LA-UR -83-885

CONF-830520--2

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--83-885

DE83 009887

TITLE EVAPORATIVE-COOLING POTENTIAL FOR OFFICE BUILDINGS

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SUBMITTED TO The Second International Congress on Building Energy Management at Ames, Iowa, on May 30-June 3, 1983.

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EVAPORATIVE-COOLING POTENTIAL FOR OFFICE BUILDINGS*

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ABSTRACT

This paper presents the results of both a performance and an economic assessment of the evaporative-cooling potential for office buildings in 11 US climate zones. Evaporative-cooling systems of the direct and combined direct/indirect type that are part of the heating, ventilating and air-conditioning (HVAC) system were evaluated. Thermal storage strategies were not considered in this study. The DOE-2 building-energy-analysis computer program was used to simulate the evaporative-cooling performance of typical single-story and multistory office buildings

Performance results are presented as energy and peak demand reductions for each type of office building in each climate zone. Economic results are summarized as investment targets and aggregate/energy cost savings.

KEY WORDS

Cooling, evaporative cooling, passive solar, office buildings.

INTRODUCTION

As part of a US Department of Energy assessment of passive solar cooling technologies, the Los Alamos National Laboratory has studied the evaporative cooling potential for new office buildings in the US. The overall Passive Cooling Technology Assessment Project, conducted jointly by Lawrence Berkeley Laboratory, Los Alamos National Laboratory, and Booz Allen and Hamilton, Inc., included performance and economic studies of several passive cooling technologies applied to office buildings. The project description, methodology, and results are presented in Ref. [1].

In its part of the study, Los Alamos determined system performance, as well as energy and cost savings, resulting from alternative configurations of a direct and a combined direct/indirect evaporative cooling system. Only evaporative cooling systems integral to the heating, ventilating, and air-conditioning (HVAC) system were studied; the wet-skin types, such as sprayed roofs or roof ponds, were not considered. Furthermore, thermal storage strategies were not considered in this study.

Two types of prototypical office buildings were simulated hour by hour for a year using the DOE-2 building energy analysis computer program. A 929 m^2 (10,000 ft^2) single-story and a 9,290 m^2 (100,000 ft^2) multistory office building were simulated in 11 US climate zones that represented solar, dry-bulb temperature, and humidity conditions in these geographic climate regions. A base case building, with a conventional vapor compression cooling system, was established for each building type as a reference against which energy, demand, and cost savings were compared.

Performance results were determined in terms of the electrical energy use for cooling and the peak electrical demand for the building. These results are presented in detail below.

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*Work sponsored by the US Department of Energy, Office of Solar Heat Technologies.

Economic results are summarized in terms of investment targets and aggregate energy cost savings for geographic regions corresponding to the climate zones. Details of the economic analysis are presented elsewhere [2].

APPROACH

Base Line Office Buildings

Two base line office buildings--a small, one-story building and a large, ten-story building--were defined as references for this assessment as representative of future new office building construction. The base line buildings were not meant to represent innovative, energy-conserving designs, but were chosen to reflect average current design practice. The small office building was typical of speculatively built and leased space, whereas the large structure typified an owner-built and -occupied office building. Both were intended to provide an energy performance benchmark from which to draw meaningful comparisons between the alternative passive cooling strategies evaluated in the Passive Cooling Technology Assessment Project. Detailed definitions of the base line buildings are given in Ref. [1].

Climate Zones

Eleven regions were used to describe the range of climate conditions for cooling in the US. The procedure for selection of these regions is described in Ref. [3]. Weather parameters were selected to represent the salient climate characteristics of each Standard Metropolitan Statistical Area (SMSA) in the US. SMSAs were grouped together to form a region and then population-weighted regional averages of the climate parameters were used to determine which single SMSA best represented the entire region. The set of climate regions selected, and the climate center cities chosen to represent each region, are shown in Fig. 1. Weather tapes of Typical Meteorological Years (TMYs) for the center cities were used in the DOE-2 simulations.

