

## CHAPTER 8

## ENERGY CONSERVATION IN LARGE BUILDINGS

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## ABSTRACT

As energy prices rise, newly energy aware designers use better tools and technology to create energy efficient buildings. Thus the U.S. office stock (average age 20 years) uses 250 kBTU/ft<sup>2</sup> of resource energy, but the guzzler of 1972 uses 500 (up x 2), and the 1986 ASHRAE standards call for 100-125 (less than 25% of their 1972 ancestors). Surprisingly, the first real cost of these efficient buildings has not risen since 1972. Scaling laws are used to calculate heat gains and losses of buildings to obtain the  $\Delta T$  (free) which can be as large as 15-30°C (30-60°F) for large buildings. The net thermal demand and thermal time constants are determined for the Swedish Thermodeck buildings which need essentially no heat in the winter and no chillers in summer. The BECA and other data bases for large buildings are discussed. Off-peak cooling for large buildings is analyzed in terms of saving peak-electrical power. By downsizing chillers and using cheaper, off-peak power, cost-effective thermal storage in new commercial buildings can reduce U.S. peak power demands by 10-20 GW in 15 years. A further potential of about 40 GW is available from adopting partial thermal storage and more efficient air conditioners in existing buildings.

## I. SCALING LAWS FOR BUILDINGS.

As one might expect, big 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 heat gains and losses are external, the heat/coolth from the outside climate passing through the envelope, or shell, of the building. Let's roughly examine this transition from small to big by considering some scaling laws for energy gains and losses. Our building will be a cube of length  $L$  and of volume  $L^3$ .

The rate of winter heat loss from our building is proportional to its surface area, or  $L^2\Delta T$ , where  $\Delta T$  is the inside-outside temperature difference. If the thermal conductivity of the building 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 of the building which is proportional to the volume of a multistory building, or  $L^3$ , or  $\dot{Q}(\text{gain}) = GL^3$ . We ignore a smaller term  $SL^2$  for solar gain in winter. Without space heat or

airconditioning the gains and losses are equal, or

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

and the building floats above the ambient temperature by an amount

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

Obviously the thermostat will not call for heat until  $T(\text{ambient})$  drops  $\Delta T(\text{free})$  below the comfort temperature  $T(\text{thermostat})$ . This 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,  $\dot{Q}(\text{gain})$  raises  $\Delta T(\text{free})$ . For a "free heat" of  $15^\circ\text{C}$  ( $30^\circ\text{F}$ ), the length  $L$  must be about  $15(K/G) = 10$  m for the example in Sec. II. 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 U.S. 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. In the next section we will equate the gains to the losses, using the appropriate numerical parameters and determine the amount of "free heat" available in a building.

## II. FREE HEAT, $\Delta T(\text{free})$ , FOR BUILDINGS

The average (sensible) power of a person<sup>1</sup> is 75-100 watts (350 BTU/h). In a large building the density of people is such that they provide a heat intensity of about  $11 \text{ W/m}^2$  ( $1 \text{ W/ft}^2$ ). The lighting and equipment gains can be about three times (or more) this amount, or  $33 \text{ W/m}^2$  ( $3 \text{ W/ft}^2$ )\*\*. Since the internal and solar gains can vary widely, we shall use a range of values for the internal gain of  $66 \pm 22 \text{ W/m}^2$  ( $6 \pm 2 \text{ W/ft}^2$ ). 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:

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

The steady state loss rate from a building is

$$\dot{Q}(\text{loss}) = \sum_i U_i A_i \Delta T + \rho \dot{V} c \Delta T \quad (4)$$

where  $A_i$  is the area of each envelope component,  $U = 1/R$  where  $U$  is the conductance and  $R$  is the thermal resistance,  $\rho$  is the density of air,  $\dot{V}$  is the flow of incoming air (m<sup>3</sup>/s), and  $c$  is the specific heat of air. The metric  $R$  values are obtained from the

\*\* See Fig. 13 for a breakout of electricity and fuel use.

English values with

$$R(m^2 K/W) = R(hr ft^2 \text{ } ^\circ F/ BTU)/5.69 . \quad (5)$$

The following SI (English) parameters represent a medium level of energy tightness for high-rise office buildings (one version of the 1985 California standards, see Fig. 13 plotted near the bottom.)

Ceilings: R-2.62 (R-14.9)  
 Walls: R-1.14 (R-6.5)  
 Single Glazing: R-0.158 (R-0.9) 30% of wall area  
 Basement (about 50% of ceiling loss)  
 Infiltration/Ventilation (about 30% of total UA $\Delta$ T)

The loss rate from the cubic structure is

$$\dot{Q}(\text{loss}) = 1.3\{\dot{Q}(\text{ceiling/basement}) + \dot{Q}(70\% \text{ walls}) + \dot{Q}(\text{windows})\} \quad (7)$$

$$\begin{aligned} \dot{Q}(\text{loss}) &= 1.3L^2 \Delta T(1.5/2.62 + 0.7(4)/1.14 + 0.3(4)/0.158) \quad (8) \\ &= 13.8 L^2 \Delta T. \end{aligned}$$

Equating the losses (Eq. 8) to the internal gains (Eq. 3), we obtain:

$$\Delta T(\text{free}) = (1.6 \pm 0.5) L \quad (L(\text{m}), T(^{\circ}\text{C})) \quad (9)$$

$$\Delta T(\text{free}) = (0.9 \pm 0.3) L \quad (L(\text{ft}), T(^{\circ}\text{F})) \quad (10)$$

The "free temperature rise"  $\Delta T(\text{free})$  for our balanced (occupied, unheated) new office building of 10 m (33 ft) on a side is  $16 \pm 5$   $^{\circ}\text{C}$  ( $29 \pm 10^{\circ}\text{F}$ ). If the thermostat was set at  $20^{\circ}\text{C}$ , the furnace would turn on at the balance point of  $4^{\circ}\text{C}$  ( $20^{\circ}\text{C} - 16^{\circ}\text{C}$ ). These values of free heat would be  $30^{\circ}\text{C}$  ( $60^{\circ}\text{F}$ ) by doubling the product of internal gains and the net thermal resistance. 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 ( $\text{kWh}/\text{m}^2$ ,  $\text{BTU}/\text{ft}^2$ ) 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.

Houses have 1/5 to 1/10 the intensity of internal heat, perhaps 1 kW for a typical house of  $120 \text{ m}^2$  ( $1300 \text{ ft}^2$ ), or less than  $1 \text{ W}/\text{ft}^2$ , compared with  $6 \text{ W}/\text{ft}^2$  for an office.\*\* 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 big buildings in order to have balance

\*\* Electricity use in houses and office buildings are compared in Fig. 13.

points similar to that of large buildings. A conventional house has 3-6°C (5-10°F) of "free heat," but a superinsulated house can have 15°C (25°F) or more.

TABLE I. California thermal resistance standards in SI (English) units for high rise office buildings (1987) and residences (1985). The R values for walls depend on their heat capacity.

|           | 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) |

### III. HEAT AND COOLTH STORAGE IN HOLLOW-CORE CONCRETE SLABS.

Concrete floor/ceiling slabs have a large heat capacity (100 Wh/m<sup>2</sup>°C), but for accoustical reasons this is normally poorly coupled to the room air. In the Swedish "Thermodeck" system<sup>2</sup>, the supply air is distributed via hollow cores in the floor slabs as shown in Fig. 1. These cores are already extruded in slabs to reduce weight/thickness, but are normally not exploited for energy conservation. In this way, the concrete mass is made available for the storage of heat. Even though Stockholm (3580°C-day, 6444°F-day) is colder than Chicago, the Thermodeck office buildings annually use only about 4 kWh/ft<sup>2</sup> for electric resistance heating, so little that it does not pay to hook up to the Stockholm district heating system.

