Science and society test X: Energy conservation

David Hafemeister

Center for Building Sciences, Lawrence Berkeley Laboratory, Berkeley, California 94720 and Physics Department, California Polytechnic University, San Luis Obispo, California 93407

United States energy consumption has remained essentially constant at about 80 exajoules/year (75 quads/year) since the oil embargo of 1973–1974, while the GNP in constant dollars has increased by about 30%. This article will discuss the physics behind some of these improvements in end-use efficiency in such areas as: (i) buildings (scaling laws, "free-heat," superinsulated houses, thermal storage in large buildings, off-peak cooling), (ii) solar energy (passive, photovoltaics), (iii) utility load management ("smart meters," capital recovery fees, voltage control), (iv) appliances (life-cycle costs, refrigerators), and (v) lighting (isotopic enhancement).

I. INTRODUCTION

A decade has passed since the oil embargo of 1973–1974. The physics community initially responded to the problem of the "energy crisis" by conducting a study in 1974 at Princeton University on the Efficient Use of Energy.[1] The impact of this book went far beyond the physics community as it became the largest selling AIP Conference Series book. Many of the technical ideas discussed by physicists in AIP **25** were untested concepts at the time; some of these ideas later became the focus of research, development and, ultimately, commercialization.

The oil embargo of 1973–1974 and the sharp rise in the price of petroleum from $2.50/barrel in 1972 to $30/barrel in 1980 (and about $15 in 1986) forced the world to think more seriously about the fuels that drive our economic engine. Prior to 1973, the era of cheap energy had propelled the industrial revolution and helped develop inefficient and expansive consumer lifestyles. The government responded to the energy crisis in many ways: incentives for more production of energy from many different sources, incentives to encourage reduced consumption of energy by enhanced end-use efficiency, a strategic petroleum reserve to give the US protection from sudden disruptions in imports, efficiency labels for appliances and automobiles, mileage standards for automobiles, and so forth. As we now look back on the results, it is clear that the new sources of energy did not produce very much in the decade after the oil embargo. What is also clear is that conservation (enhanced end-use efficiency) made the lion's share contribution to our present state of relative well being.

Because of progress on energy, the US has improved its status in financial, political, and environmental matters. The US is importing about 40% less petroleum than in the peak year of 1977; a drop from 8.8 million barrels per day (Mb/d) in 1977 to 5.4 Mb/d in 1984. This reduction in imports alone has saved the US about $25 billion per year. The total savings from all sources of energy is about $140 billion per year when compared to projections of energy consumption of more than 100 quads/year for 1985. The "lock-step" relation between the GNP and energy has been unlocked; as the GNP increased by 30% since 1974, total energy consumption has remained relatively constant.

The euphoria arising from the above results should be tempered for a variety of reasons. In February 1985, the Department of the Interior slashed its estimates for offshore oil and natural gas resources by about a factor of 2 from 27 to 12 billion barrels of oil, and from 163 to 91 trillion cubic feet of gas. In spite of the $250 billion investment to discover and develop new petroleum wells, the US oil reserves have declined[2] by 13% in 6 yr and the US natural gas reserves have remained essentially constant. The US still spends about \$40 billion per year to import oil, about 20% of the present deficit of \$200 billion. There is continued concern about the greenhouse effect since the CO_2 content of the atmosphere has risen from 330 to 345 ppm in the last decade. And, acid rain threatens lakes and forests.

In 1985 the APS Forum on Physics and Society reviewed the technical progress on the conservation technologies since the oil embargo in a book,[3] *Energy Sources: Conservation and Renewables*. This paper applies basic physics in a question–answer format[4] to discuss some of the topics covered in AIP **135** such as buildings, thermal storage, passive and photovoltaic solar energy, utility management, appliances, and lighting.

II. ENERGY AND BUILDINGS

In 1984, US buildings[5] used about \$165 billion (B) for energy, or about 38% of the total US energy budget of \$430 B. About \$100 B of the \$165 B was spent on electricity in buildings, \$55 B in the residential sector and \$45 B in the commercial sector. Since the \$100 B for electricity in buildings is 75% of the national electrical bill of \$135 B, it is clear that the use of electricity in buildings will strongly determine the future growth of electricity in the US.

A. Scaling laws

As one might expect, large commercial buildings have quite different energy characteristics from small buildings or residences. In large buildings the main source of heat gain is internal (equipment, people, lighting, solar, etc.). In small buildings the main external heat gains and losses are caused by the climate, the heat passing through the envelope, or shell, of the building. Examine the transition from small to large buildings by considering some scaling laws for energy gains and losses by considering buildings that are cubes of length L and volume L^3.

1. Answer

The rate of winter heat loss from our building is proportional to its surface area $L^2\Delta T$, where ΔT is the inside–outside temperature difference. If the thermal conductivity of the buildings envelope (and fresh air) is KL^2, then $\dot{Q}(\text{loss}) = KL^2\Delta T$. On the other hand, the internal heat gains in our building are proportional to the floor space which is proportional to the volume of a multistory building, or $\dot{Q}(\text{gain}) = GL^3$. [The solar gain ($\propto L^2$) will be considered in Sec. III.] Without space heat or air conditioning the steady-state gains and losses are equal, or

$$\dot{Q}(\text{gain}) = GL^3 = \dot{Q}(\text{loss}) = KL^2\Delta T(\text{free}) \tag{1}$$

and the building floats above the ambient temperature by the "free-temperature,"

$$\Delta T(\text{free}) = (G/K)L\,. \tag{2}$$

The thermostat will not call for heat until T(ambient) drops ΔT(free) below the comfort temperature T(thermostat). The temperature when the furnace turns comes on (ignoring thermal mass) is called the "balance point" of a building, when $T(\text{ambient}) = T(\text{thermostat}) - \Delta T(\text{free})$. At the balance point, the internal heat gains are exactly balanced by the heat losses without auxiliary space heat and the occupants are at the thermostat temperature. As we scale up the size of the building, $\dot{Q}$(gain) raises ΔT(free). For a ΔT(free) of 15 °C (30 °F), the length L must be about $15(K/G)$. At outdoor temperatures below the balance point, the net steady-state rate of heat loss is

$$\dot{Q}(\text{net}) = \dot{Q}(\text{loss}) - \dot{Q}(\text{gain}) = KL^2[\Delta T - \Delta T(\text{free})]$$
$$= KL^2(\Delta T - (G/K)L)\,, \tag{3}$$

where KL^2 is the "lossiness" of the building. Additional insulation (lower K) saves fuel in the three ways: (i) The loss coefficient K is reduced. (2) ΔT(free) from internal gains is subtractive and it is increased $(1/K)$. (3) The distribution of degree days favors the initial improvements in ΔT(free). If $\Delta T(\text{free}) = 5$ °C over a heating season of 120 days in an average US location of 2700 °C degree days (°Cdd), the number of heating degree days is reduced by (600 °Cdd/2700 °Cdd) = 22%.

