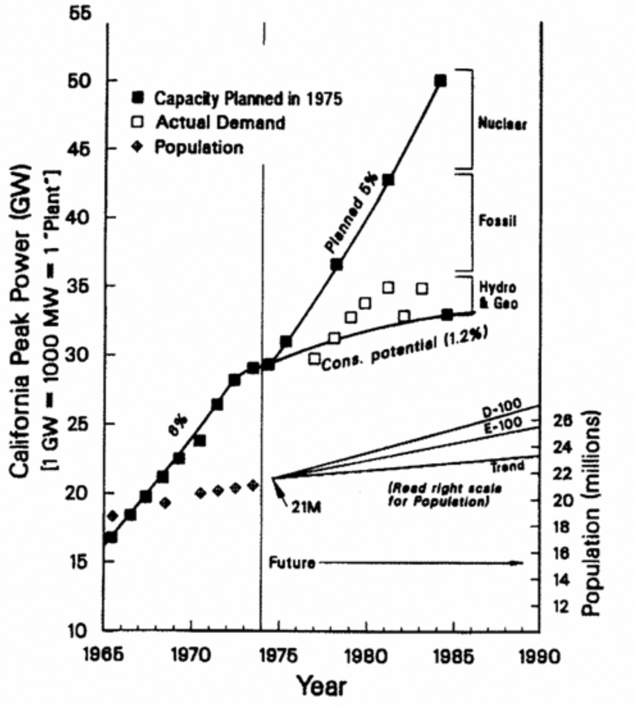

Figure 3. 1975 Projections of California Power Demand: Business as Usual vs. Goldstein & Rosenfeld Efficiency Scenario.

Goldstein and I were determined to cut through the noise surrounding this hot-button issue with the first rigorous study of peak demand forecasts, shown in Figure 3.[10] We hoped that if the rising demand for electricity could be slowed through more efficient performance standards then the contentious issue of new power plants might be avoided.

The left side of Figure 3 shows the actual supply curve during the high-growth decade leading up to 1974, when peak production capacity reached about 30 gigawatts (GW). The right side of the figure compares two future (post-1974) scenarios. Under the "business as usual" (BAU) scenario assumed by the utilities, demand would continue to grow at 5 percent per annum, requiring the construction of an average of two large (one-GW) power plants every year, mainly nuclear or fossil fueled. More than half of that new electricity (i.e., more than one plant per year) would be used to supply electricity to new construction. In the days before Title 24, two of the most egregious sources of waste were widespread electric resistance heating in residences and 24/7 lighting in commercial buildings. When we calculated the potential savings from eliminating these practices, we came to the remarkable conclusion that the state's annual growth rate could drop to 1.2 percent. This scenario would eliminate the need not only for the contentious nuclear plants but also for planned fossil fueled plants. When we demonstrated our findings at a State Assembly hearing in December 1975, the utility companies were so skeptical that Pacific Gas & Electric (PG&E) called Director Sessler to suggest that I be fired on the grounds that physicists were unqualified to forecast electricity demand.

Over the course of the later 1970s and early 1980s, our vision was slowly vindicated and the hostility of PG&E was gradually replaced with a productive collaboration. After 1975, the actual growth of peak demand dropped to 2.2 percent per annum, much closer to our forecast than to that of the utilities. (For purposes of comparison, we later added this actual growth curve to the original version of Figure 3.) The fall from favor of nuclear power plants due to a combination of public opposition and unexpectedly high costs is well known, but in fact no application to build *any* kind of large power plant (nuclear, coal, or gas) was filed in California between 1974 and 1998.[11] Demand continued to grow during that time, of course, but new supply came from small independent producers and co-generators, from renewables (hydroelectric, geothermal, and wind resources), and from sources outside the state. Improved efficiency was the largest single source of new electric services during that period.

After the deregulation of California's energy supply system in the late 1990s, and the ensuing electricity "crisis" of 2001, policies were put in place to encourage the procurement of a "reserve margin" large enough to guarantee reliability. In response to state incentives, investments in both power plants and efficiency accelerated. Fortunately, the benefits of efficiency were not forgotten in the rush to increase capacity. In 2003, the CPUC and the CEC issued the first Energy Action Plan (EAP I)[12] to guide energy policy decisions. A major function of EAP I and of subsequent updates has been to prescribe a "loading order" of energy supplies whenever increased demand needs to be satisfied. For immediate demand crises, demand response (e.g., shutting off unnecessary load) should take precedence over costly purchase of peaking generation from the market. For longer-term supply planning, investments in efficiency should "load" into the supply system before investments in generation; when new generation is necessary, renewable generation should load before fossil generation. From 2001 to 2009, over 15,000 MW of generation resources, including renewables, have been built in California, yet efficiency investments are increasing.[13]

INITIATING APPLIANCE STANDARDS IN CALIFORNIA

Whereas gaining acceptance for state oversight of energy standards in buildings was relatively straightforward, creating a state appliance standard proved more controversial. Since manufacturers usually sold to the national market, federal responsibility seemed more appropriate and effective to most people. In addition, the appliance industry was more concentrated and organized than the construction sector, and thus better able to mount opposition to changes. This did not deter David Goldstein and me from satisfying our curiosity about the correlation