Modern Swedish buildings have small internal gains and are relatively small by American standards since every office must have a window, but they are so well insulated that their temperature floats upwards during a typical occupied winter day. The net winter heat gain in a modern Swedish building is about 15 W/m<sup>2</sup> for the 8 occupied hours. Figure 2 (curve "a") shows that in a normal office, with an insulated suspended ceiling, this 15 W/m<sup>2</sup> will raise the temperature to an unacceptable level within an hour or so, making it impossible to continue storing the heat gain (free energy) in the structure. But with Thermodeck (curve "b"), the full 8 hour gain can be stored with a temperature rise of 1-2°C, which is readily acceptable to the occupants. During the winter, this stored heat is used to compensate for night/weekend heat losses.

During the summer, daytime heat gain is again stored in the pre-cooled slabs. In Stockholm, the outdoor air temperature seldom exceeds 30°C (86°F), and the minimum temperature at night is usually 18-20°C, so the slabs can be cooled by circulated night air (and thus made ready for the next morning) without the need of air conditioning. In roughly half of the U.S., nights are not cool enough to pre-cool the building, and cheap off-peak air conditioning would still be required, but the concrete's heat capacity will still handle the daytime load. Only enough peak air conditioning is needed to dry outside ventilation air. This peak can be made negligible with a water-permeable heat exchanger.

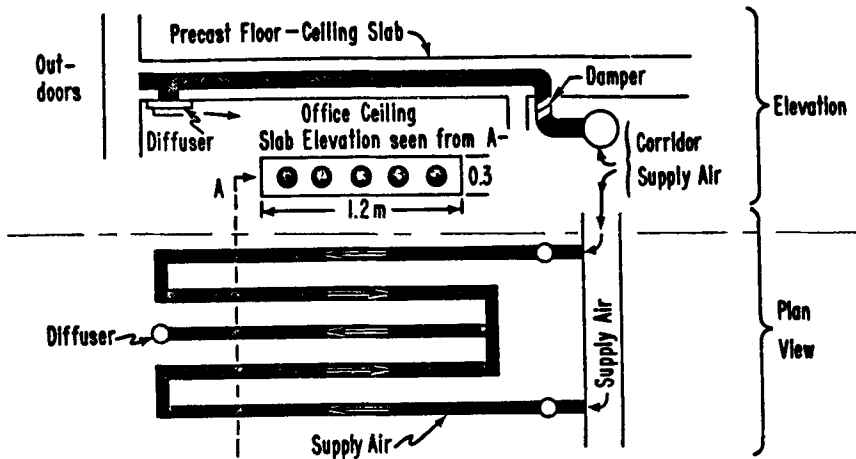


Fig. 1. Forced convection and increased thermal surface area enhance the thermal storage of a Swedish Thermodeck Office Building. Each  $10 \text{ m}^2$  office module has two slabs ( $1.2 \text{ m} \times 4.2 \text{ m}$ ). Source: LBL- 8913. XBL7910-13105

Fig. 2 shows some computer simulations of heating cycles in the Thermodeck building. These buildings have a thermal relaxation time similar to an RC circuit (Appendix F). The choice of  $\tau = RC$  for a building is critical for energy management. From Fig. 2 (curve "a", no hollow cores) we see that a typical office has  $\tau \approx 5$  hours, but when the mass of the concrete is coupled to the room,  $\tau$  is raised to about 100 hours, and enough heat can be stored to carry the space through unoccupied hours, and even weekends of 60 hours.

Let us estimate the heat gains and losses for a Thermodeck building to confirm these energy management concepts. A single-occupant Thermodeck office is  $2.4 \text{ m}$  wide by  $4.2 \text{ m}$  deep by  $2.7 \text{ m}$  high, or  $10 \text{ m}^2$  in area and  $27 \text{ m}^3$  in volume. We will assume a cold day in Stockholm of  $-8^\circ\text{C}$  ( $18^\circ\text{F}$ ) for a temperature difference between inside and outside of  $\Delta T = 22 - (-8) = 30^\circ\text{C}$  ( $54^\circ\text{F}$ ).

HEAT GAINS per  $10 \text{ m}^2$  office when occupied:

1. 1 person/ $10 \text{ m}^2 = 100 \text{ W}$  (sensible heat only)
  2. Lights and machines =  $300 \text{ W}$
  3. Solar Gain (small in winter) through  $1.5 \text{ m}^2 = 30 \text{ W}$
- TOTAL GAIN 8 OCCUPIED HOURS =  $430 \text{ W}/10 \text{ m}^2$

HEAT LOSSES per  $10 \text{ m}^2$  office: (losses are negative gains)

1. Wall  $(U)(A)(\Delta T) = (0.25)(5)(30) = -38 \text{ W}$
  2. Window  $(U)(A)(\Delta T) = (2)(1.5)(30) = -90 \text{ W}$
  3. Outside Air =  $-200 \text{ W}$  (occupied),  $-50 \text{ W}$  (unoccupied.)
- TOTAL LOSS =  $-330 \text{ W}$  (occupied),  $-180 \text{ W}$  (unoccupied)

GAINS-LOSSES: Occupied =  $+100 \text{ W}$ , Unoccupied =  $-180 \text{ W}/10 \text{ m}^2$

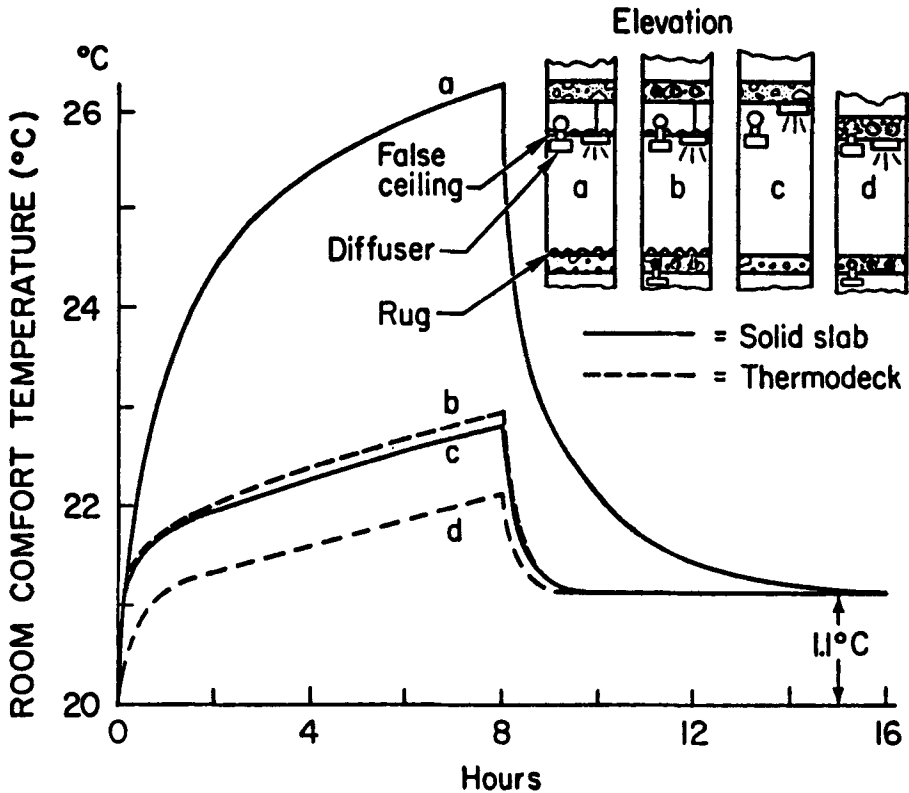


Fig. 2. Response/relaxation curves calculated by the BRIS computer program for equal rooms with two different slabs, each with a heat capacity of  $100 \text{ Wh/m}^2 \cdot ^\circ\text{C}$ . The surroundings are assumed symmetric on all sides (as in an office in the core of a building). Lighting ( $15 \text{ W/m}^2$ , 50% radiation) is turned on for the first 8 hours of each run. The cases are as follows:

- 20-cm thick solid concrete slab, with rug, insulated, suspended ceiling, and plenum. Resistances assumed were: rug ( $0.1 \text{ m}^2 \cdot ^\circ\text{C/W}$ ); insulated false ceiling (0.5); plenum (0.17).
- Same as a., but slab is 30-cm thick Thermodeck.
- 20-cm thick concrete slab, but bare — no rugs, suspended ceilings, plenum.
- Same as c., but slab is 30-cm thick Thermodeck.

Source: LBL-8913. XBL7910-13104

The heat loss from heating cold, outside air is the largest loss for the Thermodeck building. As in all office buildings, to control indoor contaminants,  $20 \text{ m}^3/\text{hr}$  of outside air is mixed with the  $120 \text{ m}^3$  of air recirculated to each office, thus, changing the building air every 1.3 hours. During unoccupied hours, fans are off, but natural infiltration is about  $5 \text{ m}^3/\text{hr}$  per office. During the 8 hour work day, this outside air corresponds to a 200 W heat loss, and 50 W during the unoccupied hours. If additional heat is needed, air-to-air heat exchangers could be used to recover about 70% of the heat in the exhaust air stream.

Thus far, we have treated the curves of Fig. 2 as exponentials, but now we want to calculate their numerical slope. Because of the

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  $t = 0$ , with an offset (precooled or preheated) temperature  $T_0$ . Then  $T$ , the temperature of the room air is given by

$$T = T_0 + \dot{Q}t / C \tag{11}$$

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  $100 Wh/m^2\text{ }^\circ C$ ; this number is increased by 20% to account for the heat capacity of the walls and furnishings. Using these values, we obtain:

$$\text{Occupied (} W = 10 W/m^2 \text{), } T = T_0 + 0.1t \tag{12}$$

$$\text{Unoccupied (-} 18 W/m^2 \text{), } T = T_1 - 0.2t \tag{13}$$

Eq. 12 gives a small temperature rise of  $1^\circ C$  during the day. The temperature drop during the evening (with the fan off) is closer to  $1^\circ C$  (and not  $2^\circ C$  from Eq. 13) since the rooms are allowed to become quite cool, reducing their thermal losses through the envelope. These results agree with the data of Fig. 3 for heating in the winter and Fig. 4 for cooling in the summer. In the US the storage of summer night coolth is much more significant than winter heat. As can be seen in Fig. 13 for a medium office in Washington DC, annual cooling per  $ft^2$  costs 35¢; heating costs only 5¢. During the deep cooling season, one can run the chillers at night to precool the slabs. There is no saving of kWh, but by avoiding peak power charges one saves annually \$50-100/kW shifted. A slab does not quite have the heat capacity to keep an American office cool all day, but can be aided with a small water or ice storage system, or with phase change material, tuned to about  $21^\circ C$ , canned and loaded loosely into the cores. In mid-season, nights are cool enough to precool without running the chiller, thus saving kWh.

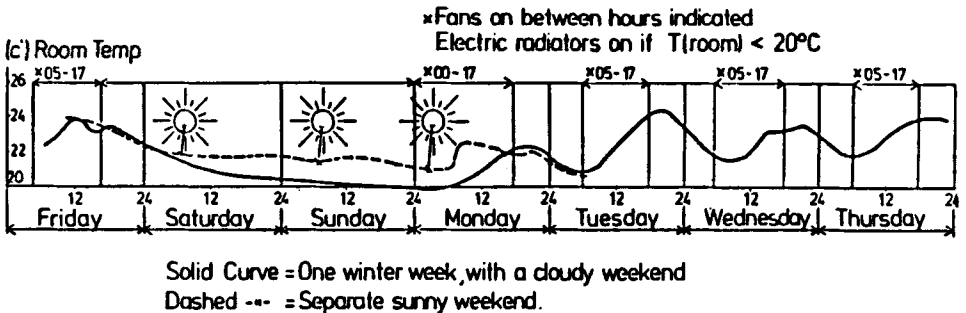


Fig. 3. Winter. During a winter week, the outdoor temperature varied between  $-2$  and  $-10^\circ C$ . On Friday afternoon, when the internal gains end and the fans and radiators are turned off, the indoor temperature starts to fall from  $24^\circ C$ . By about Monday morning,  $20^\circ C$  is reached. Fans are turned on (the ventilating air system runs with 100% recirculation) and the air is heated one or a few  $^\circ C$  depending on the outdoor temperature. At 8:00 Monday morning, the temperature level is still about  $20^\circ C$ . Each weekday the occupied offices climb  $2-3^\circ C$  in temperature, and empty rooms remain about  $20^\circ C$ . Each night the indoor temperature falls  $1-2^\circ C$ . By Friday afternoon, the cycle is complete. Source: LBL-8913. XBL7910-13107

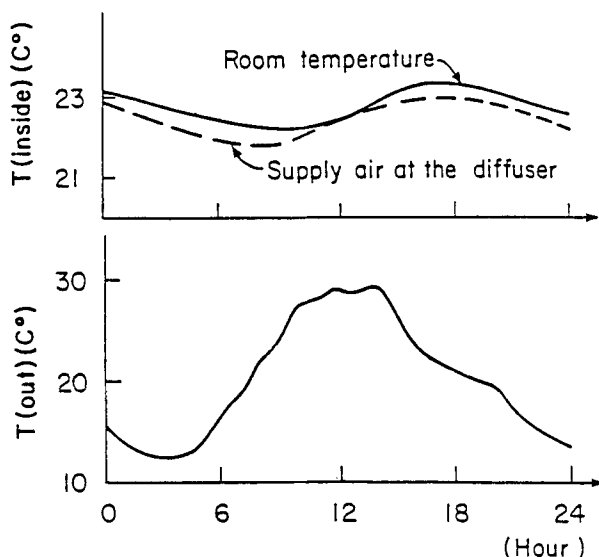


Fig. 4. Summer. During the day, the outdoor air temperature varies between 12°C and 30°C and the air going into the system has about the same temperature. The supply air, after passing through the slab cores, has a much smaller variation (22.5 ± 0.5°C) and the room temperature during office hours increases from 22°C to 23°C. Source: LBL-8913. XBL7910-13106

#### IV. THERMAL STORAGE CAN REDUCE PEAK POWER DEMANDS

A. The Potential for Savings of Peak Power (kW). 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 2 or 3 times the demand at night.\*\* And as more air conditioning is installed, the utilities demand problem worsens. Table II contains some estimates of peak cooling and possible displacements of this cooling by using cost-effective thermal storage for large buildings. 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/year. Presently 58% of U.S. homes<sup>3</sup> are air conditioned. The high growth rate for new commercial buildings (annually 5% = 2.5 B ft<sup>2</sup>) causes peak demand growth of about 1.6 GW/year. Table II shows that residential and commercial air conditioning each account for 80 GW, totalling 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 on new commercial buildings would avoid the need of about 10-20 standard 1 GW plants in the next 15 years, with a further potential savings of about 40 GW by adopting partial thermal storage and more efficient air conditioners in existing buildings.