B. Free-heat

Even in winter, the internal heat gains in a large building can overwhelm the loss of heat through the walls, overheating the building. In summer the air conditioning used to remove the excess heat from the buildings causes most US utilities to experience their peak demand in the afternoon. On the other hand, the internal gains can be beneficial since they are sufficient to heat a large building or a superinsulated small building. Equate the gains to the losses, using the appropriate numerical parameters from Table I, and determine the amount of "free-temperature" available in a building. The average (sensible) power of a person is 75–100 W (350 BTU/h). In a large building the density of people is about one person/10 m^2 (100 ft^2), providing a heat intensity of about 11 W/m^2 (1 W/ft^2). The lighting and equipment gains can be about three times (or more) this amount, or 33 W/m^2 (3 W/ft^2). Since the internal and solar gains can vary widely, we shall use a range of values for the internal gain of 66 ± 22 W/m^2 (6 ± 2 W/ft^2).

1. Answer

The floor area of a building is $nL^2 = L^3/H$, where n is the number of floors in the building and H is the interfloor height of about 3 m (10 ft). The internal gain of the occupied building in SI units (watts, mks) is

$$\dot{Q}(\text{gain}) = (66 \pm 22)(nL^2) = (22 \pm 7)L^3\,. \tag{4}$$

The steady-state loss rate from a building is

$$\dot{Q}(\text{loss}) = \sum_i U_i A_i \Delta T + \rho \dot{V} c \Delta T\,, \tag{5}$$

Table I. California thermal resistance standards in SI (English) units for high rise office buildings (1987) and residences (1985). The standards for the R values for walls depend on their heat capacity. In addition, assume the following for the office buildings: (i) glazing is 30% of wall area, (ii) basement losses are about 50% of ceiling losses, infiltration and ventilation losses are about 30% of total $UA\Delta T$.

	High rise office buildings	Residences
Ceilings	$R-2.62$ ($R-14.9$)	$R-5.27$ ($R-30$)
Walls	$R-1.14$ ($R-6.5$)	$R-3.34$ ($R-19$)
Glazing	Single $R-0.16$ ($R-0.9$)	Double $R-0.26$ ($R-1.5$)

where A_i is the area of each envelope component; $U = 1/R$, where U is the conductance and R is the thermal resistance; ρ is the density of air; $\dot{V}$ is the flow of incoming air (m^3/s); and c is the specific heat of air.

The loss rate from the cubic structure is

$$\dot{Q}(\text{loss}) = 1.3[\dot{Q}(\text{ceiling} + \text{basement}) + \dot{Q}(70\% \text{ walls}) + \dot{Q}(\text{windows})], \quad (6)$$

$$\dot{Q}(\text{loss}) = 1.3L^2\Delta T[1.5/2.62 + 0.7(4)/1.14 + 0.3(4)/0.158] = 13.8L^2\Delta T. \quad (7)$$

Equating the steady-state losses [Eq. (7)] to the internal gains [Eq. (4)], we obtain

$$\Delta T(\text{free}) = (1.6 \pm 0.5)L\ [L(\text{m}), T(°\text{C})]. \quad (8)$$

The free-temperature for a balanced (occupied, unheated) new office building of 10 m (33 ft) on a side is 16 ± 5 °C (29 ± 10 °F). If the thermostat were set at 20 °C, the furnace would turn on at the balance point of 4 °C (20° − 16 °C). A large building (or a superinsulated building) can have a balance point close to the average winter ambient temperature. Of course, this example is pedagogical in nature, but the basic physics is correct; large office buildings have useful free-heat in winter, and too much heat in summer (and often in winter) that necessitates either air conditioning or thermal storage. Because the internal loads dominate in large buildings, the annual energy intensity (kW h/m^2, BTU/ft^2) of large buildings does not depend very much on the climate. Proper controls can minimize heating and cooling by ventilation, thermal storage, and heat recovery systems, so that in actual practice large buildings can consume less energy/area than small buildings.

C. Superinsulated houses

Houses have $\frac{1}{5}$–$\frac{1}{10}$ the intensity of internal heat, about 1 kW for a typical[6] house of 110 m^2 (1200 ft^2), or 8 W/m^2, compared with 66 W/m^2 for a large office building. Houses also can lose their internal energy more easily since they have a larger surface to volume ratio; thus the energy intensity of a house is much more dependent on its climate than for a large building. These physical facts require that houses have considerably higher insulation standards (Table I) than large buildings.

The heating bill for a superinsulated house in Minnesota can be less than \$200/yr. Compare the "free-temperature" and balance points for a house with strict building standards (lossiness of $KL^2 = 200$ W/°C) and a superinsulated house ($KL^2 = 100$ W/°C). Both houses have an internal heating rate of $GL^3 = 1$ kW.

1. Answer

From Eq. (2),

$$\Delta T(\text{free}) = GL^3/KL^2 = 1000\text{ W}/200\text{ W/°C} = 5\text{ °C}$$

and a balance point of (20° − 5 °C) = 15 °C for the house with energy standards. By reducing the lossiness by 50% for the superinsulated house, we obtain ΔT(free) = 10 °C and a balance point of (20° − 10 °C) = 10 °C. The \$200 heating bill for the superinsulated house results from the three savings mentioned in Sec. II A [reduced conduction, increased ΔT(free), degree-day distribution function]. The heating bills could be further reduced to less than \$100/year with additional reductions in the lossiness. In Sec. III C we will consider the solar gains for these two houses.

