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Building and Environment, Vol. 25, No. 2, pp. 95–103, 1990.
Printed in Great Britain.

0360–1323/90 $3.00+0.00

Assessment of the Energy Savings due to the Building Retrofit

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This paper explores a weather-normalization method for estimating the energy savings due to building retrofit, eliminating the effect of different weather conditions. The detailed computer program DOE-2.1B was used to estimate the energy consumption of an office building, and then the predictions of the daily energy use along with the daily average outdoor temperature were used to develop the energy signature of the building. One can observe that the energy signature, developed for one year, remains constant for all subsequent years, provided that no modifications of the building are performed. Therefore, the normalized energy consumption is calculated using the energy signature and the number of hours of occurrence of different outdoor temperature bins for the same reference year. The energy savings due to the building retrofit are obtained as the difference between the normalized energy consumptions before and after retrofit. The estimations of the proposed method are compared with the results of DOE-2.1B computer program, for gas and electrical consumption of an office building with complex schedules of operation and thermal control.

NOMENCLATURE

- A surface area, ft^2
- a non-weather dependent energy consumption, for gas in 10^6 Btu day^{-1}, for electricity in 10^3 kWh day^{-1}
- b heating or cooling slope, for gas in 10^6 Btu day^{-1} F^{-1}, for electricity in 10^3 kWh day^{-1} F^{-1}
- B_L base level of gas consumption, 10^6 Btu day^{-1}
- B_{L1} base level of electrical consumption outside occupancy, 10^3 kWh day^{-1}
- B_{L2} base level of electrical consumption during occupancy, 10^3 kWh day^{-1}
- E daily energy consumption, in 10^6 Btu for gas, in 10^3 kWh for electricity
- H heating or cooling degree days, F
- L heat loss, Btu h^{-1}
- M monthly energy consumption, Btu or kWh
- $\dot{m}_{INF}$ air infiltration rate, ft^3 min^{-1}
- N_1 number of days of operation at the base level B_L for gas, or B_{L1} for electricity, in days $year^{-1}$
- N_2 number of days of operation of the HVAC system, days $year^{-1}$
- N_3 number of operation hours per day of the HVAC system, h day^{-1}
- N_4 number of days of operation at the base level B_{L2}, in days $year^{-1}$
- NAC normalized annual consumption, in 10^6 Btu for gas, in 10^3 kWh for electricity
- n number of temperature bins
- Q internal heat gains, Btu h^{-1}
- T_R indoor air temperature, F
- T_{DB} daily average dry-bulb temperature, F
- T_{WB} daily average wet-bulb temperature, F
- U overall heat transfer coefficient, Btu h^{-1} F^{-1} ft^{-2}.

INTRODUCTION

ENERGY consumption in envelope-load dominated buildings is greatly influenced by the weather conditions. Hence, the comparison between the energy consumption of the pre- and post-retrofit buildings must take into consideration the weather variations.

Although several weather-normalization techniques have been proposed, there is no single method, unanimously accepted, to correct the energy consumption for the weather conditions [1]. For example, the heating or cooling degree-days are used to take into consideration the differences in weather conditions. A linear relationship is assumed between the gas consumption and the heating degree-days or between electrical consumption and cooling degree-days [1]:

$$\text{Energy} = a + bH, \tag{1}$$

where: a is the intercept or non-weather-dependent energy use; b is the heating or cooling slope; H is the heating or cooling degree-days.

The degree-days are calculated with respect to an outdoor reference temperature for which the internal plus solar heat gains offset heat loss of the building. Early approaches considered a fixed value of the reference temperature, while the latest developments calculate the reference temperature, sometimes called balance temperature, and then the corresponding degree-days.

The PRISM (Princeton Scorekeeping Method) uses the so-called "Normalized Annual Consumption—NAC", developed from the utility meter readings M_i (usually monthly values), before and after the building retrofit, together with the average daily temperatures [2]. A linear model between the average daily consumption $E_i = M_i/(\text{number of days})$ expressed in Btu and the heating degree-days per day H_i computed to reference temperature T_{ref} is assumed.

$$E_i = a + bH_i(T_{ref}), \tag{2}$$

where: a is the base level (e.g. non-weather dependent daily consumption such as domestic hot water, lighting or appliances), in Btu day^{-1}; $b = c(L/\eta)$ is the ratio between the heat losses rate of building (L) and the

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efficiency of heating system (η), in Btu F^{-1} (the constant C is for units conversion).

$$T_{ref} = T_R - \frac{Q}{L},$$

where: T_R is the design indoor temperature, in F; Q represents the internal heat gains (lighting, people, appliances) and the solar heat gains, in Btu h^{-1}.