\*\* For power profiles, see Rosenfeld's introduction to Peddie/Bulleit.



Table II. Peak power demand for cooling U.S. buildings extrapolated 20-fold from So. Calif. Edison's 1985 summer peak of 13 GW, to U.S. peak capacity of 500 GW. The a/c peak includes both chiller-and-pumps (which can be shifted off peak with thermal storage) and also fans (which cannot). Of the residential 80 GW, about 10% is fan power; for small commercial, fan power runs around 20%, and for large commercial up to 30%.

| A.<br>Sector<br>Peak<br>(GW) | B.<br>a/c<br>Peak<br>(GW) | C=B/A<br>a/c<br>Fraction<br>of Peak | D.<br>'77-'82<br>Annual<br>Growth<br>(GW) | E=C*D<br>Annual<br>a/c<br>Growth<br>(GW) |       |
|------------------------------|---------------------------|-------------------------------------|---|--|-------|
| Residential                  | (170)                     | (80)                                | (47%)                                     | (4)                                      | (2.0) |
| Commercial                   | (195)                     | (80)                                | (40%)                                     | (4)                                      | (1.6) |
| Buildings                    | 365                       | 160                                 | 44%                                       | 8  | 3.8   |
| Industrial                   | 135                       | -                                   | 0%  | ~0                                       | 0.0   |
| Total                        | 500                       | 160                                 | 32%                                       | 8  | 3.6   |

Comments:

Column C - These fractions apply only to SCE, but we assume that they apply to the U.S. We should, of course, use a weighted average of the peak fractions for about 10 utilities.

Column D - We have no U.S.-wide annual data on peak demand (GW) disaggregated by sector, but annual sales (BkWh) by sector are readily available, so to estimate GW growth, we use BkWh growth and assume that the GW/BkWh does not change. This ratio, for example in 1982, was 2086 BkWh/418 GW peak demand = 5000 hours equivalent production per peak watt.

Column E - For the Total, E is simply not equal to C times D.

B. Off-Peak Cooling with Thermal Storage. In order to gauge the potential for saving peak power, one should examine the disaggregation of peak power demands in large buildings. Fig. 5 displays the peak power components in the summer for a large office building in Madison, Wisconsin, as calculated with DOE.2 (Appendix E). Nearly 2 W/ft<sup>2</sup>, fully one-third of the peak demand of 5 W/ft<sup>2</sup> is used to run the chillers that could be operated in the off peak hours. Many new commercial buildings store "coolth" in chilled water or ice during the unoccupied hours. This approach allows the downsizing of the chillers by 50-60%. The block diagrams in Fig. 6 compare:

(top) Conventional Cooling on Demand; chillers run 8 hours per day, no thermal storage.

(left) Partial Storage; small size chiller (40% of conventional) runs the entire day, storing 2/3 of the coolth during the unoccupied hours for later use during peak demand.

(right) Demand Limited Storage; medium size chiller (50% conventional) runs only during the unoccupied, 2/3 of the day, and the thermal storage is about 50% larger than for partial storage.

The economics<sup>4</sup> for the transition to off-peak cooling are very favorable. The price of off-peak electricity is as much as 6 ¢/kWh cheaper than the peak price, and the demand charges for power during peak hours can be as large as \$9/kW-month. Thus the annual savings

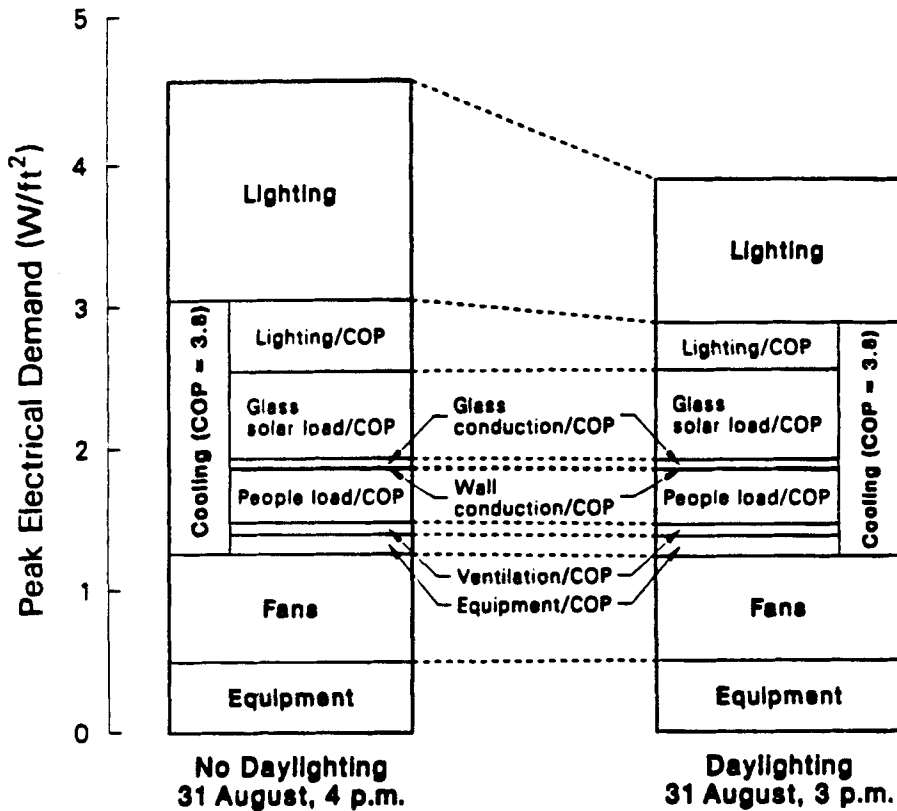


Fig. 5. Peak Power demand per square foot for a large office building, as simulated for Madison, WI weather by the DOE.2 program. Each floor has 10,000 ft<sup>2</sup> of core (cooled only) plus 6000 ft<sup>2</sup> of perimeter floor area.

If built according to ASHRAE Standard 90-75, its peak demand would be 6.7 W/ft<sup>2</sup>; if it satisfies Standard 90-E (revised, 1985), with daylighting it would use only 4 W/ft<sup>2</sup>. Thus its peak demand is down 40%, its yearly energy use is down by 40%, yet its first cost is also slightly down, mainly because of savings by downsizing the air conditioning.

Note that about half the peak demand goes to running chillers. With *thermal storage* this 2 W/ft<sup>2</sup> can be moved entirely off peak for a first cost of about \$0.50/W, which is only half of the utility's cost for new peak capacity. The residual peak demand is then down to about 2 W/ft<sup>2</sup>. Alternatively, and cheaper, the chilling can be partially (60%) moved off peak for only \$(0.00 to 0.25)/W. XCG 855-223, 1985

by shifting 1 kW of chilling off-peak is \$30-100. The combined savings from reduced electrical bills and from downsizing the chillers by 50-60% provides a strong economic incentive to use off-peak cooling with thermal storage in new and existing buildings.