D. Heat and coolth storage in large buildings

Concrete floor/ceiling slabs have a large heat capacity (100 W h/m^2 °C), but for acoustical reasons this is normally poorly coupled to the room air. In the Swedish "Thermodeck" system,[7] the supply air is distributed via hollow cores in the floor slabs. These cores are already extruded in slabs to reduce the ratio of weight to thickness, but they are normally not exploited for the heat storage. Even though Stockholm (3580 °C day, 6444 °F day) is colder than Chicago, the Thermodeck office buildings annually use only about 4 kW h/ft^2 for electric resistance heating, which is so little that it does not pay to hook up to the Stockholm district heating system.

Estimate the heat gains and losses for a Thermodeck building to determine if it is possible to operate the Thermodeck building essentially without fuel for heating. A single-occupant Thermodeck office is 2.4-m wide by 4.2-m deep by 2.7-m high, or 10 m^2 in area and 27 m^3 in volume. We will assume a cold day in Stockholm of − 8 °C (18 °F) for a temperature difference between the inside and outside of ΔT = 22 °C − (− 8 °C) = 30 °C (54 °F). Assume one person/office (100-W sensible heat only) and that the lights and machines contribribute 300 W/office. Because Swedish offices must all have windows, the Thermodeck building has a large surface/volume ratio. Thus its insulation standards are quite high: Each office contains 1.5 m^2 of triple-glazed windows/office ($U = 2$, metric), 5 m^2 of wall surface ($U = 0.25$), natural infiltration of 5 m^3/h during unoccupied hours, and a total air flow of 20 m^3/h during occupied hours to maintain air quality. (Air $\rho = 1.2$ kg/m^3, $c = 1000$ J/kg °C). The solar gain is 30 W/office during the occupied hours in winter.

1. Answer

The energy loss/office from infiltration during the unoccupied hours is

$$\dot{Q} = \dot{m}c\Delta T = (5\text{ m}^3/\text{h})(1.2\text{ kg/m}^3) \times (1000\text{ J/kg °C})(30\text{ °C}) = 50\text{ W} \quad (9)$$

and 200 W during the occupied hours.

Heat gains per 10 m^2 office when occupied:
(i) One person/10 m^2 = 100 W (sensible heat only).
(ii) Lights and machines = 300 W.
(iii) Solar gain (small in winter) through 1.5 m^2 = 30 W.

Total gain eight occupied hours = 430 W/10 m^2.

Heat losses per 10 m^2 office (losses are negative gains):
(i) Wall = $(U)(A)(\Delta T)$ = (0.25)(5)(30) = − 38 W.
(ii) Window = $(U)(A)(\Delta T)$ = (2)(1.5)(30) = − 90 W.
(iii) Outside Air = − 200 W (occupied), − 50 W (unoccupied).

Total loss = − 330 W (occupied), − 180 W (unoccupied).

Gains − Losses: occupied = + 100 W, unoccupied = − 180 W/10 m^2.

Because forced convention gives good thermal contact between the hollow cores and the room air, the temperature of the concrete is not very different from the temperature of the room air. We start at time $t = 0$ h, with an offset (precooled or preheated) temperature T_0. Then the temperature T of the room air is given by

$$T = T_0 + \dot{Q}t/C , \qquad (10)$$

where C is the heat capacity of the concrete slabs and $\dot{Q}(W/m^2)$ is the net internal rate of heating the room. The heat capacity of the 30-cm-thick slabs is about 100 W h/m^2 C; this number is increased by 20% to account for the heat capacity of the walls and furnishings. Using these values, we obtain

$$\text{occupied } (W = 10\ \text{W/m}^2), \quad T = T_0 + 0.1t , \qquad (11)$$

$$\text{unoccupied } (-18\ \text{W/m}^2), \quad T = T_1 - 0.2t . \qquad (12)$$

The small temperature rise of 1 °C during the day [Eq. (11)] agrees with measurements. The temperature drop during the evening (with the fan off) is closer to 1 °C [and not 2 °C from Eq. (12)] since the rooms are allowed to become quite cool, reducing their thermal losses through the envelope. In the US the storage of summer night coolth is much more significant than winter heat. During the deep cooling season, one can run chillers at night to precool the slabs; this does not save much energy (kW h), but does avoid annual peak power charges of \$50–\$100/kW. A slab does not quite have the heat capacity to keep an American office cool all day, but it can be aided with a small water or ice storage system. In mid-season, nights are cool enough to precool without running the chiller, thus saving kilowatt hours.

E. Thermal storage to reduce peak power demands

Since internal heat gains dominate in large buildings, air conditioning must be used to make these buildings both comfortable and useable. Primarily because of air conditioning, the nation's power grids have a severe peak power problem. The peak demand on hot afternoons can often be two or three times the demand at night. Presently 58% of US homes are air conditioned. The fraction of new, single-family homes installing air conditioning has dramatically risen from 25% in 1966 to 70% in 1983, increasing the peak demand of electricity by about 2 GW/yr. The high growth rate for new commercial buildings (replacement plus growth $= 5\%/\text{yr} = 2.5$ B ft^2/yr) causes a growth in peak demand of about 1.6 GW/yr. Residential and commercial air conditioning each account for 80 GW, totaling to 160 GW (32% of peak summer power demand of 500 GW). The potential savings in peak power (kW) are very large; the adoption of off-peak cooling with thermal storage and down-sized chillers could help reduce these peak loads.

In 1977, Stanford University realized that its daytime cooling requirements were going to rise from 5 MW (5000 tons of air conditioning) during the peak hours to about 8 MW by 1986. The additional 3 MW of chillers and cooling towers were going to cost about \$1.5 million, but Stanford discovered that for \$1 million it could build a 4-million-gallon insulated tank for cold water storage and connect it to the present chillers. In this way Stanford could meet one-half of its 8-MW afternoon load by running its present capacity at night, saving 50% of its peak power charges. Thus Stanford saved \$0.5 million in initial investment costs, and shaved 3.5 MW in its peak load, which saved \$200 000 per year.