First, the values of the parameters a and b are calculated by least squares linear-regression, for a given value of reference temperature T_{ref}. Then, optimum value of T_{ref} yields linear relationship between E_i and $H_i(T_{ref})$, for which the correlation coefficient R^2 is highest.

The Normalized Annual Consumption is, then, obtained by applying the parameters a and b to a long term annual average of heating degree-days $H_0(T_{ref})$:

$$\text{NAC} = 365a + bH_0(T_{ref}). \tag{3}$$

As the reference temperature T_{ref} is assumed constant over the heating season, the following factors are, also, assumed to be constant:

- indoor temperature T_R
- internal heat gains and solar heat gains Q
- heat losses of building.

The commercial buildings have HVAC systems with different schedules for operation and control of indoor temperature (e.g. weekday vs weekend, dead band, set-back or set-up), and then the assumption of constant T_R appears to be no more valid.

As an alternative method, Kusuda [4] suggested for the first time the use of the energy signature of a building, defined as Daily Load vs Daily Average Outdoor Temperature, along with the frequency of occurrence of different temperature bins, to compare the thermal performance of buildings. So far, no results have been published to prove the accuracy of his idea.

In this paper, the use of the building energy signature to eliminate the effect of weather severity in the analysis of energy savings due to the building retrofit is presented. The method uses the energy signatures of the pre-retrofit and post-retrofit building, along with the temperature bin data of the post-retrofit year.

BUILDING ENERGY SIGNATURE

The dependency of heating or cooling consumption on the climatic conditions can be determined by plotting the energy consumption E for a given period (e.g. day, month) vs the corresponding average outdoor temperature T_o. Then a curve fitting technique is used to define the relationship between the energy use and the outdoor temperature, which is called the building energy signature for heating/cooling (Fig. 1). Usually, a linear model, such as $E = a - bT_o$, is obtained with acceptable level of accuracy [3–7]. Other works reported a non-linear relationship between the electrical consumption for heating and cooling in commercial buildings, and the average outdoor temperature [2, 8].

The slope of this curve is usually given by factors such as conductive heat loss rate (UA), convective heat loss due to air infiltration ($\dot{m}_{INF}C_p$), efficiency of different

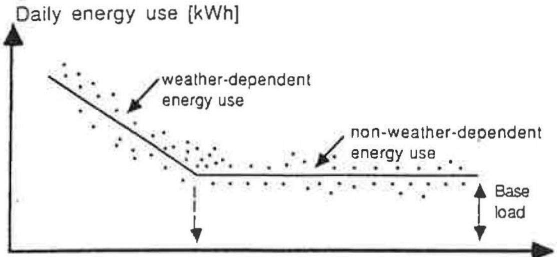

Fig. 1. Building energy signature.

HVAC components or schedules for thermal control and operation. The intersection between the weather-dependent curve and the base level curve, which represents the non-weather dependent energy use (e.g. domestic hot water, lighting or appliances), gives the reference temperature T_{ref}. Therefore, the building requires energy for heating only when the outdoor temperature T_o is lower than the reference temperature T_{ref}, and the energy use is proportional to the difference $T_{ref} - T_o$.

The deviations of the measurements from the linear model around the reference temperature in milder months, are mainly due to the thermal mass of building, the solar radiation and the decrease of boiler/furnace performance for part load conditions. The scatter of the measurements is usually due to daytime overheating and night-time overcooling.

In this paper, the building energy signature is proposed to be used for the analysis of energy savings, eliminating the differences in weather conditions before and after retrofit. The method consists of the following steps (Fig. 2).

(i) The available data (daily energy consumption and daily average outdoor temperature) are used to develop the building energy signatures before retrofit $E_1 = a_1 - b_1T_0$ and after retrofit $E_2 = a_2 - b_2T_0$. The method is based on the assumption that the energy signatures E_1 and E_2 do not vary from year to year, that is different successions of sunny warm days or cloudy cold days do not modify the energy signature. This assumption will be proved within the paper.

(ii) The energy signatures are used together with the outdoor temperature bins of the post retrofit year (reference year), to obtain the normalized energy consumption before and after retrofit, and then to calculate the energy savings.

COMPUTER SIMULATION

To test the accuracy of the proposed method, the detailed computer program DOE-2.1B developed at the Lawrence Berkeley Laboratory and the Los Alamos Scientific Laboratory, was used to estimate the energy consumption of a commercial building located in Winnipeg, Manitoba (Canada) and having complex schedules of operation and thermal control.