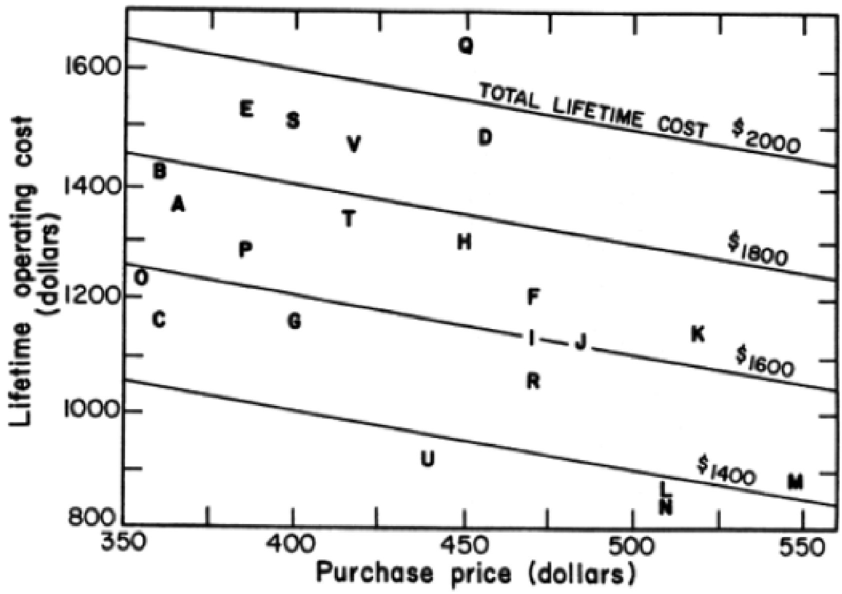

Figure 4. Supporting Appliance Standards: Lifecycle Operating Cost of 1975 Refrigerator Models.

between refrigerator price and efficiency. Our interest in the refrigerator was motivated by its place as the most energy-thirsty appliance in the family home: in the 1970s it accounted for more than a quarter of the typical residential electricity bill. We tested 22 units from model year 1975, expecting to see some correlation between higher sticker price and higher performance, defined as the cooling service delivered per energy input. In other words, if we could establish a correlation between sticker price and efficiency, we could support informed consumer choices based on payback time (how long it takes to offset a high purchase price with lower energy bills) and life-cycle cost (purchase price plus lifetime operating costs).

Figure 4 displays the results of our refrigerator tests as a "scatter chart," the only feasible choice of format given that the data were truly scattered![14] Despite our efforts to control for every factor imaginable (volume, door configuration, options, etc), there was very poor correlation between purchase price and performance. Some of the lowest priced models (C, O) showed the same or even cheaper life-cycle costs than models costing $100 to $200 more (I, J, K). We quickly realized that if the less efficient half of the model group were deemed unfit for the market, the consumer would not perceive any change in the market range of prices or options while being "forced" to save on average $350 over the 16-year service life of a refrigerator. Presumably, as performance standards spurred further technical improvements, these savings would grow. The macroeconomic conclusion was even more exciting: since statewide energy use by refrigerators alone already accounted for about five GW, implementing even mild state standards

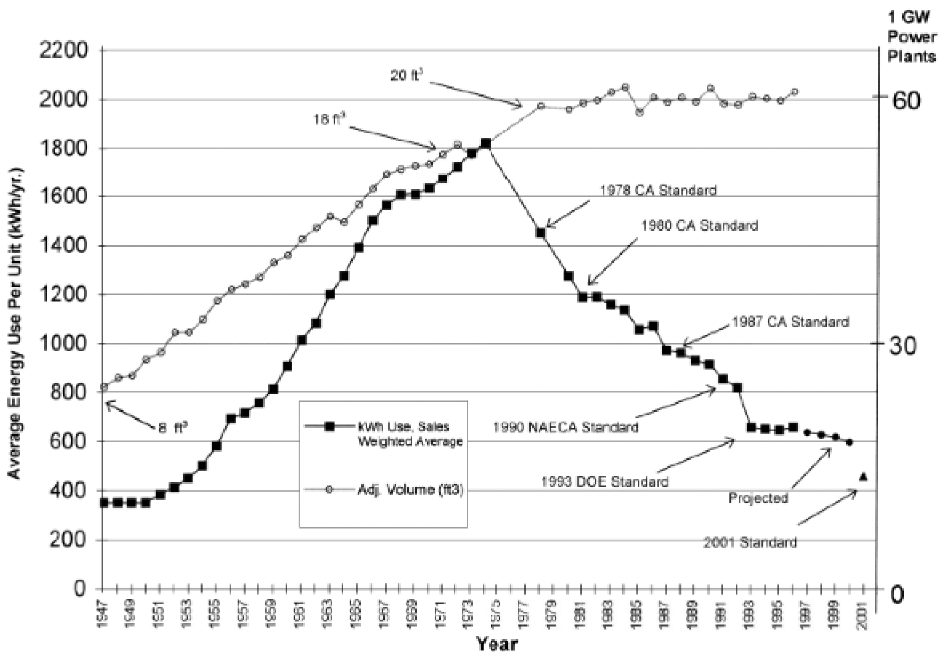

Figure 5. U.S. Refrigerators 1947-2001: Energy Use, Volume, Savings.

could avoid the need to construct numerous power plants.