The headquarters for the Alabama Power Company[8] in Birmingham, Alabama has installed five large ice cells containing 550 tonnes of ice to cool the 110 000-m^2 (1.2 million ft^2) building, or 5 kg/m^2. Without this thermal storage it would have taken 2.8 MW to cool the building. How much peak electrical power can be saved by freezing the ice during the 16 off-peak hours? Assume a COP of 2.5 to make the ice.

1. Answer

The latent heat per m^2 is

$$Q = (5\ \text{kg})(3.4\times10^5\ \text{J/kg}) = 1.7\times10^6\ \text{J/m}^2 . \qquad (13)$$

The electrical power needed to make this ice during the 16 off-peak hours is

$$P = Q/(\text{COP})(\Delta t)$$
$$= (1.7\times10^6)/(2.5)(16\ \text{h}) = 12\ \text{W/m}^2 . \qquad (14)$$

This gives a total of 1.3 MW for the entire building, which is less than $\frac{1}{2}$ the 2.8 MW required without thermal storage. Since the air conditioning runs during the day, the cool stored in the ice is only about $\frac{2}{3}$ of the cooling requirement. The daily gain must be about $(\frac{3}{2})$ $(1.7\times10^6\ \text{J}) = 2.6\times10^6$ J/m^2, which corresponds to an average heating intensity (solar plus internal) of about 100 W/m^2 (10 W/ft^2) during the day.

III. SOLAR ENERGY: PASSIVE AND PHOTOVOLTAICS

In this section we will discuss two solar technologies: (i) passive solar[9] (glass + mass) heated houses which can compete in the marketplace and (2) electricity from photovoltaics[10] which is not yet competitive for normal uses, but sales of 25 MW in 1984 indicate a beginning.

A. Solar flux as a function of angle

When the sun is in the zenith position (overhead), the solar flux above the atmosphere is 1.353 kW/m^2. Because of absorption in the atmosphere, this flux is reduced to about 0.970 W/m^2 at sea level. What is the solar flux at sea level as a function of the angle (θ) of the sun from the zenith position?

1. Answer

The solar flux (S) is diminished by small amounts of air mass (dm); $dS = -\beta S dm$, where β is a constant, which gives

$$S = S_0 \exp(-\beta m) . \qquad (15)$$

Sunlight at an angle of θ from the zenith passes through N times as much air mass as sunlight in the zenith direction ($m = m_0$ at $\theta = 0$), giving a total air mass of

$$m = N m_0 = m_0 \sec(\theta) . \qquad (16)$$

This modifies the expression for the solar flux to

$$S = S_0 \exp[-\beta m_0 \sec(\theta)] . \qquad (17)$$

The constant βm_0 is determined by comparing the solar fluxes above the atmosphere (S_0) and at sea level (S_Z)

when $\theta = 0$:

$$S_Z = 0.97 = S_0 \exp[-\beta m_0 \sec(0)]$$
$$= 1.353 \exp(-\beta m_0), \quad (18)$$

which gives $\beta m_0 = 0.333$. Thus

$$S = S_0 \exp[-\sec(\theta)/3] \quad (19)$$

for the normal solar flux on a clear day at sea level. The flux through a horizontal surface is obtained by multiplying by $\cos(\theta)$. The flux through a vertical surface is obtained by multiplying by $\sin(\theta)$ when the azimuthal angles of the vertical surface and the sun are the same.

B. Integrated solar flux

What is the daily flow of solar energy through a south-facing, vertical window surface at 40 °N latitude on the winter solstice (22 December)? The scattered solar flux is about 25% of the direct flux. The average transmission of light through glass is about $T_r = 0.9$.

1. Answer

At solar noon on the winter solstice, $\theta = \theta(\text{latitude}) + 23°$ (the tilt of the Earth) $= 40° + 23° = 63°$; on the summer solstice, $\theta = 40° - 23° = 17°$. The vertical solar flux on the winter solstice at solar noon is about

$$S'_V = 1.25 \times 1.353 \sin(63°) \times \exp[-\sec(63°)/3] = 0.72 \text{ kW/m}^2. \quad (20)$$

The data in Fig. 1 shows that the solar flux over the day can be roughly approximated by

$$S_V(t) = S'_V \sin(2\pi t/T), \quad (21)$$

where $t = 0$ is sunrise and $T/2$ is sunset. This ignores the additional air absorption and misalignments at angles larger than θ, but it is not a serious error. The integrated solar flux obtained by a window on a clear day over the daylight hours ($T/2 = 10$ h at 40 °N latitude) is

$$I = \int_0^{T/2} S'_V T_r \sin\left(\frac{2\pi}{T}\right) dt = S'_V T_r T/\pi$$
$$= (0.72 \text{ kW/m})(0.9) \frac{(20 \text{ h})}{\pi} = 4.1 \text{ kW h(heat)/m}^2. \quad (22)$$

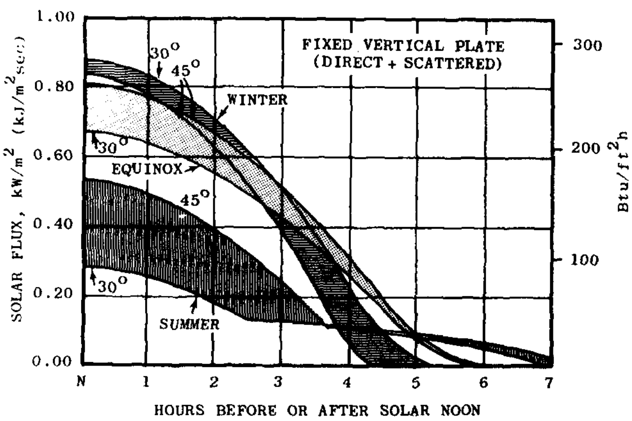

Fig. 1. Variation of flux from direct plus scattered sunlight on a vertical flat plate as a function of latitude and of time of day and season. [A. Meinel and M. Meinel, *Applied Solar Energy: An Introduction* (Addison-Wesley, Reading, MA, 1976).]