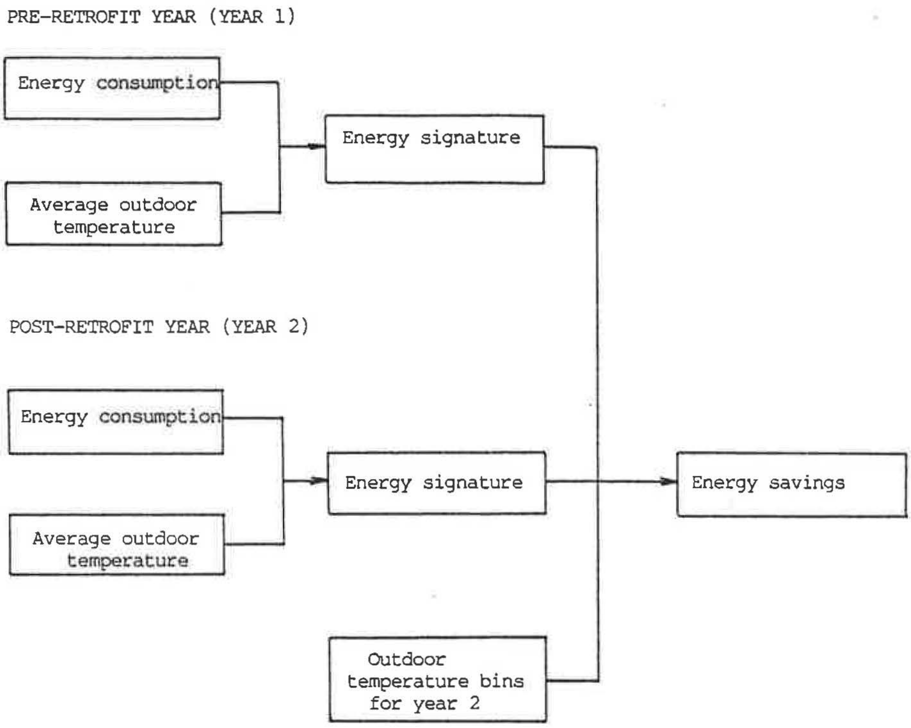

Fig. 2. Flowchart of the proposed method.

The hourly weather data monitored by the meteorological services in Winnipeg between 1980 and 1983 are used in the simulation by the DOE program.

The daily energy use as predicted by the computer program are considered as actual data, and then along with the daily average outdoor temperature are used in the present analysis.

The pre-retrofit building is a 75 × 30 × 11 ft (22.5 × 9 × 3.3 m), one storey office building, and the main characteristics are presented in the Appendix.

During the building retrofit, the thermal insulation of walls and roof is increased from R-11 (RSI-1.9) to R-19 (RSI-3.3), giving an average thermal resistance of 19.86 ft^2 hF Btu^{-1} (3.5 $m^2 \cdot C\ W^{-1}$) (wall) and 19.40 ft^2 hF Btu^{-1} (3.4 $m^2 \cdot C\ W^{-1}$) (roof) after retrofit. Double glass windows are installed, and the lighting power is reduced by about 20%.

It is assumed that 1981 is the pre-retrofit year, and 1983 is the post-retrofit year. However, the pre-retrofit building is simulated for a few years (1980–1983) and the annual gas and electrical consumptions, as estimated by the DOE-2.1B program, are presented in Table 1.

A short discussion on this table shows the need for comparing the energy consumptions before and after retrofit for a reference year, to eliminate the severity of climate. The effect of different weather conditions on the gas and electrical consumption of the pre-retrofit building can be observed in columns 2 and 3. For example, the gas consumption in 1983 is greater by about 2.0×10^7 Btu (5.9×10^3 kWh) than in 1981. The difference between the gas energy consumption in 1981 (pre-retrofit) and 1983 (post-retrofit) shows savings of about 8.75×10^6 Btu (2.5×10^3 kWh), which are due to the building retrofit and to the different weather conditions. As the average dry-bulb temperatures were higher in 1981 than 1983 (Table 2), it seems the energy savings are underestimated. If the pre- and the post-retrofit buildings are compared for the reference year 1983, then savings of $(173.87–144.97)10^6 = 2.89 \times 10^7$ Btu (8.4×10^3 kWh) due only to the retrofit are obtained (Table 1).