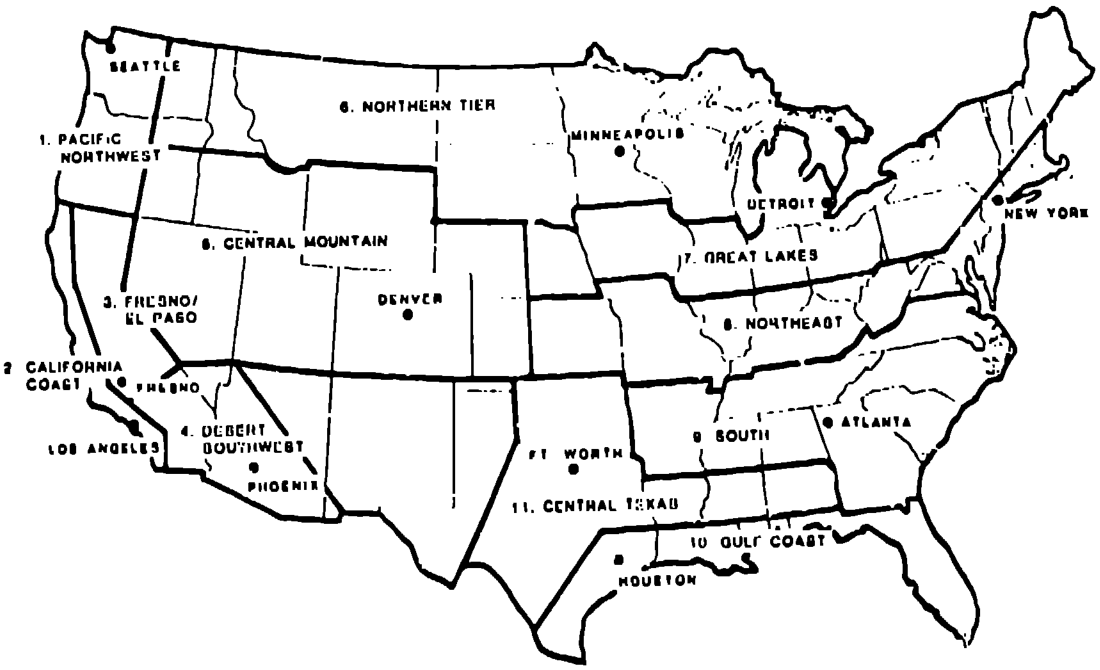

Fig. 1. Climate centers and climate regions.

Evaporative Cooling Processes Simulated

Two evaporative cooling processes were simulated and evaluated in this study:

- Direct evaporative cooling - in which an air stream is passed through an air washer which reduces the dry-bulb temperature while increasing the moisture content, and
- Indirect evaporative cooling - in which two air streams are passed through an evaporatively cooled heat recovery unit; the air stream on the wet side undergoes a direct evaporative cooling process that in turn cools the other air stream through a sensible heat exchange process. The dry side air stream dry-bulb and wet-bulb temperatures are both reduced. Because the wet and dry streams do not mix, moisture is not added to the supply air in this part of the process.

Whereas the first method has been extensively developed over many years, the latter has been more recently developed; many commercial units are available from which to determine basic operating characteristics.

Evaporative Cooling Systems Simulated

For this study these evaporative cooling processes were combined to form two distinct systems:

- Direct system - in which a direct evaporative process alone is used (Fig. 2), and
- Direct/indirect system - in which the indirect process is used to precool the air before it enters the direct evaporation air washer (Fig. 3). The well-known psychrometric paths followed in this two-stage evaporative process are described in Ref. [4].

For both of these systems, the auxiliary system included a conventional chilled water cooling coil/centrifugal chiller system.