C. Solar sizing

How much south-facing glass would be needed to heat the two houses from Sec. II C at 40 °N latitude? Assume an average outside temperature of $T_0 = 0$ °C, clear skies, and $R = 0.26$ for the additional glazing.

1. Answer

By adapting Eq. (3), the daily heat loss, including the additional south-facing window, for the house with strict building standards is

$$Q/d = (200 + A/0.26)(20° - 5 °\text{C})(24 \text{ h})$$
$$= 72 \text{ kW h(heat)} + 1.4A, \quad (23)$$

where A is the area of the additional windows in m^2. For the superinsulated house, $Q/d = 24$ kW h $+ 0.92A$. By decreasing the lossiness (KL^2) by a factor of 2, ΔT(free) was increased by a factor of 2, reducing the heat requirement (for this case) by a factor of 3. The area of south-facing glass for the house with standards is

$$Q/d = (A)(I) = (A)(4.1 \text{ kW h/m}^2)$$
$$= 72 \text{ kW h} + 1.4A, \quad (24)$$

which gives $A = 26$ m^2 for the house with standards on a clear day. The slogan of "insulate before you insolate" is relevant since the superinsulated house requires only 7.5 m^2, or only $\frac{1}{4}$ that of the house with standards.

D. Thermal time constants

The time constant for the storage of passive solar energy should be at least 15 h in order to sustain room temperatures through the night. What is the approximate time constant of a barrel of water with an area of $A = 2$ m^2 and a mass of $m = 140$ kg? The net conductance from radiation and convection of a surface is about $U = 6$ (metric).

1. Answer

The heat loss from the barrel reduces the water temperature,

$$\dot{Q}(\text{loss}) = UA\Delta T = mc(\Delta \cdot T). \quad (25)$$

The temperature difference falls exponentially as

$$\Delta T = \Delta T_0 \exp(-t/\tau), \quad (26)$$

where the time constant

$$\tau = mc/AU$$
$$= (140 \text{ kg})(4200 \text{ J/kg °C})/(2 \text{ m}^2)(6) \cong 14 \text{ h}. \quad (27)$$

E. Photovoltaic cells

Since solar powered PV cells can be installed by homeowners on their roofs, they are potentially attractive because electricity could be decentralized and independent of public utilities. The main impediments are the high capital costs of PVs and electrical storage. As long as PVs are a small part of the electrical grid, they can be used to reduce the peak power demands during the daytime, or they can be used in conjunction with stored hydropower which can be turned on in the evening when the sun is not shining. What is the efficiency of a silicon PV that has the following properties: (i) Band gap of 1.1 eV. (2) Open circuit voltage of 0.6 V which indicates that about 45% of the electrical energy (0.5/1.1) is lost as internal heat in the PV. (3) The solar spectrum varies between $\lambda = 0.4 - 0.8\,\mu$ (1.6 – 3.1 eV). (4) About 90% of the PV area can be effectively used and about 10% of the light is reflected.

1. Answer

The band-gap energy (E_g) of a semiconductor directly affects the theoretical efficiency of a semiconductor: (i) Photons with an energy less than E_g cannot promote electrons to the conduction band. (ii) Some of the energy of the absorbed photon appears as internal heat by exciting states above the bottom of the conducting band. Thus the efficiency of a PV can be maximized if the bandgap is chosen to accommodate the solar spectrum; a PV with a very small E_g will mostly heat the PV and a PV with a very large E_g will absorb only a few solar photons.

The useful electrical energy of a photon (1.1 eV) is reduced by the following multiplicative factors: reflection (0.9), useful area (0.9), and internal losses (0.6 eV/1.1 eV = 0.55). Since the silicon band edge of 1.1 eV corresponds to $\lambda = 1.1\,\mu$, the entire solar spectrum can be utilized (average energy of 2.3 eV). The maximum efficiency of the silicon PV is about

$$\eta = (0.9)(0.9)(1.1\text{ eV})(0.55)/(2.3\text{ eV}) = 21\%\,. \quad (28)$$

This is consistent with the best values in the laboratory (19%), while the production line modules are somewhat less efficient (11%–15%).

F. Costs/kW h from PVs

What is the cost (¢/kW h) at 40 °N latitude on the solstice days (22 June and 22 December)? Assume that (i) Module cost of \$7 per peak watt (approximate cost in 1984), and \$2/W_p for amorphous silicon in the future (plus some system costs). A peak watt is the power developed by the PV when the sun is in the zenith position on a clear day (about $S_p = 1\text{ kW/m}^2$). (ii) Clear skies and 50% clouds. (iii) Allow the collectors to be seasonally adjusted so that the plane of the PV is perpendicular to the sun's rays at solar noon. This configuration gives 9 h of sunshine for the winter solstice and 14 h for the summer solstice at 40 °N latitude. (iv) Capital recovery costs of 10%/yr (in constant dollars) to cover all costs except energy storage and land.

1. Answer

The daily cost of 1 kW_p at the present cost of \$7/W_p is

$$(\$7000)(0.10/\text{yr})(1\text{ yr}/365\text{ d}) = \$1.92/\text{kW}_p - \text{d}\,. \quad (29)$$

The area needed for a collector with $\eta = 14\%$ is

$$A = (1\text{ kW}_p)/(S_p)(\eta)$$
$$= (1\text{ kW}_p)/(1\text{ kW}_p/\text{m}^2)(0.14) = 7\text{ m}^2\,. \quad (30)$$

Since the direction of the PV collectors can be seasonally adjusted, and since $\cos(\theta)$ varies slowly about $\theta = 0$, we will ignore the $\cos(\theta)$ correction here. The normal solar flux at solar noon on the winter solstice is obtained from Eq. (20), $S'_V/\sin(63°) = 0.81\text{ kW/m}^2$. Under the assumption of sunny skies in the winter, the number of kW h generated is

$$N = S'_n T A \eta/\pi$$
$$= (0.81)(20)(7)(0.14)/(\pi) = 5.1\text{ kW h/d} \quad (31)$$

and for the summer solstice, $N = (0.95)(28)(7)(0.14)/(\pi) = 8.5$ kW h/d. For the case of \$7/W_p capital costs, the electricity will be (\$1.92)/(5.1 kW h) = 38 ¢/kW h for the winter solstice and (\$1.92)/(8.5 kW h) = 23 ¢/kW h for the summer, for a yearly average of about 31 ¢/kW h. For the case of 50% clouds, multiply by 2 to get 76 ¢/kW h and 46 ¢/kW h, for a yearly average of about 62 ¢/kW h. If the projected[10] cost of \$2/W_p (by 1995 in 1984 dollars) for amorphous silicon is realized, these costs would be reduced to about 9 ¢/kW h for clear skies and 18 ¢/kW h for 50% cloudy skies. In 1985 the California Energy Commission projected the costs for centralized PV facilities for the years 1990–2020; they obtained 8.5–13.3 ¢/kW h at the bus bar (1984 dollars) which corresponds to 13–18 ¢/kW h for the consumer.