Table 1. Gas and electricity consumptions

Year	Pre-retrofit Gas (10^6 Btu)	Pre-retrofit Electricity (10^3 kWh)	Post-retrofit Gas (10^6 Btu)	Post-retrofit Electricity (10^3 kWh)
1980	179.55 (52.6×10^3)*	28.65	–	–
1981	153.72 (45×10^3)	27.45	–	–
1982	176.40 (51.7×10^3)	30.66	–	–
1983	173.87 (50.9×10^3)	28.77	144.97 (42.5×10^3)	24.20

* Gas energy consumption expressed in kWh.

ANALYSIS OF RESULTS—GAS CONSUMPTION

The building energy signature is defined as the relationship between the daily energy consumption and the daily average outdoor temperature. The daily energy consumption can be obtained from: (i) monitored daily values or (ii) monitored monthly values divided by the number of days (daily average). As the monthly energy consumption data are more easily obtained (for example from the utility bills), the users can be attracted

Table 2. Average dry-bulb and wet-bulb temperatures of outdoor air. Winnipeg, Canada

Month	Average outdoor temperature (F) 1980	1981	1982	1983
Jan.	−0.9/−1.3	7.3/6.8	−12.7/−12.8	10.7/10.2
Feb.	4.7/4.3	14.5/13.6	6.2/5.5	13.9/13.2
Mar.	13.1/12.0	29.9/27.1	19.5/18.1	23.9/22.5
Apr.	45.4/37.3	40.2/34.8	37.2/32.1	37.6/33.0
May	61.2/48.0	53.2/44.1	56.3/48.7	47.4/40.2
Jun.	62.8/53.0	60.9/54.0	57.3/49.4	62.7/55.7
Jul.	69.0/59.6	68.9/61.2	67.8/61.2	71.7/64.0
Aug.	63.1/57.4	67.8/61.0	62.5/55.9	72.3/62.8
Sep.	52.1/47.5	54.5/48.8	54.1/48.2	54.9/48.7
Oct.	39.7/36.4	41.5/38.0	43.0/40.0	42.0/38.8
Nov.	29.2/27.3	33.8/31.1	21.6/20.1	28.9/27.5
Dec.	4.2/3.7	9.0/8.5	13.9/13.2	−2.4/−9.8
Yearly average	37.1/32.2	40.3/35.9	35.7/31.8	38.8/34.4

to use the daily average values. However, it is important to evaluate the effect of using these values instead of the daily values, in defining the building energy signature.

Use of daily values

The analysis of the daily gas consumption during the summer months and the weekends/holidays gives a base level of energy use of 19 000 Btu (5.6 kWh), that does not depend on weather conditions. Then, the days corresponding to this level of energy use are eliminated from the further analysis of the weather-dependent gas consumption.

The building is unoccupied 111 days year^{-1}, when it operates at the base level of the energy use. The HVAC system is on 365 days and 17 h day^{-1}.

It is assumed a linear relationship between the daily gas use E, and the daily average dry-bulb temperature T_{DB}: $E = a - bT_{DB}$, and then the coefficients a and b are obtained by using the least squares method. The results show (Table 3):

- small differences between the values of coefficients a and b, obtained for different years (1980–1983); therefore, the building energy signature does not depend on the weather conditions occurring in a particular year
- small standard errors in estimating the coefficients a and b
- the reference temperature has values within the range 53.8–55.8 F (12.1–13.2°C)
- correlation coefficient R^2 has values between 0.83 and 0.86, that is almost 85% of the variation in daily gas consumption is due to the variation of the dry-bulb outdoor temperature.

Table 3. Gas energy signature of the pre-retrofit building using daily values. $E = a - bT_{DB}$ (10^6 Btu)

Year	a (10^6 Btu)	b (10^6 Btu F^{-1})	R^2	T_{ref} (F)
1980	1.743±0.03	0.031±0.001	0.84	55.6
1981	1.752±0.03	0.031±0.001	0.86	55.8
1982	1.793±0.04	0.033±0.001	0.83	53.8
1983	1.806±0.03	0.032±0.001	0.85	55.8

Hence, the energy signature based on the pre-retrofit data (1981) (Fig. 3) can be used along with the number