Algorithms representing these systems were added to the DOE-2.1A computer program so that the analysis could be conducted; constant air washer and heat recovery heat exchanger effectivenesses were used. For the indirect evaporative process, outside air enters the wet side of the evaporative heat recovery unit at a dry-bulb temperature T_{DB} and is reduced to temperature T_1, as shown in Fig. 3:

$$T_1 = T_{DB} - \eta_{IE}(T_{DB} - T_{WB}), \tag{1}$$

where $\eta_{IE} = 0.85$ is the effectiveness of the evaporative process and T_{WB} is the wet side entering wet-bulb temperature. This cooled air then exchanges heat with the incoming outside supply air on the dry side cooling it to T_2:

$$T_2 = T_{DB} - \eta_H(T_{DB} - T_1), \tag{2}$$

where $\eta_H = 0.65$ is the effectiveness of the heat recovery unit. A bypass is included with the indirect evaporative cooler so that a sufficient flow of outside air is mixed with the cooled supply air to maintain a mixed air temperature downstream of the bypass, T_3, equal to the cold deck temperature, T_C.

For the direct process, the temperature of the incoming supply air stream, T_3, is lowered to T_4, as shown in Fig. 2:

$$T_4 = T_3 - \eta_{DE}(T_3 - T_{WB,3}), \tag{3}$$

where $\eta_{DE} = 0.85$ is the effectiveness of the direct evaporative cooler and $T_{WB,3}$ is the wet-bulb temperature of the air entering the air washer. If the temperature of the air leaving the air washer is lower than the cold deck temperature, that is, $T_4 < T_C$, the bypass will divert sufficient flow so that the cold deck setpoint is maintained. If the temperature of the air leaving the air washer is greater than the cold deck temperature, that is, $T_4 > T_C$, the conventional coil is used to lower the temperature of the supply air to the cold deck set-point,

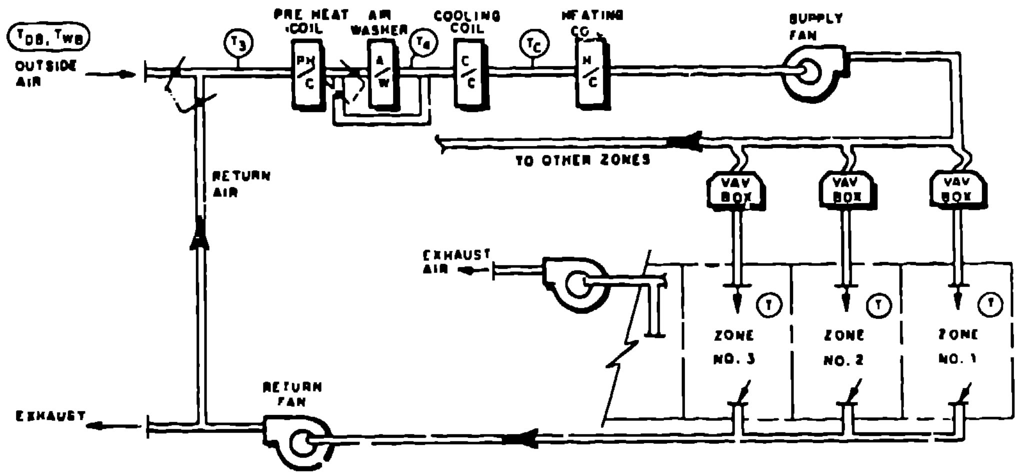

Fig. 2. Direct evaporative cooling.