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 found out that for the the same

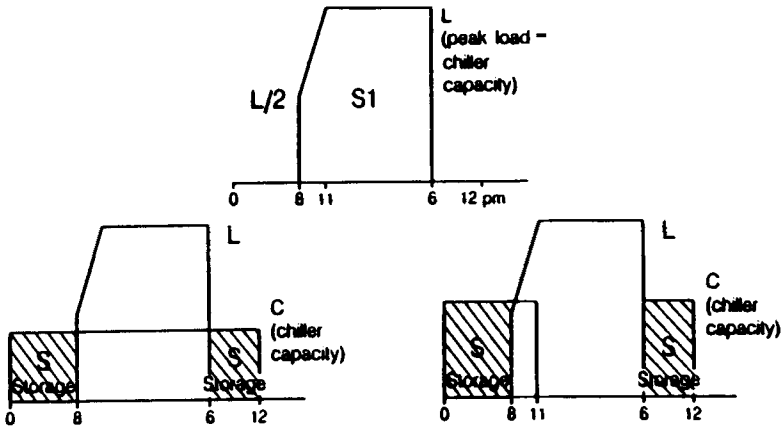


Fig. 6. Off-peak thermal storage. Conventional system (top); Partial storage (left); Demand limited storage (right). Calculation of the capacities of chiller and storage according to the load profile. S1 is the daily cooling load, C is the chiller capacity, and S is the storage capacity. Source: A. Rosenfeld and O. de la Moriniere.

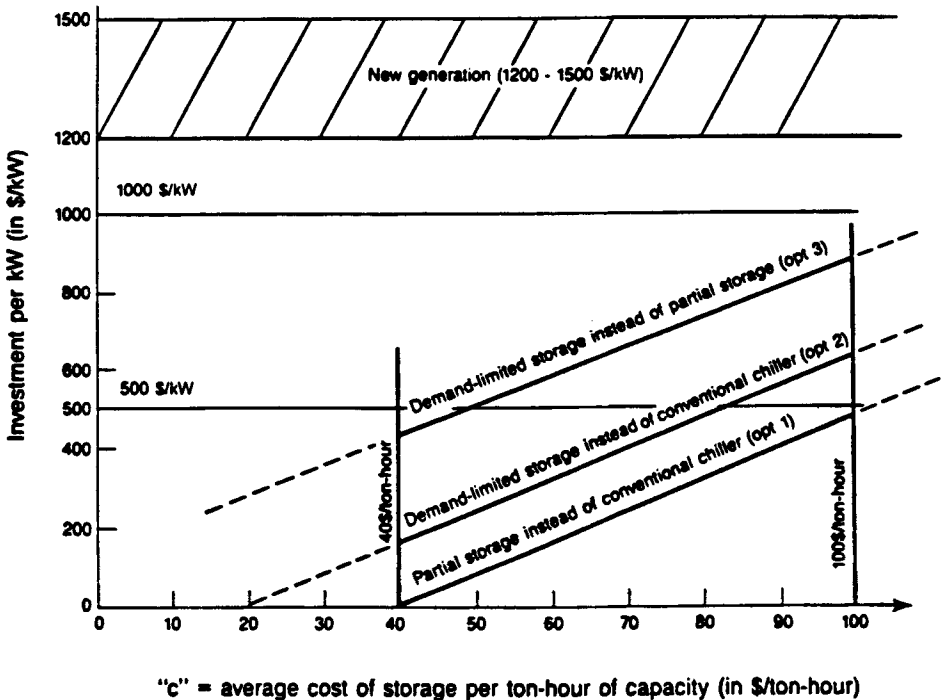


Fig. 7. Investment to save one peak kW using cool storage. For an office building, the cost range of installed storage is from \$40 to \$100 per ton-hour. At \$40, the saving from downsizing the chiller pays for the storage. To go from partial to demand-limited storage costs about \$500/avoided peak kW, still much cheaper than the indicated cost of new generation. This figure does not include the cost savings from moving electricity charges off-peak. Source: A. Rosenfeld and O. de la Moriniere, ASHRAE Transactions, HI-85-15, #4 (Hawaii Meeting).

price 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 its 8 MW afternoon load by running its present capacity at night, saving all peak power charges. Thus Stanford, at no increase in first cost, saved operating and peak power costs, and shaved 5-8 MW in its peak load, which saves \$300,000 to \$500,000/year.

The investment necessary to save 1 peak kW with off-peak cooling are considered in Fig. 7. For the case of partial storage, an optimistic cost of \$40/ton-hour would take no additional investment, and would save the utility about \$1200-1500. For a pessimistic cost of \$100/ton-hour, there is a finite first cost of \$500/peak kW avoided. To go from this most lucrative option (partial storage) to full demand-limited storage is more expensive; the incremental increase in first cost is \$450/kW, and the payback time is about 7 years. This is attractive to a utility, which otherwise must pay off the expensive new plants over 30 years, but it is not as attractive (without incentives) to most builders.

C. An Example. In order to gain a quantitative understanding for these large savings, let us examine the partial storage system of a single<sup>5</sup> facility, the headquarters of the Alabama Power Company in Birmingham. The five large ice cells contain 550 tonnes of ice to cool the 1.2 million ft<sup>2</sup> building, or 0.46 kg/ft<sup>2</sup> (an equivalent layer 5 mm thick per ft<sup>2</sup> of floor). The latent heat/ft<sup>2</sup> is

$$Q = (0.46 \text{ kg})(3.4 \times 10^5 \text{ J/kg}) = 1.6 \times 10^5 \text{ J/ft}^2 . \quad (14)$$

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

$$P = Q/(\text{COP})(\Delta t) = (1.6 \times 10^5)/(2.5)(16 \text{ hr}) = 1.1 \text{ W/ft}^2 . \quad (15)$$

This gives a total of 1.3 MW for the entire building, which is less than 1/2 of the 2.8 MW required without thermal storage. From this, we can determine the average heating intensity during a summer day (solar, internal, envelope). Since the coolth stored in the ice is only about 2/3 of the cooling requirement, the daily gain is about  $2.4 \times 10^5 \text{ J/ft}^2$  which corresponds to a heating intensity of about  $10 \text{ W/ft}^2$  in the day.

#### V. DATA ON COMMERCIAL BUILDINGS

Commercial buildings use a considerable amount of energy, about one-seventh of the U.S. total annual consumption of energy. The commercial sector builds at the rate of 5%/year of which about half it to replace old buildings, leaving 2.5%/year net growth. In spite of these high growth and replacement rates, the commercial sector has a considerable longevity because commercial buildings last 50 years, with the result that about 2/3 of the projected floorspace for the year 2000 is already in place. The average annual cost for energy in a commercial building is about \$1.20/ft<sup>2</sup>, or about 1.5%/year of the total capital cost of a typical new building of \$75/ft<sup>2</sup>. Over the lifetime of a building, the cost of energy for the building approaches the cost of constructing the building.