In 1976 California Governor Jerry Brown was looking for a way to avoid approving Sundesert, the only application still pending for a one-GW nuclear power plant. I took advantage of a chance meeting at the Berkeley Faculty Club to sketch out Figure 4 for him on a napkin. Thinking our findings too good to be true, the governor called Energy Commissioner Gene Varanini for corroboration. I believe his exact words were, "Is this guy Rosenfeld for real?" Commissioner Varanini vouched for us, Sundesert was cancelled, and California's Appliance Efficiency Regulations (Title 20) were implemented later that year.

REFRIGERATORS: AN EFFICIENCY SUCCESS STORY

The dramatic improvement in refrigerator energy efficiency over the last half-century is illustrated in Figure 5, which shows electricity use by new U.S. refrigerators for the model years 1947–2001.[15]

The heavy line with dark squares represents the annual kWh use of the sales-weighted average new refrigerator. Note that the energy consumption of new models has declined steeply in absolute terms, even though this line is not adjusted for increasing volume. In fact, the volume of the average model grew from 8 cubic feet to 20 during this period, as shown by the line marked with open circles; if the consumption line were adjusted for volume, the efficiency gains would look even more impressive. The right-hand scale shows the number of large (one-GW) base-load

(5,000 hours/year) power plants required to power 150 million average refrigerator-freezer units. The difference between the annual energy consumption of an average 1974 model (1,800 kWh) and an average 2001 model (450 kWh) is 1350 kWH. The energy savings from this 1,350 kWh/year difference, multiplied by 150 million units, is 200 TWh/year, equivalent to the output of 50 avoided one-GW plants. The monetary savings of course depends on the price of electricity, which varies considerably. To give a rough sense of the magnitude of savings, at 8 cents/kWh, the avoided annual expense to consumers is $16 billion.

The other factor contributing to the sudden drop in refrigerator energy use in the mid-1970s was the advent of a new manufacturing technology, blown-in foam insulation. The coincidence of California's first performance standards with the market entry of better-performing models began a positive reinforcing cycle that continues to this day. Targeted, government-assisted R&D helps make possible the introduction of increasingly efficient new models, which themselves become the basis for tightening the efficiency standards, because they demonstrate that meeting a tighter standard is technologically feasible. When California standards were tightened in 1980 and 1987, followed by federal standards in 1990, 1993, and 2001, manufacturers were able and willing to meet the challenge, an example of government-industry partnership that has served society very well.

BRINGING THE UTILITY COMPANIES ON BOARD

Turning the utility companies from opponents of energy conservation into stakeholders was a key part of California's innovation in energy efficiency. As mentioned earlier, the encouraging results of initial efficiency policies gradually changed a contentious relationship into a collaborative one. High oil prices lasting through the late 1970s until 1985 helped PG&E and other companies perceive that their interests might lie in supporting affordable conservation rather than in pursuing expensive new energy supplies. However, telling utilities to promote efficiency was essentially asking them to sell less of their primary product and thus to lose revenue, at least according to a traditional business model.

A new business model aligning market incentives with policy objectives was needed. The CEC, the CPUC, and the Natural Resources Defense Council created a new utility business model disconnecting profits from the amount of energy generated. A compensatory revenue stream from public goods charges was awarded to companies that agreed to promote efficiency through consumer education programs or fluorescent lightbulb subsidies. The technique of disconnecting utility company revenue from sales became known as "decoupling." Working out the details of decoupling was, and remains, a complex process, described more fully in the following article by Ralph Cavanagh, one of its chief architects.[16]

One serious obstacle to the innovation of decoupling was the inability to easily compare conventional energy supplies with the potential of conservation. The value of the utilities' efficiency programs could not be established without a stan-