IV. UTILITY LOAD MANAGEMENT

Utilities have responded to peak power loads of a factor of 2–3 lower than the minimal load by using less capital intensive "peaking units" which have reduced efficiencies of about 25%, by building capital intensive pumped storage units to store electrical energy from base-loaded units, and by establishing "time-of-day" pricing for industrial and commercial facilities. In this section we would like to discuss some other possible remedies which would help flatten the daily load shape, reduce the number of power plants needed (kW), and save some energy (kW h).

A. Smart meters and the spot pricing of electricity

At this time, electricity is primarily priced at an average price for consumers. Utilities have carried out experiments using dual meters to keep track of consumption during two different time regimes with differing prices during the peak and off-peak periods. These time-of-use studies have shown that a factor of 2 in price has encouraged the consumer to reduce consumption during the peak hours by about 10%–20%. With the increased availability of inexpensive computer logic, it is now possible to keep track of the consumption of electricity with smart meters[11] (costing about \$100) during time intervals as small as 5 min or less. For as little as \$10 each, small switches can be used with individual appliances to respond to ten choices for the price of electricity, which is carried over the power lines at 30 kHz. When the spot price rises above the selected price, the appliance is automatically turned off; our choices would be based on the spot price of electricity rather than an average price. The first appliances that would be controlled by such devices would be air conditioners, electric water heaters, dryers, pool pumps, etc. Refrigerators would need a special switch which would limit "downtimes" to about 1 h, and to limit defrosting to the evenings. (1) How would the smart meters and switches help stabilize the power grid? (2) What financial incentives are there for the utility to spend \$200 per customer to set up such a system?

1. Answer

(1) When a utility loses one or more large power plants in its grid, it can quickly raise the price of electricity and shed enough of the load to balance its electrical supplies. (2) The utility would annually save about \$12/customer by not having to read the meters directly. The utility could avoid building new peaking power plants at the cost of

about \$1/W, or, for example, \$100 for a 100-W light bulb or \$4000 for a 4-kW air conditioner used during peak hours. If each house shifted 20% of its peak load of 5–10 kW, this would save the utility (and the customers) 1–2 kW/house, which costs \$1000–\$2000/house, Since the efficiency of generating electricity by base-loaded plants is about 35%, compared to 25% for peak-loaded plants, it would be possible to save about $(1/0.25 - 1/0.35)/(1/0.25) = 25\%$ in resource energy. For new houses, the cost of the smart meters is similar to the more traditional mechanical meters.

B. Capital recovery fee

The customers (N) of an electrical utility pay an average price (P) for electricity. New customers (ΔN) want to purchase electricity from the grid, but the cost of new power is more expensive (P'). What is the new price of electricity? How much of a price break is given to the new customers by the old customers? Let $\Delta N = 0.1N$, $P = 6$ ¢/kW h, and $P' = 2P = 12$ ¢/kW h (new coal plants in California). What would be the approximate magnitude of a hook-up fee, a capital recovery fee (CRF), that each customer might pay to enter the system? What are some advantages and disadvantages to a CRF?

1. Answer

The average price of electricity rose from P to

$$P(\text{avg}) = (PN + P'\Delta N)/(N + \Delta N) = P + (P' - P)[\Delta N/(N + \Delta N)] . \quad (32)$$

This gives $P(\text{avg}) = 1.1\ P = 6.5$ ¢/kW h, which means that the old customers have their bills raised by 10% so that the 10% new customers can have their bills reduced by 50% from 12 ¢/kW h to 6.5 ¢/kW h. The California Public Utility Commission did not allow a CRF for a variety of complicated reasons, but "smart meters" would allow the utility to address the equity issue of additional charges for peak power in a more quantifiable manner. Since the power company would have to add 5–10 kW of additional capacity for each house, the CRF could pragmatically be as large as 50% of the added costs, or (0.5)(5–10 kW) (\$1000/kW) = \$2500–\$5000 for the hookup. When the customers are faced with this initial, up-front payment, they would consider investing in energy efficient technologies which would reduce the CRF by reducing peak-power charges.

C. Voltage control

Prior to 1977 utilities allowed their bus bar voltages to vary between 114 V (during peak-power periods) and 126 V (during off-peak-power periods). Regulations by the California Public Utility Commission (PUC) have reduced the allowable variation to between 114 and 120 V. What fraction of electrical energy can be saved by the PUC's voltage control plan? For simplicity, assume that the load of the peak-load power plants is the same as the base-load plants and that the peak-load plants are used at a constant rate for only $\frac{1}{2}$ the day (12 h/d). Under this demand schedule the peak-load plants will produce N kW h/d and the base-load plants will produce twice as much, or $2N$ kW h/d. The thermal efficiency of the base-load plants is about 35% and the peak-load plants is about 25%.