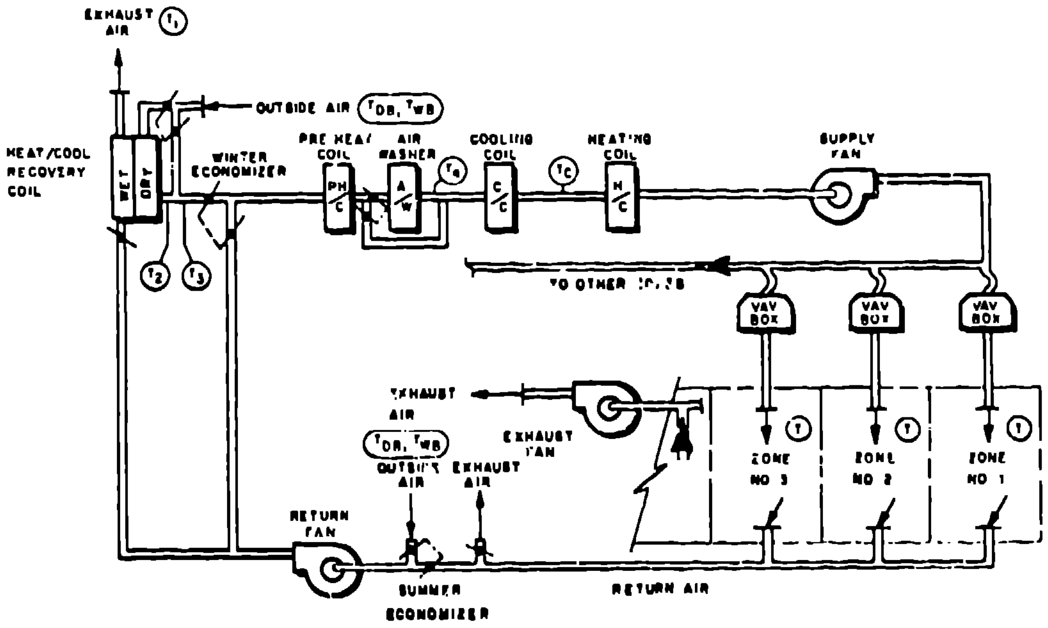

Fig. 3. Direct/Indirect evaporative cooling.

T_C. No bypass operation is required when $T_4 = T_C$. Auxiliary power required to operate the evaporative coolers was neglected in the simulations, as was any additional parasitic pressure loss across the evaporative cooling components.

Operation of the Systems Simulated

The evaporative cooling systems were allowed to operate only during the cooling season, a period of approximately 5-1/2 months, whose length was set such that heating loads were not increased in the swing seasons by the operation of the evaporative cooler. This period was adjusted for each climate. In both system configurations, the space humidity was constrained to not exceed 70% relative humidity; the cooling coil/cold deck temperature was lowered whenever this constraint was not met.

The modes of operation for these two systems are as follows:

- Direct (see Fig. 2)
  - (1) 100% outside air was used whenever the operation of the air washer could save energy over the conventional coil alone. Logic checks were made to determine if the enthalpy of the air leaving the air washer was greater than the mixed air enthalpy of the conventional system operating at minimum outside air fraction.
  - (2) Minimum outside air was used with the air washer bypassed whenever there was no advantage to using the washer.
- Direct/Indirect (see Fig. 3)
  - (1) 100% outside air was put through both the wet and dry side of the heat recovery unit; that is, whenever it was advantageous to use evaporative cooling (as determined by the logic checks mentioned above) the two coolers were operated in series with 100% outside air. The heat recovery unit provided sensible precooling (lowering both dry-bulb and wet-bulb temperatures) so that the air washer performance was improved; this strategy provided two-stage evaporative cooling.
  - (2) 100% outside air was put through the dry side of the heat recovery unit (and air washer) with return air exhausting through the wet side. This mode provided improved performance for the heat recovery cooler for those operating conditions where the return air enthalpy was less than the outside air enthalpy. A logic check was made here to determine whether this strategy or mode 1 should be used.
  - (3) Minimum outside air and conventional cooling was used; the two evaporative coolers were bypassed when it was not advantageous to use them.

Other possible operating modes will be evaluated in future studies.

RESULTS

Performance

Annual base case energy consumption for cooling and related energy savings for the evaporative cooling systems predicted by DOE-2 and expressed on an absolute and fractional basis are presented in Tables 1 and 2. As expected, the better performance of combined direct/indirect evaporative cooling strategy shows it to be a more attractive option than direct evaporative cooling alone.