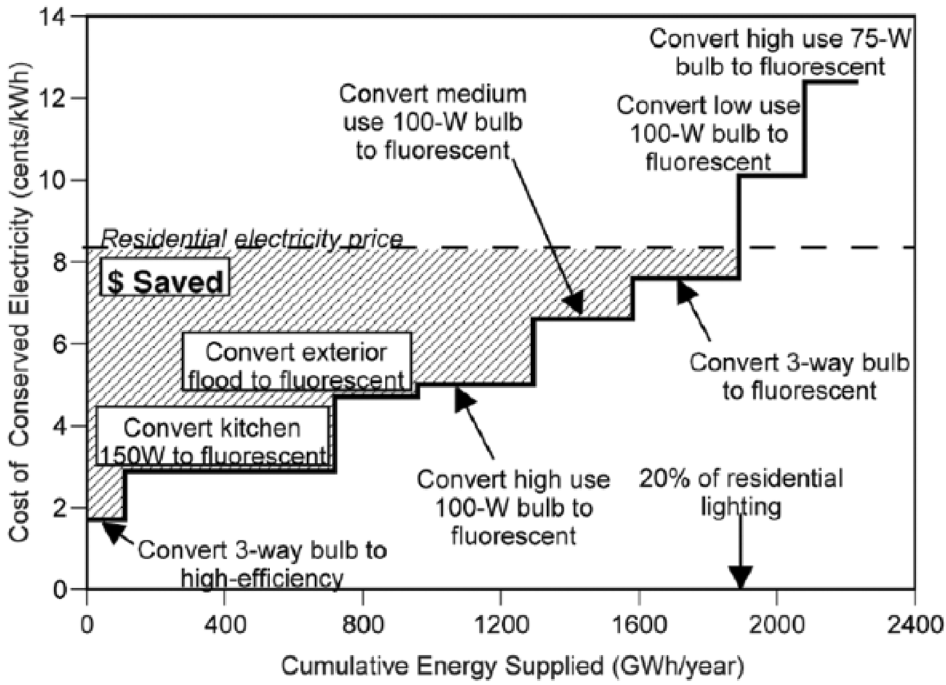

Figure 6. Supply Curve of Conserved Residential Lighting.

dardized way to set equivalencies in cost and scale. Conventional energy supplies tend to be large and concentrated, thus easy to measure, whereas conservation practices tend to be small and diffuse, thus difficult to measure in aggregate. Our task as scientists was to provide data to counter the skeptics who argued that the granular nature of efficiency—a lightbulb here, a new refrigerator there—could not possibly add up to a significant "supply." Alan Meier and Jan Wright of the Lawrence Berkeley National Labs unraveled this tangled methodological problem in the late 1970s by standardizing "bookkeeping" methods for avoided use, and creating a new investment metric, "the cost of conserved energy."[17] This allowed us to aggregate the energy and cost impacts of scattered conservation steps into a unified supply curve.

The basic assumption when calculating the cost of conserved energy (CCE) is that any conservation measure begins with an initial investment, which then creates a stream of energy savings for the lifetime of the measure. Thus:

CCE = [annualized investment cost]/[annual energy savings]

The equitable yearly repayment to an investor (e.g., the utility) should be the annualized cost of energy conserved. In the case of avoided electricity use, the energy savings can be expressed in units of $/kWh, or in other cases in units for gas ($/MBtu), or wind, or geothermal. Since the CCE does not depend on a particular local price or type of displaced energy, the comparisons have the virtue of "portability" across regional price variations and types of supply.

Figure 6, "Supply Curve of Conserved Residential Lighting,"[18] demonstrates the application of rigorous efficiency bookkeeping methods to one sector of energy end-use, residential lighting. The costs of eight different steps to improve lighting efficiency are plotted against the electricity that each measure would save (measured in gigawatt hours per year), and then compared to the actual retail price of electricity. Thus the savings derived from, say, Step 2 ("fluorescent kitchen lighting") are shown by the area between Step 2 and the "price" line, that is, a savings of \$0.05/kWh X 600 GWh = \$30 million. The great virtue of this conceptually straightforward approach was that the cost-effectiveness of various methods was clear at a glance. For example Steps 7 and 8 of Figure 6 are clearly not worthwhile. Furthermore, the supply curves of conserved energy provided a simple way to compare proposed new energy technologies with energy-saving actions.[19] The challenge of creating reliable supply curves is that deriving sound "macro" estimates from the "micro" contributions of individual changes rests on the painstaking collection of data on population, household size, and consumer purchasing practices, along with lightbulb cost, performance, and life span, and much more. Working out the proper energy accounting methods is the core of this work.

ELECTRONIC BALLASTS

The development of electronic ballasts for fluorescent lamps is the key technical innovation behind the recently burgeoning use of compact fluorescent lights (CFLs), which has resulted in tremendous energy savings. The story of electronic ballasts (also known as "high-frequency" or "solid state" ballasts) is a typical example of how innovations in engineering, policy, and commerce need to be aligned to achieve efficiency improvements.

At the APS Efficiency Summer Study in 1974, we considered the feasibility of creating an electronic ballast that would boost current to 1,000 times that delivered by the power line. We knew that such a device would increase the efficiency of fluorescent lights by 10 percent to 15 percent, and also eliminate the annoying buzz that was a major obstacle to replacing quiet but wasteful incandescent bulbs in residential settings. Moreover, electronic ballasts would enable miniaturization, dimming, remote control, and other user friendly, energy-saving features not possible with magnetic ballasts.

Around that time, the major ballast manufacturing firms did in fact consider developing an electronic ballast, but rejected the idea due to the substantial capital investment required and the losses from early retirement of existing infrastructure. As is often the case in overly concentrated sectors—two large firms accounted for 90 percent of the ballast industry—the market provided more disincentives than incentives for innovation. It was clear to us that the impetus for R&D would have to come from elsewhere. In the wake of the APS study, Sam Berman resigned a tenured post at Stanford University to lead LBNL's research on solid-state ballasts (as well as the low-E windows discussed earlier).