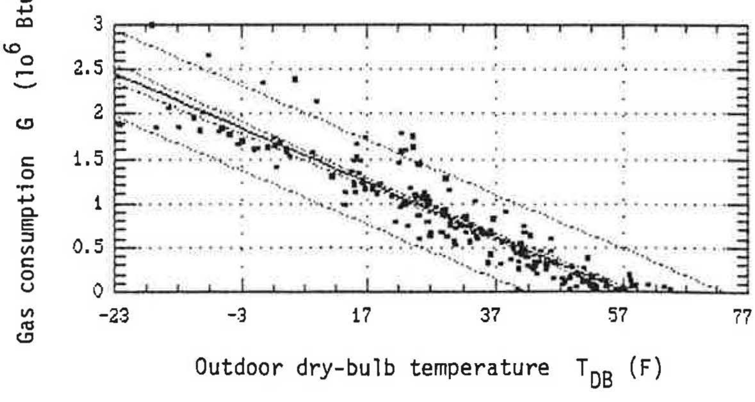

Fig. 3. Energy signature of the pre-retrofit building. Daily gas consumption vs daily average dry-bulb temperature.

of hours of occurrence for temperature bins during the operation of HVAC unit, on the post-retrofit year (1983), to calculate the normalized energy consumption of the pre-retrofit building (NAC_g).

$$NAC_g = B_L N_1 + \begin{cases} \frac{N_2}{365N_3}\sum_{i=1}^{n}(a - bT_{DB,i} - B_L)\,BIN(T_{DB,i}) & \text{if } T_{DB} < T_{ref} \\ 0 & \text{if } T_{DB} \geq T_{ref}, \end{cases} \quad (4)$$

where: NAC_g is the normalized annual gas consumption, in 10^6 Btu; B_L base level of the daily gas consumption, in 10^6 Btu; N_1 number of days of operation at the base level (e.g. weekends, holidays), in days $year^{-1}$; N_2 number of days of operation of the HVAC system, in days $year^{-1}$; N_3 number of operation hours per day of the HVAC system, in h day^{-1}; BIN (T_{DB}) number of hours of occurrence of the dry-bulb temperature bin having T_{DB} as centre, during the operation of the HVAC system (8:00 a.m.–12:00 p.m.) on the post-retrofit year (Table 4); n = number of temperature bins ($n = 28$; Table 4).

The energy signature of the post-retrofit building, developed in similar way, is presented in Fig. 4. The difference between the normalized gas consumption before and after retrofit shows savings of 3.3×10^7 Btu (9.7×10^3 kWh) (Table 5). The comparison between these savings and those estimated by the DOE-2.1B program shows that the proposed method overestimates the energy savings by $(33.02–28.90)/28.90 \times 100 = 14.2\%$.

Use of daily average values

The analysis of the daily average gas consumption vs the daily average temperature was performed in similar manner. The results for the pre-retrofit building (Table 6) show, as in the previous case, small differences between the values of coefficients a and b, obtained for different years. The difference between the normalized gas consumption before and after retrofit shows savings of 2.134×10^7 Btu (6.25×10^3 kWh), which indicates an underestimation of $(21.34–28.90)/28.90 \times 100 = -26.2\%$, with respect to the results of the DOE-2.1B program. Therefore, the use of daily average values

Table 4. Number of hours of occurrence of temperature bins from 8:00 a.m. to 12:00 pm. Winnipeg 1983

Temperature bin (F)	Dry-bulb temperature	Wet-bulb temperature
102/107	—	—
97/102	5	—
92/97	14	—
87/92	101	—
82/87	217	—
77/82	259	10
72/77	342	142
67/72	317	351
62/67	375	471
57/62	317	409
52/57	352	323
47/52	360	492
42/47	445	503
37/42	310	427
32/37	472	544
27/32	395	478
22/27	401	440
17/22	341	364
12/17	291	284
7/12	216	231
2/7	154	183
−3/2	139	138
−8/−3	114	99
−13/−8	117	140
−18/−13	87	91
−23/−18	56	69
−28/−23	8	16
−33/−28	—	—
Total	6205	6205

in this particular case provides less accurate estimations.

One can conclude that the use of daily average values, instead of daily values, leads to less accurate results in the case of gas consumption.

ANALYSIS OF RESULTS—ELECTRICAL CONSUMPTION

Use of daily values

The analysis of the daily electrical consumption during the winter months and the weekends/holidays gives the following base levels of the energy use: (a) pre-retrofit building (occupancy 102.8 kWh day^{-1}; outside occu-