For the single-story office building, the fractional cooling energy saved by the direct/indirect evaporative cooling strategy is highest in the Pacific Northwest at 43.4% and lowest in the Gulf Coast at 3.7%. For the multistory office building, the fractional energy saved ranges from a high of 23.4% in the Central Mountain region to a low of 2.5% in the Gulf Coast. Note the strong climate dependence of evaporative cooling; only minor savings are possible in very humid regions.

The fractional energy savings are lower for the multistory office building because its cooling energy consumption, per unit of floor area, is lower than that for the single-story building. Both the cooling energy consumption and cooling energy saved in the multistory building are lower, per unit of floor area, because the cooling equipment is more efficient and the economizer operation allows more ventilative cooling in the multistory building. Hence, the

Table 1. Annual evaporative cooling potential of one-story office building.

Region[a]	Cooling consumption[b] base building GJ (10^6 Btu)	Cooling energy saved[b] GJ (10^6 Btu)		Cooling energy saved (%)	Electric demand base building (kW)	Electric demand reduction (kW)		Electric demand reduction (%)
		Dir	Dir/Ind			Dir	Dir/Ind	
Pacific Northwest	66.4 (62.9)	19.6 (18.6)	28.8 (27.3)	43.4	48.9	0.0	6.7	13.7
California Coast	109.8 (104.1)	20.7 (19.6)	32.5 (30.8)	29.6	53.0	-0.9	3.8	7.2
Fresno/ El Paso	154.9 (146.8)	24.1 (22.8)	40.6 (38.5)	26.2	63.0	0.0	-3.2	-5.1
Desert Southwest	208.1 (197.2)	20.8 (19.7)	43.2 (40.9)	20.7	67.4	-0.3	-3.8	-5.6
Central Mountain	74.9 (71.0)	26.5 (25.1)	31.3 (29.7)	41.8	53.9	0.9	2.3	4.3
Northern Tier	96.7 (91.7)	18.1 (17.2)	22.4 (21.2)	23.1	62.1	0.6	0.6	1.0
Great Lakes	94.6 (89.7)	15.6 (14.8)	19.2 (18.2)	20.3	59.2	0.0	0.0	0.0
Northeast	98.5 (93.4)	12.4 (11.8)	17.1 (16.2)	17.3	59.5	-0.3	-0.3	-0.5
South	141.2 (133.8)	10.4 (9.9)	15.2 (14.4)	10.8	63.9	-0.3	-0.6	-0.9
Gulf Coast	200.1 (189.7)	5.0 (4.7)	7.4 (7.0)	3.7	67.1	0.0	0.0	0.0
Central Texas	166.7 (158.0)	22.1 (20.9)	26.6 (25.2)	15.9	66.8	-0.3	-0.3	-0.4

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[a] Cold deck temperature = 15.6°C (60°F). Relative humidity = 70%.

[b] Cooling consumption and energy saved include energy delivered to the chillers, cooling tower, fans, and cooling water pumps.

Table 2. Annual evaporative cooling potential of multistory office building.