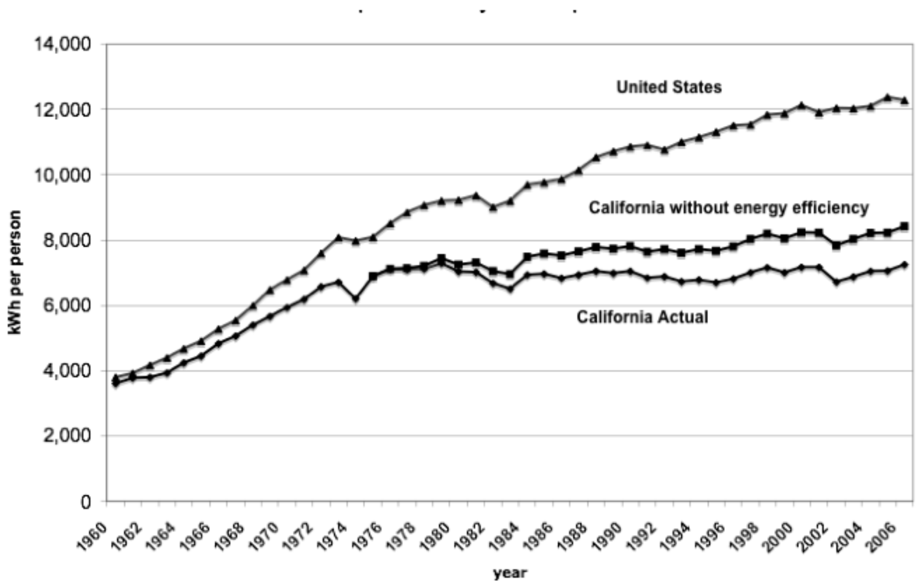

Figure 7. The California Effect? California vs. U.S. Per Capita Electricity Consumption 1960-2006.

Fortunately the newly-formed DOE included a small Office of Conservation and Solar Energy, which was willing to fund both these projects. From 1977 to 1981, the DOE supported the development, evaluation, and introduction of electronic ballasts into the U.S. marketplace. Basic research took place at LBNL and two subcontracting laboratories. Three small, innovative firms new to the ballast field were awarded cost-sharing contracts to carry out development.[20] Berman shepherded the prototypes through UL certification and persuaded PG&E to host a critical field test in its San Francisco skyscraper, which demonstrated electricity savings of greater than 30 percent over magnetic ballasts.

When the first electronic ballasts came to market in the late 1980s, they were so clearly superior that the major lighting manufacturers felt compelled to adopt and continue to develop the technology. Philips, in particular, reasoned that if large electronic ballasts were effective for traditional tubular fluorescent lamps, they could miniaturize ballasts to produce very efficient CFLs. The appearance of products such as Philips' 16-W CFLs, radiating as much light as a 70-W incandescent light and lasting 10,000 hours instead of 750, was a turning point in the penetration of fluorescent lamps into the residential market.

The risk and expense of converting lighting plants to manufacture a new generation of ballasts was an important difference from the earlier case of improving refrigerators. Converting to blown-in foam insulation was comparatively simple, and invisible to the end-user, so it required no consumer re-education. It is unlikely that the large manufacturers would have taken this step without the assurance of market success afforded by DOE-funded research. In the case of electronic bal-

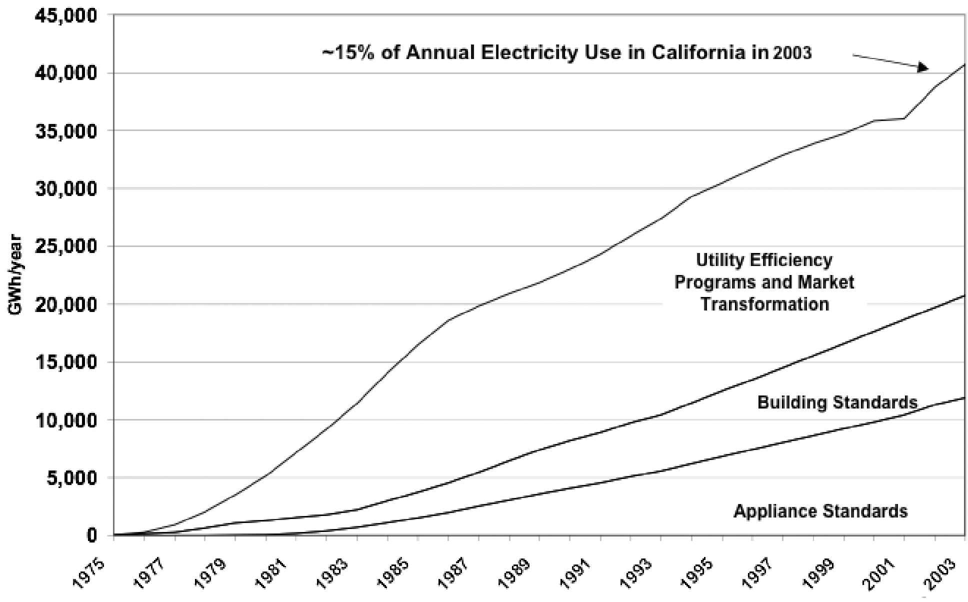

Figure 8. California's Annual Energy Savings Attributed to Efficiency Measures.

lasts, it was much harder to launch a positive reinforcing cycle of tightening standards and improving technologies. States did promulgate efficiency standards for fluorescent ballasts (California in 1983, New York in 1986, Massachusetts and Connecticut in 1988, and Florida in 1989). By themselves, however, state standards could not drive market transformation, since they could be satisfied by conventional magnetic ballasts (which, not coincidentally, improved once the electronic ballasts were developed). The experience suggests that in some cases, the seeding effect of publicly funded research is essential for market transformation.