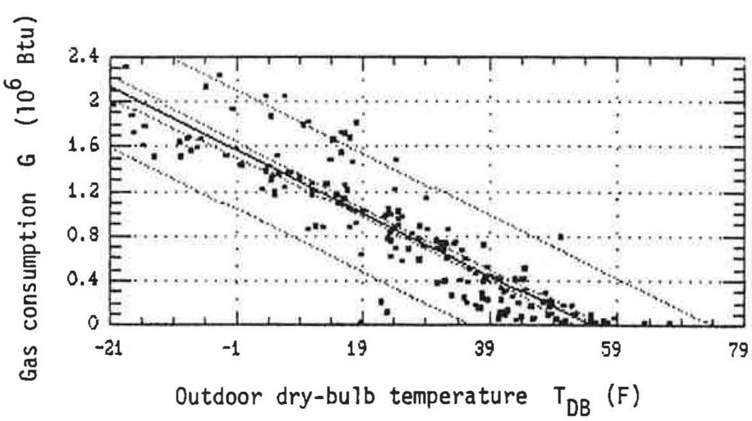

Fig. 4. Energy signature of the post-retrofit building. Daily gas consumption vs daily average dry-bulb temperature.

Table 5. Comparison between the gas energy savings estimated by the DOE-2.1B program and by the proposed method, using daily values

	a (10^6 Btu)	b (10^6 Btu F^{-1})	R^2	T_{ref} (F)	Gas consumption (10^6 Btu) DOE-2.1B	Proposed method
Pre-retrofit	1.752	0.031	85.8	55.8	173.87 (50.9×10^3)*	227.72 (66.7×10^3)
Post-retrofit	1.538	0.028	80.4	50.7	144.97 (42.5×10^3)	194.70 (57.1×10^3)
Savings (10^6 Btu)					28.90 (8.5×10^3)	33.02 (9.7×10^3)

* Gas energy consumption expressed in kWh.

Table 6. Gas energy signature using daily average values. $E = a - bT_{DB}$ (10^6 Btu)

Year	a (10^6 Btu)	b (10^6 Btu F^{-1})	R^2	T_{ref} (F)
Pre-retrofit				
1980	1.244 ± 0.05	0.021 ± 0.0015	0.97	58.2
1981	1.217 ± 0.03	0.021 ± 0.001	0.99	57.2
1982	1.183 ± 0.03	0.020 ± 0.001	0.99	58.1
1983	1.210 ± 0.07	0.019 ± 0.002	0.94	62.7
Post-retrofit				
1983	1.032 ± 0.06	0.017 ± 0.001	0.93	59.1

pancy 7.8 kWh day^{-1}); (b) post-retrofit building (occupancy 86.3 kWh day^{-1}; outside occupancy 7.8 kWh day^{-1}).

The assumption of the linear relationship between the daily electrical consumption E, and the daily average dry-bulb temperature T_{DB}, leads to low correlation coefficients R^2. Figure 5 shows the spread of points around the fitted curve for the case of pre-retrofit building, with $R^2 = 0.61$. Therefore, some other parameters have great effect on the electrical consumption, and then the energy signature cannot be defined in terms of dry-bulb temperature.

A higher correlation coefficient $R^2 = 0.81$ is obtained for the same case between the daily electrical consumption E, and the daily average wet-bulb temperature T_{WB} (Fig. 6). This result suggests that the operation of the HVAC unit to cool the outdoor air plays an important role in the electrical consumption.

The analysis of the building signature $E = a + bT_{WB}$ for 1981–1983 shows (Table 7):

- correlation coefficients R^2 between 0.73 and 0.85;
- large standard errors in calculating the coefficient a;
- the reference temperature has values within the range 28.4–31.8 F (−2–0°C).

The energy signatures for 1980–1983 (Table 7) were used to calculate the daily electrical consumption, and

Table 7. Electrical energy signature of the pre-retrofit building. $E = a + bT_{WB}$ (10^3 kWh)

Year	a (10^3 kWh)	b (10^3 kWh F^{-1})	R^2	T_{ref} (F)
Daily values				
1980	26.0 ± 6.70	1.74 ± 0.12	0.73	28.5
1981	21.32 ± 5.42	1.70 ± 0.094	0.81	28.4
1982	12.44 ± 6.56	2.16 ± 0.11	0.85	29.1
1983	7.41 ± 6.30	2.03 ± 0.10	0.85	31.8
Daily average values				
1980	50.58 ± 6.7	0.684 ± 0.14	0.82	36.4
1981	62.27 ± 12.0	0.407 ± 0.23	0.51	18.1
1982	74.91 ± 3.6	0.306 ± 0.09	0.59	0.95
1983	61.49 ± 8.9	0.51 ± 0.18	0.68	20.60