1. Answer

Since the savings in electrical power ($P = V^2/R$) takes place only during the high-voltage, off-peak hours, voltage control does not help the peak load problem. The fractional savings is

$$\Delta P/P = 2\Delta V/V = (2)(126V - 120V)/126V = 9.5\% . \quad (33)$$

Since only $\frac{1}{3}$ of the electrical energy is generated during the off-peak hours, the voltage reduction would save $(9.5\%)/3 = 3.2\%$ of the total electrical production and 4.8% of the base-loaded electricity. The rate of energy consumption per day before the PUC took action was $[(2N/0.35) + (N/0.25)] = 9.71N$, where N is the number of kW h/d produced by the peak-load plants. The rate of energy consumption after the PUC acted is $[(2N)(1 - 0.0475)/0.35) + (N/0.25)] = 9.44N$. The fractional energy savings is $(9.71N - 9.44N)/9.71N = 2.8\%$. The reduction in peak voltage not only saves energy, but also lengthens the lifetime of electric bulbs by about 40%–70%, increases the lifetime of appliances, and increases the efficiency of electrical motors by about 5%. On the other hand, there will be no savings for the case of electrical resistance heating.

V. APPLIANCES

The energy efficiency of some appliances has improved considerably since the oil embargo of 1973–1974. As shown in Fig. 2, the California mandatory standard for refrigerators has been progressively improved from 1900 kW h/yr in 1977, to 1500 kW h/yr in 1979, to 1000 kW h/yr in 1987, and to 700 kW h/yr in 1993. These improvements have been cost effective (as required by California law) with a payback period of 1–2 yr. In 1984, the major appliances (refrigerators, freezers, space and water heating, air conditioners) consumed 8.9 quads/yr, or about 12% of the national energy budget of 74 quads/yr. Additional investments in energy conserving appliances can save about 30% of this (2.7 quads/yr). According to Le-

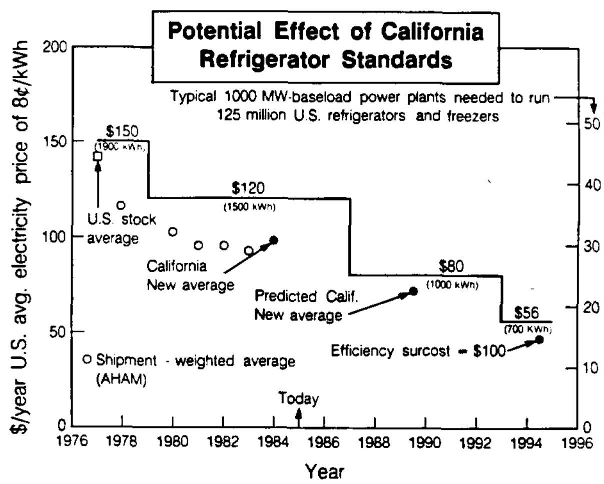

Fig. 2. California Mandatory Refrigerator Standards reduce the average energy intensity from 1900 kW h/yr in 1977 to 700 kW h/yr in 1993. The operating costs have been calculated with an electricity price of 8 ¢/kW h. The number of 1-GW base-loaded power plants needed to run the nation's 125 million refrigerators and freezers is displayed on the right-hand scale. (A. Rosenfeld, Ref. 3, p. 103.)

vine *et al.*,[12] a steady-state investment of $7 B/yr would recover about $17 B/yr (assuming a real discount rate of 10%/yr). In July 1985, the US Appellate Court ruled that the Executive Branch must implement mandatory energy standards for these appliances. One of the debating points in this decision was the choice of the discount rate (d) for investments, the cost of money to the consumer without monetary inflation. Perhaps the best way to examine the economic tradeoffs for investing additional money to save future energy is to determine the life cycle cost of an appliance over its lifetime (T). In order to determine the life cycle cost, we must determine the present value (PV) of all future benefits (B) and costs (C) by properly "discounting" the net cost to the present since their future values are larger than their present values,

$$PV = \int_0^T [C(t) - B(t)]\exp(-dt)d't . \quad (34)$$

The present values of the future costs and benefits become smaller as the discount rate is increased. The annual consumption of energy (E) depends on the purchase cost of the appliance (PC) in approximately the following[12] manner:

$$E = E_\infty + (E_0 - E_\infty)\exp[-A(PC/PC_0 - 1)] , \quad (35)$$

where E_∞ is the minimum rate of consumption of energy possible during the base year and E_0 is the rate of consumption during the base year at a purchase cost of PC_0.

A. Minimum life-cycle cost

Obtain an expression for the optimal investment by minimizing the life cycle cost, $LCC = PC + PV$, over the product lifetime. Allow the price of energy (P) to grow exponentially at the fractional rate of λ /yr.

1. Answer

Using the annual cost of energy, $C = (E)[P\exp(\lambda t)]$, the present value of the cost of all the energy over the appliance's lifetime is

$$PV = \int_0^T (E)\{P\exp[-(d-\lambda)t]\}d't$$

$$= EP\frac{1-\exp[-(d-\lambda)T]}{(d-\lambda)} . \quad (36)$$

The LCC for the appliance is $LCC = PC + PV$, or

$$LCC = PC_0\{1 - \ln[(E - E_\infty)/(E_0 - E_\infty)]/A\} + PV . \quad (37)$$

The minimum LCC is obtained by minimizing LCC with respect to E,

$$d(LCC)/dE)|_{E_{min}} = 0 = -(PC_0/A)/(E_{min} - E_\infty)$$
$$+ P\{1 - \exp[-(d-\lambda)T]\}/(d-\lambda) , \quad (38)$$

which gives the financially optimal energy consumption E_{min} at the minimum LCC,

$$E_{min} = E_\infty + (d-\lambda)(PC_0)/(A)(P)$$
$$\times\{1 - \exp[-(d-\lambda)T]\} . \quad (39)$$

The minimum values of the LCC and the corresponding purchase cost are obtained by inserting E_{min} into Eq. (37).

B. A numerical example

How much electrical power would the US save if the minimum LCC was adopted for the 125 million refrigerators and freezers in the 85 million US residences? Use the following parameters from Ref. 12 for refrigerator–freezers: $E_0 = 1217$ kW h/yr, $E_\infty = 475$ kW h/yr, $P = \$0.069$/kW h, $A = 21.6$, and $PC_0 = \$674$. We will use two values of the discount rate, $d = 5\%$ and 10%/yr, and we will ignore future rises (or declines) in the price of energy, $\lambda = 0$. What are the life cycle costs, the purchase prices of the improved refrigerators, and the payback periods?