IS THERE A "CALIFORNIA EFFECT"?

There is little doubt that California's energy efficiency policies have been successful. How successful, exactly, remains an open question. There is an ongoing debate about how much of California's lower per capita electricity consumption is due to policy differences, and how much to climate or the comparatively low level of heavy industry. As the need to reduce energy consumption and CO_2 emissions becomes more urgent, the so-called "California Effect" is coming under increasing scrutiny. Whether or not to emulate California's efforts hangs on the question of their efficacy. Figure 7 shows the difference in per-capita electricity consumption between California and the U.S. for the period 1960 to 2006. In 1960, California's per-capita consumption was within 5 perecent of the national average. The curves gradually diverged between 1960 and the mid 1970s, but the difference was still only about 15 percent at the time of the OPEC embargo. By 2006, however, Californians were using over 40 percent less electricity per capita than the nation-

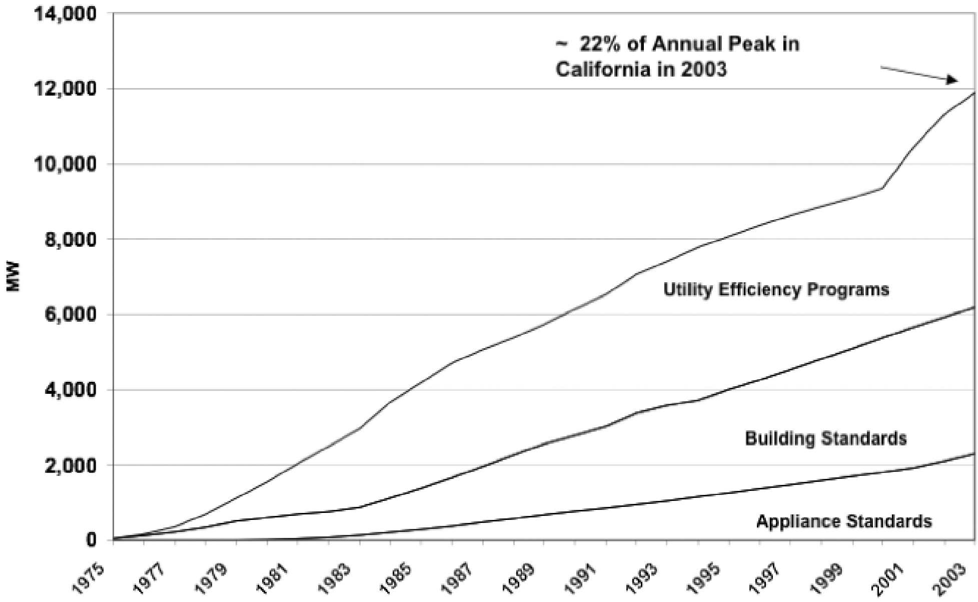

Figure 9. California's Peak Annual Energy Savings Attributed to Efficiency Measures.

al average—and only about 10 percent more than they had in 1975.

Calculating the proportion of electricity savings directly traceable to our efficiency efforts is a complicated task. Our best conservative estimate, shown by the middle line in Figure 7, is that at least 25 percent of the observed difference can be directly attributed to policy—an estimate that does not include any secondary effects due to changes in building practices, and appliance markets. Differences in climate and industrial mix, electricity price, demographic trends, and other factors help explain some of the difference,[21] but other trends have been at work as well. In California, for example, building standards and electricity prices have discouraged the use of electric water heating in favor of natural gas, which reduces electricity consumption relative to the national average.

At the same time, most new housing has been built in the hotter inland valley and desert areas, dramatically increasing energy consumption for air conditioning. Also, most appliance standards initiated in California were eventually adopted nationally, so the policy impacts of appliance standards also affect the national per-capita consumption average, an effect that is not captured by the difference in per-capita consumption. Thus, for a variety of reasons, electricity use in California has been essentially flat and should either continue or even decrease as California extends standards to new devices, accelerates building performance requirements, and expands programs aimed at improving efficiency.

Figures 8 and 9 show California's savings in greater detail, breaking down the part of the consumption gap that can be attributed to efficiency efforts.[22]

Performance standards for buildings and appliances, which as noted have been progressively strengthened every few years, account for roughly half the savings. The other half has resulted from utility company programs that promote adoption of energy efficient technologies, such as commercial lighting retrofit incentives and residential appliance rebates. Through 2003, these measures have resulted in about 40,000 GWh of annual energy savings and have avoided 12,000 megawatts (MW) of demand—the same as 24 500-MW power plants (the MW data is not shown in the graph).[23] These savings have reduced CO_2 emissions from the electricity generation sector by nearly 20 percent compared to what otherwise might have happened without these programs and standards.[24] This equates to an avoidance of CO_2 emissions in the state as a whole of about four percent, due to historical energy efficiency programs and standards.[25] These savings will only continue to grow.