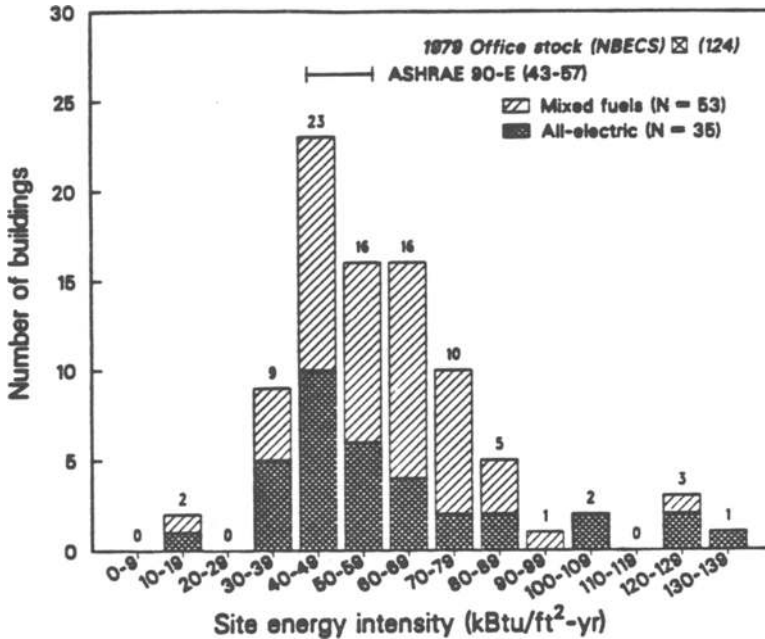


Fig. 8. Actual site energy intensity for new office buildings. The distribution for all-electric and mixed-fuel buildings are similar. Over 60% use a site intensity of 40-70 kBtu/ft<sup>2</sup>-yr. The average U.S. office stock (EIA, 1981) and the proposed ASHRAE 90-E values for large offices are included for reference. Source: LBL BECA-CN. A compilation of current standards and data can be found in figures 12 and 13. XCG 851-48

In order to quantify progress in reducing energy use in the commercial sector, the BECA (Buildings Energy-Use Compilation and Analysis) project of the Building Energy Data group at LBL has compiled data bases on existing, retrofitted, and new commercial buildings. From these compilations of actual, measured data, the BECA group has estimated the cost-effectiveness of various retrofit measures. Since most of the energy consumed in new large buildings is electrical energy, the intensity of energy used on site is approximately 1/3 of the intensity of energy resources used. Some of the results from BECA are as follows: The data set for the new<sup>6</sup> commercial buildings (Fig. 8) is a selected set mainly comprised of buildings that have energy efficient designs. Most of these new buildings use a site energy intensity of 40-70 kBtu/ft<sup>2</sup>-yr (resource intensity of 125-220 kBtu/ft<sup>2</sup>-yr). The large office median site intensity is 59 kBtu/ft<sup>2</sup>-yr (resource intensity of 185), while small office buildings use a median site intensity of 47 kBtu/ft<sup>2</sup>-yr (resource of 148). The data on commercial buildings is disaggregated among building types in Fig. 9. The average intensities for both large and small buildings are well below the intensities of the existing U.S. building stock (resource intensity of 264 kBtu/ft<sup>2</sup>-yr), but slightly higher than the simulations for buildings designed to the proposed ASHRAE standards (90-E).

### Summary of Energy Performance in Comparison to Baseline (NBECS) and Standards (ASHRAE 90-E)

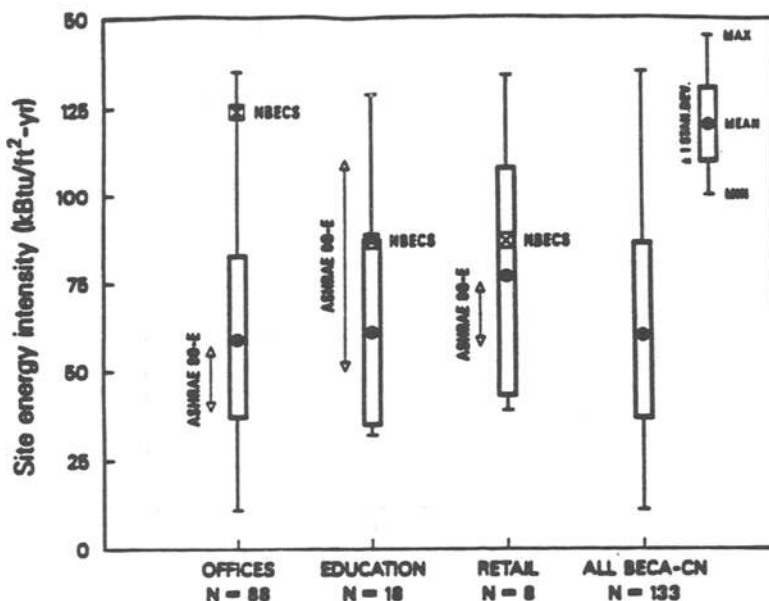


Fig. 9. Summary of energy performance by building type for BECA-CN compared to 1979 average U.S. stock (EIA, 1981) and proposed ASHRAE Standard 90-E. The minimum, maximum, mean, and standard deviation are presented for each of the four BECA-CN categories of buildings. No NBECS average or Standard 90-E data are presented for the fourth category because of the wide variety of building types in the total data base. For all three building types the BECA-CN mean is clearly below the U.S. average stock, but in only one case is it within the range of the standard. The high value for one DOE-2.1 calculation on educational buildings was caused by high ventilation rates and high use of hot water (40% of total). Source: BECA-CN. XCG 851-24

A variety of measures can be used to retrofit existing buildings to save energy by improving operation and maintenance, HVAC (heating, ventilation, and air conditioning) systems, lighting, building envelopes, windows and doors, and so forth. The BECA-CR data set<sup>7</sup> shown in Fig. 10 shows that building owners and managers are biased towards retrofit measures which had a short payback period. This compilation shows that about 10 to 40% of a building's annual energy use can be saved by cost-effective measures. The median cost of the energy saved was about \$0.90/MBTU with a payback period of about 1 year (using a discount rate of 7% and an amortization of 10 years).

## VI. COMPARISON OF ELECTRIC GROWTH IN TEXAS AND CALIFORNIA

While Texas is still a "laissez-faire" state, California practices vigorous conservation with multi-tier increasing residential gas and electric rates, mandatory standards for appliances and new buildings, zero- and low-interest loans, rebates for efficient appliances, home energy ratings, etc., and in 1985

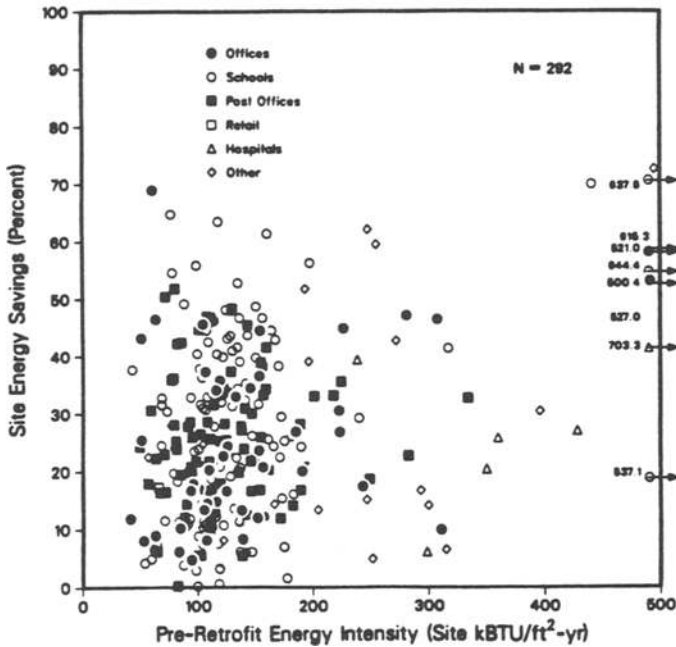


Fig. 10. Percent site energy savings vs. site energy intensity (kBtu/ft<sup>2</sup>-yr). There does not appear to be any correlation between the pre-retrofit energy intensity and the percentage savings realized. Both high and low energy users achieved a wide range of percentage savings. Source: BECA-CR. XCG 805-13075

California completed its millionth residential audit. An example<sup>8</sup> of the success of this policy is the drop in the median capacity of air conditioning units sold; from 4 "tons" in 1977 to 3 "tons" in 1985.