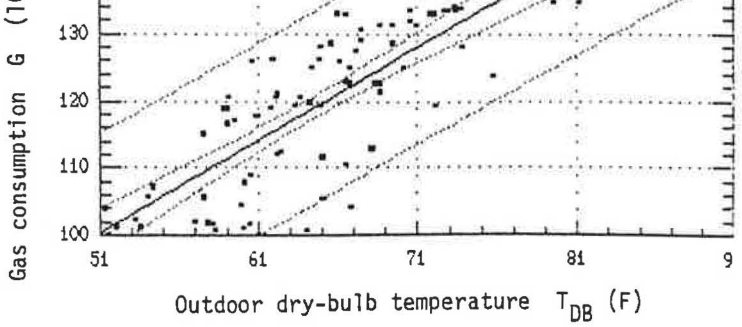

Fig. 5. Energy signature of the pre-retrofit building. Daily electrical consumption vs daily average dry-bulb temperature.

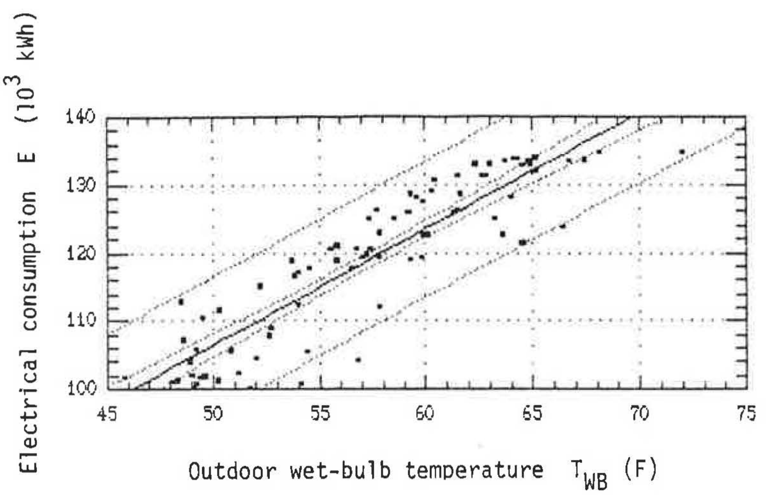

Fig. 6. Energy signature of the pre-retrofit building. Daily electrical consumption vs daily average wet-bulb temperature.

the results show differences less than 11%, when the wet-bulb temperature T_{WB} varies between 30 and 80 F (−1–26.7°C).

Hence, the energy signature based on pre-retrofit data (1981), can be used to calculate the normalized electrical consumption of the pre-retrofit building (NAC_e).

$$NAC_e = B_{L1}N_1 + B_{L2}N_4 + \begin{cases} \frac{N_2}{365N_3}\sum_{i=1}^{n}(a+bT_{WB,i}-B_{L2})\,\mathrm{BIN}(T_{WB,i}) & \text{if } T_{WB} > T_{ref} \\ 0 & \text{if } T_{WB} \leqslant T_{ref}, \end{cases} \quad (5)$$

where: NAC_e is the normalized annual electrical consumption, in 10^3 kWh; B_{L1} base level of the daily electrical consumption outside occupancy, in 10^3 kWh; B_{L2} base level of the daily electrical consumption during occupancy, in 10^3 kWh; N_1 number of days of operation at the base level B_{L1}, in days year^{-1}; N_4 number of days of operation at the base level B_{L2}, in days year^{-1}; N_2 number of days of operation of the HVAC system, in days year^{-1}; N_3 number of operation hours of the HVAC system, in h day^{-1}; BIN (T_{WB}) number of hours of occurrence of the wet-bulb temperature bin, having T_{WB} as centre, during the post-retrofit year (Table 4).

The energy signature of the post-retrofit building is presented in Fig. 7.

The difference between the normalized electrical consumption before and after retrofit shows savings of 4.18×10^3 kWh (Table 8), which are lower by 8.5% than those calculated by the DOE-2.1B program.

Use of daily average values

The base load of the electrical consumption is calculated from the winter months data and is found to be 61.00 kWh day^{-1}, as an average for occupied and unoccupied periods. The analysis of the energy signature based on the daily average electrical consumption shows (Table 7):

- large standard errors in calculating the coefficients a and b;
- correlation coefficients R^2 between 0.51 and 0.82, indicating the daily average values are more sen-