The effect of efficiency policies is even more pronounced at peak load. Peak loads are a serious concern in California, as in other Sunbelt states and many fast-growing economies around the world. Air conditioning loads on hot afternoons can greatly increase system demand—as much 30 percent in California. Reducing the magnitude of these warm-season spikes is one of the most pressing items on the efficiency agenda. Building standards that focus on minimizing heat gain and thermal transfer and appliance standards that set minimum efficiency levels for air conditioning equipment can reduce peak demand. This in turn lowers the customer's immediate cooling costs as well as the system-wide costs of maintaining underutilized peaking capacity year round; both measures contribute to lower bills.[26] Figure 9 repeats Figure 8's breakdown of savings derived from standards and utility programs, but for peak demand. The 12,000 MWs of capacity provided by efficiency measures have effectively avoided the need to build additional power plants to meet that demand.

FROM "INNOVATION" TO "BUSINESS AS USUAL": THE LONG-TERM ENERGY EFFICIENCY STRATEGIC PLAN

When the campaign for energy efficiency in California began four decades ago, the goal was simply to reduce the expense, pollution, and political turmoil resulting from over-dependence on generating energy from fossil fuels. However, as awareness of the climate-changing effects of GHGs grew, so too did recognition of efficiency as a low-cost, low-impact, reliable source of energy. Now that our environmental concerns must share the stage with the current economic crisis, efficiency has suddenly become something of a mantra. Since efficiency investments have some of the fastest payback times in the "green economy," and since efficiency improvements are based on currently available technology, implementation offers a uniquely practical opportunity to stimulate economic growth and reduce GHG emissions at the same time.

A year ago, the California Public Utilities Commission (CPUC) issued California's Long-Term Energy Efficiency Strategic Plan, mapping out the steps toward meeting the state's GHG reduction goals by 2020.[27] The commission estimates that the Strategic Plan will create energy savings of close to 7,000 gigawatt hours, 1,500 megawatts, and 150 million metric therms of natural gas. This is roughly equal to the avoided construction of three 500-megawatt power plants. Avoided emission of GHGs is expected to reach three million tons per year by 2012, equivalent to the emissions of nearly 600,000 cars. It is hoped that new efficiency programs will create between 15,000 and 18,000 jobs, in areas ranging from construction to education. The plan has four "Big and Bold" goals:

- All new residential construction in California will be zero net energy by 2020.
- All new commercial construction in California will be zero net energy by 2030.
- The Heating, Ventilation, and Air Conditioning (HVAC) industry will be reshaped to ensure optimal equipment performance.
- All eligible low-income homes will be energy efficient by 2020.

The budget for just the first three years of the Strategic Plan was recently set at $3.1 From my perspective as a veteran of the efficiency campaign, the Strategic Plan presbillion, making it the largest-ever state commitment to efficiency. Funding will support a wide variety of programs in pursuit of the overarching goals, including the four examples below:

- CalSPREE, the largest residential retrofit effort in the United States, will cut energy use by 20 percent for up to 130,000 existing homes by 2012.
- $175 million will go to programs to deliver "zero net energy" homes and commercial buildings.
- $260 million will go to 64 local agencies (city, county, and regional) that would otherwise lack the expertise to create more energy-efficient public buildings.
- More than $100 million will go to for education and training programs at all levels of the education system.

From my perspective as a veteran of the efficiency campaign, the Strategic Plan presents a fascinating combination of old lessons and new ambitions. Although the overall scope of the plan is far more comprehensive and coordinated than anything yet seen, clearly the content of the programs is based on many years of experience in buildings and appliance standards. Furthermore, the plan was developed in collaboration with more than 500 stakeholder groups, including the state's major investor-owned utilities (IOUs): Pacific Gas and Electric Co., San Diego Gas and Electric Co., Southern California Edison, and Southern California Gas Co. The IOUs will be responsible for actually implementing the programs in their respective regions. The budget for the programs comes from the increased public goods charges authorized by the CPUC, on the condition that the funds be invested in efficiency. The slightly increased costs to ratepayers will be quickly offset by their reduced consumption. Of course, this process of coordinating best engineering practices with policy goals and utility market mechanisms has its origins in our forays into collaboration in the early 1980s.

The most ambitious and innovative aspect of the Long-Term Energy Efficiency Strategic Plan is its insistence on re-branding the practice of energy efficiency as normative behavior rather than crisis response. Commissioners Michael Peevey and Dian Grueneich have frequently spoken of "making efficiency a way of life." If successful, this would mean a reversal of the prevailing mindset. For many years, my graphs of energy supply/demand forecasts displayed competing scenarios labeled respectively "with efficiency measures" and "business as usual." Business as usual was understood to mean "without efficiency measures." If California's Strategic Plan succeeds, the comprehensive approach to energy efficiency that we have been pursuing for over 30 years will have finally become "business as usual."