Region	Cooling consumption[b] base building GJ (10^6 Btu)	Cooling energy saved[b] GJ (10^6 Btu)		Cooling energy saved (%)	Electric demand base building (kW)	Electric demand reduction (kW)		Electric demand reduction (%)
		Dir	Dir/Ind			Dir	Dir/Ind	
Pacific[a] Northwest	545.6 (517.1)	57.0 (54.0)	103.0 (97.6)	18.9	512.7	-6.4	56.8	11.1
California[a] Coast	833.5 (790.0)	53.9 (51.1)	113.3 (107.4)	13.6	550.8	-18.2	25.8	4.7
Fresno/[a] El Paso	1343.2 (1273.1)	121.9 (115.5)	294.4 (279.0)	21.9	675.9	-32.2	-36.3	-5.4
Desert Southwest	2007.6 (1902.8)	163.1 (154.6)	368.8 (349.6)	18.4	755.6	-5.6	12.0	1.6
Central Mountain	732.4 (694.2)	117.4 (111.3)	171.7 (162.7)	23.4	594.5	39.3	58.0	9.8
Northern Tier	845.2 (801.1)	35.8 (33.9)	71.2 (67.5)	8.4	624.1	-0.6	0.0	0.0
Great Lakes	886.7 (840.4)	70.5 (66.8)	110.8 (105.0)	12.5	641.4	0.9	2.1	0.3
Northeast	861.1 (816.2)	31.0 (29.4)	67.0 (63.5)	7.8	598.6	0.0	0.6	0.1
South	1181.3 (1119.7)	24.2 (22.9)	61.4 (58.2)	5.2	642.3	-3.5	-3.5	-0.5
Gulf Coast	1827.6 (1732.2)	17.1 (16.2)	45.9 (43.5)	2.5	697.6	2.6	-23.1	-3.3
Central[a] Texas	1389.9 (1317.4)	56.4 (53.5)	88.6 (84.0)	6.4	720.5	-26.1	-28.1	-3.9

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[a] Cold deck temperature = 15.6°C (60°F); for all other regions cold deck temperature = 12.8°C (55°F). Relative humidity = 70%.

[b] Cooling consumption and energy saved include energy delivered to the chillers, cooling tower, fans, and cooling water pumps.

differences in the mechanical equipment selected for the base line buildings favors the implementation of evaporative cooling in smaller, rather than larger, office buildings. This unintentional bias results from the size factor difference between the two base line buildings used.

A more important measure of potential is the absolute cooling energy savings. Four regions, namely the California Coast, Fresno/El Paso, Desert Southwest, and Central Mountains, rank as top performers for both single- and multistory buildings, with energy savings for the direct/indirect system ranging from 31-43 GJ (30-41 x 10^6 Btu) for the small office building to 113-369 GJ (107-350 x 10^6 Btu) for the large building. These regions are characterized by either Mediterranean, Rocky Mountain, or desert climates. However, substantial energy savings are shown for all regions.

The peak electric demand is shown to be reduced in some climates by the use of evaporative cooling and increased in others. In the cases where the peak electric demand is reduced, the benefit is achieved because some of the peak cooling load is met with evaporative cooling, which uses less electric power than the vapor compression cooling system that it is displacing. For cases where the peak electric demand increases, it usually results from an increase in fan power over the base line case. However, peak electric demand is not strongly influenced by the evaporative cooling systems studied.

Economics

An economic evaluation of the evaporative cooling systems potential was conducted by the Economics Group of the Los Alamos National Laboratory. Detailed results of their analysis, for several passive cooling technologies, are presented in Ref. [2]. A few highlights are shown in Tables 3 and 4.

The largest aggregate potential savings for evaporative cooling resulted for the California Coast region, as shown in Table 3. The aggregate base case cost and savings shown in Table 3 are the typical electric utility bills or typical electric utility bill saving associated with each class of office building, either large or small, as summed within each class and totalled for both classes. Over \$1.2 million in direct savings from electric utility bills could be realized annually at current utility rates if the direct/indirect evaporative cooling systems described were implemented in all new office buildings, both single-story and multistory, to be built within this region. More then \$0.5 million could be saved in the Central Mountain region. The fractional electric utility bill savings ranged from 0-8% over all regions.

Although the actual costs of implementing these processes were not determined, investment targets commensurate with a 25-year payback were determined assuming typical economic and tax parameters. These targets are shown in Table 4. For example, one could afford to invest \$25.19 gross m^2 (\$2.34/gross ft^2) of floor space in evaporative cooling equipment for small [≤ 2,323 m^2 (25,000 ft^2)] office buildings constructed in the California Coast region and break even in 25 years. For the single-story base line office building, this amounts to a \$23,400 investment. If the equipment could be purchased and installed for less than this amount, then the investment would pay back with utility bill and tax savings in less than 25 years. Furthermore, investment targets exceed 21.53/m^2 (\$2.00/ft^2) for small office buildings in the California Coast, Central Mountain, and Fresno/El Paso regions. Investment targets for large office buildings [> 2,323 m^2 (25,000 ft^2)] were somewhat less, but exceeded \$16.15 m^2 (\$1.50/ft^2) in both the Central Mountain and Fresno/El Paso regions.