A comparison of the growth in the electricity (kWh) for Texas and California in Fig. 11 suggests that California's conservation tools are very cost effective. The 1985 population of Texas is 16 million (growing at 2.8%/year); California has a population of 26 million (58% larger and growing at 1.7%/year). As shown in Fig. 11, Texas electricity use crossed that of California in 1978-79, and since then Texas has required 1.3 nominal 1-GW plants every year, while California has needed only 1 plant in 5 years.

We won't make a big point of the 1978 difference in kWh use per capita (Texas used 70% more than California). A defiant Texan could cite a high need for air-conditioning and electricity-intensive industry. But once we have corrected for, or ignored, the higher use per capita, we do think that the difference in growth rate is significant: annually 4.3% for Texas, and 0.9% for California. If we correct for the 1.1% higher population growth of Texas, the difference is still 2.1%/year.

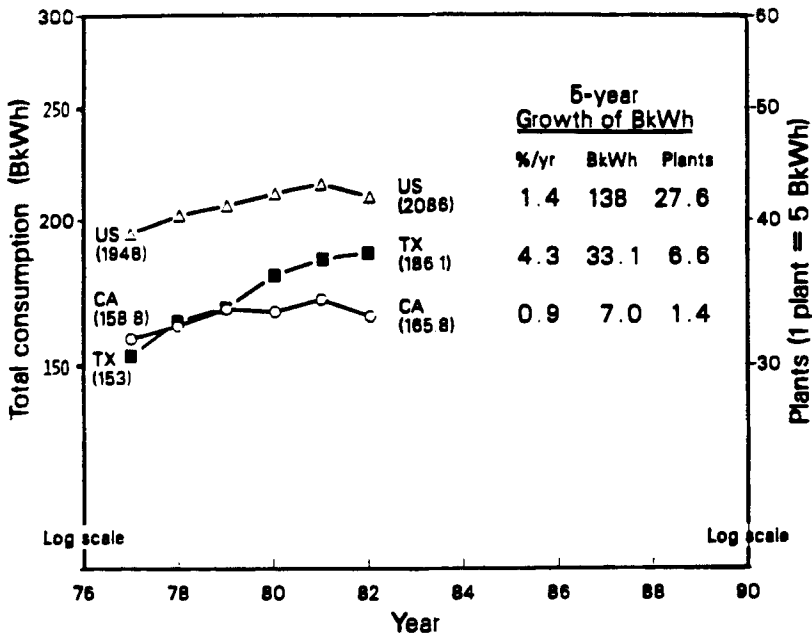


Fig. 11. Total electric consumption by all customers for CA, TX, and U.S. The y-axis is logarithmic and the U.S. is shifted down one decade. BkWh are converted to 1000 MW (1 BW or 1GW) using 1 plant = 5 BkWh/year. Source: Consumption-Electric Power Annual (EIA 0348(82)) p. 167. GW-Annual Energy Review (EIA 0384(83))p. 195 and 201. XCG 846-13083A

What are the economics to California of being able every year to avoid the construction and operation of one nominal 1 GW power plant? Let us take a 10-year perspective. If we focus only on the first cost of 10 plants, then we defer the investment of \$10-20 billion, but that is an under-estimate of the full story by about a factor of two. To make a better estimate we note that the cost of new electricity is at least 10 ¢/kWh, and from Fig. 11 we note that after 10 years California has saved about 50 BkWh/year, worth \$5 billion/year in the 10th year. The total electric bill saved over 10 years is then about \$25 billion.

In a forthcoming study by the University of Texas and LBL<sup>9</sup> (ELECTRICITY CONSERVATION IN TEXAS BUILDINGS, 1985), we discuss the Figure 11 difference in terms of the price of electricity, or growth in the individual sectors. But we find that over the five year period (1977-82), California has added the same population (2.1 million); more square feet of commercial buildings, and twice as much "industrial value added," all for the one equivalent plant, compared with Texas' need for 6.6 plants. As to price effects, in the buildings sector both states had average prices of 7 ¢/kWh, but the Texas industrial rate was indeed cheaper: 4 ¢/kWh instead of 6 ¢/kWh for California.

This discussion is surely not rigorous, but we find it suggestive that California's conservatin tools are effective and cost effective.



## VII. Trends: Saving 2 Alaskas and 70 Power Plants

In this brief conclusion we present two summary figures which point to the following remarkable facts.

Figure 12. Trends in Resource Energy Use (per year and per ft<sup>2</sup>).

1. Today's stock of (typically 20-year old) offices use 270 kBtu (costing \$1.30). Standards already enacted in California, or in draft by ASHRAE, will drop this 270 to 100 or 130 kBtu. Given further improvements in lighting, controls, and storage, already under development, 100 kBtu should become routine.

2. Because of savings by downsizing air conditioning and windows, new office buildings cost no more than the 1973 models, which use 500 kBtu.

3. Extrapolated to the whole 50 B ft<sup>2</sup> of commercial space, this future decrease by a factor of 2.7 in resource energy corresponds to a saving of 2.2 Alaska pipelines.

Figure 13. Separates the data of Fig. 12 into fuel (whose use is vanishing) and electricity.

4. Per year and per ft<sup>2</sup>, electric use is dropping from 17.5 kWh to 11.5 (both numbers within a range of  $\pm 2.5$  kWh). The California mandatory standard dropped a factor of 2 from 18 to 9 kWh in 10 years (see the CA line joining these two points low in Fig. 13). Given the further improvements under development it seems realistic to extrapolate this factor of 2 to the U.S.

5. Extrapolating again to the whole 50 B ft<sup>2</sup> sector, this gain of a factor of 2 will avoid the need to build 70 power plants.

We now return to Fig. 12 for some additional comments.

The sharp rise in resource energy use from 1950 to the OPEC embargo is explained by the low prices of energy, accompanied by buildings with acres of single-glazing, acres of lights, and oversized HVAC (heating, ventilation, and air conditioning) systems, which cooled and then reheated the same air, ignored the availability of cool outside air, failed to use free heat from the core to heat the perimeter, and, although they ran at part load most of the time, were not designed with much consideration of part-load efficiency. Consequently, after the Embargo, it was easy to improve the design of these buildings and cut their annual energy intensity from 500 to 200 Btu/ft<sup>2</sup>, with no increase in first cost.