---

1. California Energy Commission, www.energy.ca.gov/commissioners/rosenfeld.html. A.H Rosenfeld, 1999. The Art of Energy Efficiency: Protecting the Environment with Better Technology, *Annual Review of Energy and the Environment*, 24, pp. 33–82.
2. California Public Utilities Commission (CPUC) and California Energy Commission (CEC), September 2008. *California Long-Term Energy Efficiency Strategic Plan: Achieving Maximum Energy Savings in California for 2009 and Beyond*. www.cpuc.ca.gov/PUC/energy/electric/Energy+Efficiency. Budget announced September 24, 2009: sacramento.bizjournals.com/sacramento/stories/2009/09/21/daily61.html.
3. Graph by Patrick McAuliffe, based on data from the U.S. Energy Information Administration (EIA), Annual Energy Review, 2007. See also A.H. Rosenfeld, P. McAuliffe and J. Wilson, 2004, "Energy Efficiency and Climate Change," *Encyclopedia of Energy*, Vol. 2, pp. 373-382. Elsevier Press.
4. D. Fridley, Lawrence Berkeley National Lab. Savings calculated ten years after standards take effect.
5. American Institute of Physics, 1975. *Efficient Use of Energy: The APS Studies on the Technical Aspects of the More Efficient Use of Energy*. In Proceedings of AIP Conference No. 25.
6. Warren-Alquist Act: www.energy.ca.gov/reports/Warren-Alquist_Act/index.html. Appliance standards: www.energy.ca.gov/appliances/index.html. Building codes: www.energy.ca.gov/title24/index.html.
7. Rosenfeld, 1999, pp. 40-41.
8. "Energy Research at DOE: Was It Worth It?" E*nergy Efficiency and Fossil Energy Research 1978 to 2000,* Appendix E, "Case Studies for the Energy Efficiency Program," pp 100-104. Washington, DC: National Academies Press, 2001.
9. Rosenfeld 1999, 40-41.
10. D.B.Goldstein and A.H. Rosenfeld, 1976. *Projecting an Energy Efficient California*, LBL 3274//EEB 76-1, Lawrence Berkeley National Lab. See also Rosenfeld, 1999, pp. 41-42.
11. Rosenfeld, 1999, p. 42.
12. www.energy.ca.gov/energy_action_plan/index.html
13. http://docs.cpuc.ca.gov/PUBLISHED/FINAL_DECISION/106008.htm
14. D.B.Goldstein and A.H. Rosenfeld, 1977. "Facts and Fact Sheets on Home Appliances." *In Energy Extension Services*, Proceedings of 1976 Berkeley Workshop. Lawrence Berkeley National Laboratory.
15. H.S. Geller and D.B. Goldstein, 1999. "Equipment Efficiency Standards: Mitigating Global Climate Change at a Profit," *Physics and Society* 28(2).
16. For the evolution of "decoupling," formally known as the Electric Rate Adjustment Mechanism (ERAM), see, inter alia, B. Barkovich, 1989, *Regulatory Interventionism in the Utility Industry*, Quorum; and R. Hirsh, 1999, Power Loss: *The Origins of Deregulation and Restructuring in the American Electric Utility System*, Cambridge, MA: MIT Press.
17. A. Meier, J. Wright and A.H. Rosenfeld, 1983. Supplying Energy Through Greater Efficiency: The Potential for Conservation in California's Residential Sector, Berkeley, CA: University of California Press.
18. Meier et al. 1983.
19. 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, but the 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.

20. Energy Research at DOE: Was It Worth It? Appendix E, pp. 104-107. DOE's call for bids in 1977 received no responses from the major ballast manufacturers. Of the small firms that did receive a contract, one eventually developed into a significant, independent ballast manufacturer. At first, one of the large manufacturers of traditional ballasts actively sought to prevent the introduction of the electronic ballast by acquiring the technology from this firm and then preventing its dissemination. In 1990, after 6 years of litigation and a $26 million damage award, control over the technology was partially reacquired by the originating small business.
21. For a discussion of some of these factors, see Anant Sudarshan and James Sweeney, "Deconstructing the 'Rosenfeld Curve.'" Working paper, Stanford University, June 1, 2008.
22. Because California's population has been growing, the 25% of per capita effect in Figure 7 corresponds to the 15% effect on total consumption per year in Figure 8.
23. California Energy Commission, "Implementing California's Loading Order for Electricity Resources," Staff Report, CEC-400-2005-043, July 2005, p. E-4.
24. This calculation is based on a marginal CO2 emissions rate of nearly 0.5 tons per MWh for a natural gas fired power plant with a marginal heat rate of just over 9,000 btu/kWh.
25. Calculated from the product of 22% of the state's CO2 emissions from electricity consumption and the reduction of 20% in electricity use due to standards and programs.
26. California Energy Commission, Implementing California's Loading Order, p. E-4.
27. CPUC and CEC, California Long-Term Energy Efficiency Strategic Plan, September 2008; www.cpuc.ca.gov/PUC/energy/electric/Energy+Efficiency.
http://docs.cpuc.ca.gov/published/News_release/91027.htm;
www.californiaenergyefficiency.com/index.shtml;
www.reuters.com/article/topNews/idUSTRE58N70520090924.