CONCLUSIONS

The performance and economic results of this evaporative cooling assessment study support the following conclusions.

- In office buildings, a direct/indirect evaporative cooling system performs better than a direct evaporative cooling system alone.
- The energy savings resulting from the use of evaporative cooling systems in office buildings located within the US is greatest in the Mediterranean, Rocky Mountain, and desert climate regions.
- Evaporative cooling thermal performance of office buildings is more closely related to the type of mechanical systems installed than to the size of the building.

Table 3. Annual aggregated dollar savings for small and large office buildings.

Region	Base case costs ($)	Direct/Indirect evaporative savings (%) ($)
Pacific Northwest	2,063,800	79,895 (4)
California Coast	31,734,700	1,261,207 (4)
Fresno/El Paso	5,326,400	316,972 (6)
Desert Southwest	5,844,100	287,395 (5)
Central Mountain	6,420,300	548,154 (8)
Northern Tier	7,574,200	126,889 (2)
Great Lakes	42,808,500	1,258,401 (3)
Northeast	59,856,400	490,615 (1)
South	13,530.900	248,530 (2)
Gulf Coast	32,127,600	115,741 (0)
Central Texas	13,801,600	152,210 (1)
United States	226,088,500	4,886,059 (2)

Table 4. Investment targets in \$/m^2 (\$/ft^2) for a 25-year period of analysis.

Region	Direct one-story	Direct multistory	Direct/Indirect one-story	Direct/Indirect multistory
Pacific Northwest	0.86 (0.08)	0.22 (0.02)	1.29 (0.12)	0.43 (0.04)
California Coast	13.67 (1.27)	1.94 (0.18)	25.19 (2.34)	10.44 (0.97)
Fresno/ El Paso	12.70 (1.18)	5.81 (0.54)	21.64 (2.01)	16.36 (1.52)
Desert Southwest	3.44 (0.32)	2.80 (0.26)	7.75 (0.72)	6.89 (0.64)
Central Mountain	20.77 (1.93)	15.72 (1.46)	30.25 (2.81)	24.65 (2.29)
Northern Tier	2.26 (0.21)	0.43 (0.04)	2.69 (0.25)	0.97 (0.09)
Great Lakes	4.74 (0.44)	3.12 (0.29)	6.14 (0.57)	4.74 (0.44)
Northeast	2.91 (0.27)	0.97 (0.09)	3.98 (0.37)	1.72 (0.16)
South	2.58 (0.24)	0.54 (0.05)	3.88 (0.36)	1.40 (0.13)
Gulf Coast	0.65 (0.06)	0.11 (0.01)	0.86 (0.08)	0.32 (0.03)
Central Texas	3.12 (0.29)	---	4.31 (0.40)	0.22 (0.02)

- Peak electric demand in office buildings is relatively insensitive to the evaporative cooling systems studied.
- The largest aggregated utility bill savings for new office buildings built in the US with direct/indirect evaporative cooling systems can be realized in the California Coast region.
- Investment targets for direct/indirect evaporative cooling systems suggest that these systems can be built cost effectively for office buildings in the California Coast, Central Mountain, and Fresno/El Paso regions of the US.
- Additional research is needed to verify the evaporative cooling modifications made in the DOE-2 computer program.

ACKNOWLEDGMENTS

The authors wish to acknowledge the valuable assistance of two staff members of Los Alamos National Laboratory: N. M. Schnurr, for assistance in implementating the evaporative cooling algorithms into the DOE-2 computer program, and M. A. Roschke, for developing an efficient method of summarizing and plotting the results of the many DOE-2 computer simulations that were performed in this study.

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