The line starting in 1975 is the ASHRAE standard, calculated using the DOE-2 program for prototypes. Real buildings under-perform by 10-20%, with 25% of the buildings using 1.5 times the design energy--see Figs. 8 and 9.

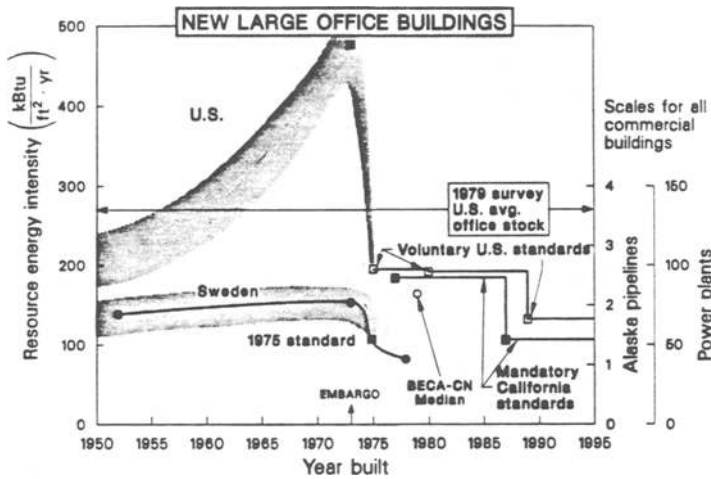


Fig. 12. Trends in annual energy intensity (use per  $\text{ft}^2$ ) of new office buildings. Electricity is counted in resource energy units of 11,600 Btu/kWh.

Dots represent data from real buildings. Squares are computer simulations from prototypes. Thus, the U.S. sequence is represented with Zipatone and is a crude measure of New York City office buildings by Charles W. Lawrence, Public Utilities Specialist for the city of New York (1973).<sup>a</sup> The 1973 (pre-embargo) square is a simulation by A.D. Little for FEA; the later squares are simulations of buildings conforming to the indicated standards.

Interpretation of right-hand scales for all commercial buildings, using data from 1979 NBECS (Non-residential Building Energy Consumption Survey, DOE/EIA-0138).

U.S. Commercial buildings in 1979 used 3.4 q (quads) of fuel and 613 BkWh of electricity (equivalent to 7.1 q), for a total of 10.5 q.

By 1985, 6 years later, with growth of 2.6%/year, use is probably up 13% to 3.8 q fuel + 690 BkWh; total 12 q.

In 1984, the Alaska pipeline carried 1.73 Mbod, equivalent to 3.5 q. Hence, commercial buildings (12 q) use the resource output of 3.5 pipelines.

A typical 1000-MW baseload power plant generates 5 BkWh each year, so commercial buildings need the output of  $690/5 = 137$  standard plants.

In 1979, according to NBECS, the average U.S. office building used  $270 \text{ kBtu}/\text{ft}^2$  of resource energy. The right-hand scales are then adjusted to that stock office energy intensity ( $270 \text{ kBtu}/\text{ft}^2$ ) corresponds to 3.5 pipelines and to 137 power plants. Next we assume that efficiency trends in offices reflect the same percentage trends for all commercial buildings. Thus, if the 1973 office building (up to  $500 \text{ kBtu}/\text{ft}^2$ ) had gained permanent acceptance, our present floorspace would need the equivalent of 6.5 Alaska pipelines, and 250 power plants.

Significant further improvements in lighting, controls, and thermal storage are already in the pipeline, so it seems plausible that office energy intensity will drop to the 1987 CA standard of  $100 \text{ kBtu}/\text{ft}^2$ , i.e. drop a factor of 2.7 compared with office stock, and that the whole sector will follow this trend. For the present floorspace, resource energy use will then drop from 3.5 to 1.3 pipelines, but one has to wait many years to achieve equilibrium.

For electricity, figure 13 and the same reasoning show that without thermal storage we can only expect to save a factor of 2.0. For the present  $50 \text{ B ft}^2$  of buildings, power plants needed will then drop from 140 to 70.

The first cost of these new energy-efficient offices is still falling, mainly because of savings from downsizing chillers.<sup>b</sup> With thermal storage, another 40% of the peak power demand could be displaced off-peak. To compare first cost of 1972 prototype with ASHRAE 90-75 see reference (a). To compare 90-75 with later version see reference (b).

a. A.D. Little, FEA Conservation Paper 43 B (1976).

b. ASHRAE Special Project 41, Vol. III. DOE/NBB 51/6(1983). XCG 853-111 D



The ASHRAE standards are targeted towards least life-cycle cost, but real-world considerations cause them to fall somewhat short, as is illustrated by the fact the the "real" (inflation-corrected) first cost of several building types (large offices, retail, hotels) has not yet begun to rise.

Next we return to Fig. 13, in which the same energy trends are separated into fuel and electricity.

As we saw in Sections I, II and III, large buildings have a large  $\Delta T(\text{free})$ , and so can have "balance" temperatures at or below freezing. Hence the need for space heat is vanishing. This is easily seen for the Swedish sequence at the left, but can be missed for the U.S. because the inefficient 1973 building falls vertically off scale by a factor of 1.7, and could be missed. Thus the discontinuity in resource energy use of Fig. 12 becomes even more striking in fuel use alone (Fig. 13).

Even by keeping the scale large enough to show the U.S. stock of existing buildings, the ASHRAE Standard 90 series fall almost on the x-axis, as does the California mandatory Title 24 sequence.

The ASHRAE voluntary standard has gone through the sequence of Standard 90-75(1975) [plotted with symbol A], 90-A(1980) [B], and soon 90.1 (for commercial buildings) [plotted as R] and 90.2 (for residences). In preparing these standards, there was a major engineering/economic study known as ASHRAE Special Project 21, cited in the figure caption 12. Some intermediate calculations are presented in the series [symbols F and G, as explained in the caption].

Residential squares are presented for comparison purposes, particularly to show the differences in internal load (kWh).

We hope that with these comments and the detailed captions, the reader can easily verify all five of the conclusions stated at the beginning of this section.

### **Shifting the Summer Peak**

To complete a discussion of trends, we must recall thermal storage for load management.

1. Thermal mass, as in Thermodeck (Sect. III) can shift 50-75% of chilling off peak and requires only about  $0.1 \text{ W/ft}^2$  of fan power. But precast slabs are currently used in only a few percent of U.S. buildings.

2.  $21^\circ\text{C}$  PCM's, i.e., phase change materials tuned to change at room temperature will eventually become cheap enough not only to handle the summer peak, but to lock the building at the comfort temperature, say  $23^\circ\text{C}$ , all year. The amount of material to do this

would be relatively small; for the partial storage mode (Sect. IV) it would take for each floor a layer of 6 cm for chilled water, 0.6 cm for ice, and 1.5 cm for phase-change polyalcohols.

An attractive combination of 1. and 2. is to load hollow cores in concrete with 21°C PCM's.

3. Water and ice storage (Sect. IV) cost about the same as thermodeck, but need about 1 W/ft<sup>2</sup> of fan power. We should strive to develop a PCM which is more attractive than water/ice; for example it could freeze at 10°C and contract as it freezes, so as to tear itself off of freezer coils.

4. To maximize thermal capacity/watt of fanpower, we should plan to use a combination of the technologies above.

5. The potential for summer peak shaving is summarized in Table II.

#### ACKNOWLEDGMENT

We want to thank Rosemary Riley for her help with the figures.

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