1. Answer

From Eqs. (37) and (39),

$E_{min} = 512$ kW h/yr($d = 5\%$), 528 kW h/yr(10%) ,

PC at $E_{min} = \$767.64(5\%)$, $\$756.23(10\%)$,

LCC(base case) = $1704.01(5%), $1388.10(10%) ,

LCC(minimum) = $1200.89(5%), $1066.18(10%) .

The amount of electrical power saved (in the steady state) by buying the minimum LCC refrigerators rather than those available in 1984 (1217 kW h/yr) is ($d = 5\%$)

$$(125 \text{ million } r/f)(1217 - 512)(\text{kW h/yr})$$
$$= 88 \text{ B kW h} . \quad (40)$$

Since a typical base-loaded coal or nuclear power plant has a load factor of about 60%, it produces about

$$(0.6)(10^6 \text{ kW})(8766 \text{ h/yr}) = 5 \text{ B kW h/GW} . \quad (41)$$

The number of power plants saved is about (88 B kW h)/(5 B kW h/GW) = 18 GW. In addition, the US would save an additional 7 GW by replacing the present stock of about 1500 kW h/yr refrigerators with the 1984 technology of 1217 kW h/yr. This totals to 25 GW, or about 6% of US electrical power.

The additional capital cost spent to the purchase cost is recovered by the reduced energy bills during its payback period of T yr:

$$\Delta PC = PC_{min} - PC_0$$
$$= \int_0^{T_p} P(E_0 - E_{min})\exp[-(d-\lambda)t]d't$$
$$= P(E_0 - E_{min})$$
$$\times\{1 - \exp[-(d-\lambda)T_p]\}/(d-\lambda) . \quad (42)$$

Solving for the payback period,

$$T_p = \ln[1 - \Delta PC(d-\lambda)/P(E_0 - E_{min})]/(\lambda - d) , \quad (43)$$

which gives $T_p = 2$ yr(5%) and 1.9 yr(10%). Since this is a high paying investment, the results are not very sensitive to the discount rate.

VI. ENERGY AND LIGHTING

About $\frac{1}{4}$ of US electricity is used for lighting. About $\frac{1}{2}$ of the 430 B kW h/yr used for lighting, the equivalent of 85 base-loaded, 1-GW power plants, is used for incandescent lights; the other $\frac{1}{2}$ is used predominately for fluorescent lights. A number of technical advances[13] have been developed over the years which have considerably increased the efficacy (lumens/W) of lighting. (1 W of visible light

$= 673$ lm/W.) New advances are emerging which should further raise the efficacy of a typical mercury fluorescent tube from its present value of about 80 lm/W. A mercury fluorescent tube converts about $\frac{2}{3}$ of the input electrical discharge energy to ultraviolet photons ($\lambda = 253.7$ nm, 4.9 eV). The radiation diffuses through the plasma, being absorbed and reemited by other mercury atoms, and it is then converted to the visible region ($\lambda = 550$ nm, 2.2 eV) by exciting phosphors on the tube wall. The ballast provides the starting voltages for the plasma discharge, but a conventional ballast consumes about 25% of the total input energy. By using high-frequency solid state ballasts operating at about 30 kHz, these losses can be reduced, raising the efficacy to about 100 lm/W.

A. Isotopic enhancement

Mercury consists of six predominant isotopes, and one very minor isotope, Hg^{196}. What would be an upper bound estimate to the increase in efficacy gained by enlarging the amount of the minor isotope, Hg^{196}? Compare typical isotope shifts in Hg (5 GHz) to the Doppler broadened resonances at 40 °C.

1. Answer

The 5-GHz isotope shift is caused by the difference in the sizes of the various Hg nuclei slightly changing the electrostatic interaction between the nucleus and the outer s electrons. The line widths of the transitions in mercury are Doppler broadened by

$$\begin{aligned} \Delta E &= (v/c)(E) = (1.5kT/mc^2)^{0.5}(E) \\ &= [(1.5\times 0.027 \text{ eV})/(200\times 10^9 \text{ eV})]^{0.5} \\ &\quad \times (4.9 \text{ eV}) = 2.2\times 10^{-6} \text{ eV}. \end{aligned} \tag{44}$$

The resonance transitions (p to s) from the various even isotopes are very resolvable since the magnitude of the isotope shift for the even isotopes,

$$\begin{aligned} \Delta E &= (\Delta f)(h) \\ &= (5 \text{ GHz})(4.1\times 10^{-15} \text{ eV} - s) = 2.1\times 10^{-5} \text{ eV}, \end{aligned} \tag{45}$$

is much larger than the line widths. Without considering the details of the mercury hyperfine structure, the efficacy would be increased since the Hg^{196} would provide a seventh channel at a slightly different energy for the photons to diffuse to the surface, and therefore reduce the number of nonradiative deexcitations by about $\frac{1}{7}$, or 15%. In reality the gain is about $\frac{1}{3}$ this amount, or 5% (about 5 lm/W), since the hyperfine lines from the odd isotopes must be considered as well as the dynamics of the line shapes. It might be possible to obtain an additional 5% (5 lm/W) by increasing the population of the odd isotope Hg^{201}.

B. Further ideas

How could the efficacy be increased by improvements in the (i) phosphors, (ii) augmentation with magnetic fields, (iii) surface confinement of the plasma of the initially excited Hg atoms, and (iv) advanced control circuits?

1. Answer

(i) Since the energy of the 253.7-nm radiation (4.9 eV) is about twice the visible region (2.2 eV), in principle it should be possible to find phosphors that would give two photons in the visible region, doubling the efficacy of the lighting. (ii) External magnetic fields can give additional hyperfine energy channels for photons to diffuse toward the tube wall as well as modifying the orbits in the plasma. By using magnetic fields of about 0.06 T, the efficacy has been increased by about 15%. (iii) By exciting the plasma with 500-MHz electric waves on the inner surface of the tube wall, the excited mercury atoms can be confined to the outer regions of the plasma rather than in the bulk of the plasma. This reduces the volume collision losses, increasing efficacy by about 30%. (iv) By using sensors that account for lighting from daylight, it is possible to considerably reduce lighting levels. By using additional sensors that respond to office occupancy demands, additional savings can be made. The combined savings with these relays can be more than 50%.

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