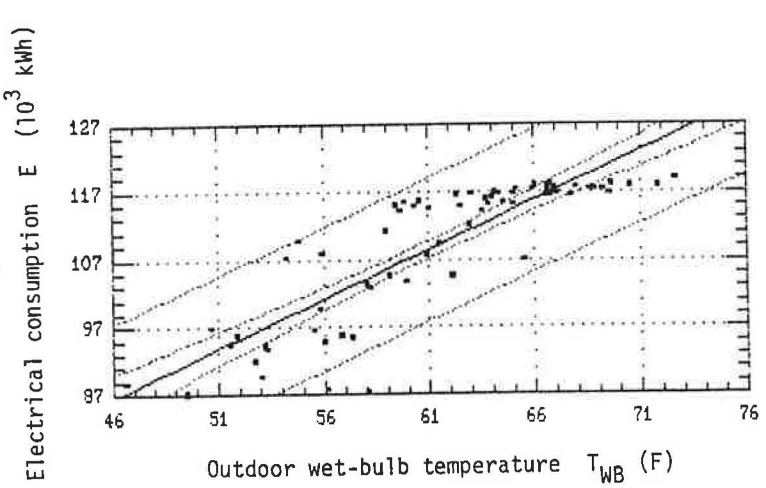

Fig. 7. Energy signature of the post-retrofit building. Daily electrical consumption vs daily average wet-bulb temperature.

Table 8. Comparison between the electrical energy savings estimated by the DOE-2.1B program and by the proposed method

	a (10^3 kWh)	b (10^3 kWh F^{-1})	R^2	T_{ref} (F)	Electrical consumption (10^3 kWh) DOE-2.1B	Proposed method
Daily values						
Pre-retrofit	21.32	1.70	0.81	28.4	28.77	26.98
Post-retrofit	19.44	1.46	0.74	28.5	24.20	22.80
Savings (10^3 kWh)					4.57	4.18
Daily average values						
Pre-retrofit	62.27	0.407	0.51	18.13	28.77	22.27
Post-retrofit	52.99	0.398	0.66	20.13	24.20	22.27
Savings (10^3 kWh)					4.57	0

sitive to the global weather conditions of a particular year;

- the reference temperature is less accurately calculated, with values between 0.95 to 36.4 F (−17.5–2.5°C).

Therefore, it is not reasonable to accept a common energy signature for these four years of analysis. However, a comparison between the estimated savings and those calculated by the DOE-2.1B program is performed (Table 8), and the results lead to the obvious conclusion that the energy signature based on the daily average electrical consumptions, which are derived from the monthly total consumptions, cannot provide reliable estimations.

CONCLUSIONS

The energy signature can be developed for one year, using the daily energy consumption and the daily outdoor temperature, and then remains constant for all subsequent years, provided that no modifications of the building envelope or HVAC systems are performed. The energy signatures of the pre- and post-retrofit building can be used along with the weather data for the same reference year to calculate the normalized energy consumptions before and after retrofit. Then the energy savings due to the building retrofit are obtained, as the difference between these two normalized energy consumptions.

This weather-normalization technique provides fast results, with acceptable accuracy. For example, the comparison presented in this paper, between the estimations of this method and those given by the DOE-2.1B program, shows that the gas energy savings are estimated within 14% of accuracy, while for the electrical energy savings the accuracy is about 9%.

Although it is easier to obtain the daily average energy consumption from the total monthly values than the daily values, these data lead to less accurate estimates of the energy signature, and then of the energy savings.

In this particular case, the linear relationship between the electrical consumption and the outdoor wet-bulb temperature provides better estimates of the energy savings, than in the case when the dry-bulb temperature is used.

This procedure can be implemented in the application software of the Energy Monitoring and Control Systems, that are already installed in several buildings. It can provide to the building manager fast and useful information about the net effect of different strategies in the operation of HVAC systems on the energy consumption.

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APPENDIX

Main characteristics of the simulated office building
Size: 75 × 30 × 11 ft

Location: Winnipeg, Manitoba, Canada

Building envelope:

- wood frame exterior wall $R = 11.86$ ft^{2}h F Btu^{-1}
- built-up roof over wood frame $R = 11.40$ ft^{2}h F Btu^{-1}
- carpeted concrete slab on grade floor $R = 10.92$ ft^{2}h F Btu^{-1}
- single pane heat absorbing glass $R = 5.5$ ft^{2}h F Btu^{-1}, shading coefficient = 0.63
- air infiltration rate 0.035 cfm ft^{-2} of exterior wall area, when supply fan is off.

Internal loads:

- 1.5 W ft^{-2} fluorescent lighting
- 0.5 W ft^{-2} receptacles
- 9 people
- domestic hot water 64 Btu h^{-1} per person.

Typical schedules of operation for office buildings are assumed.

HVAC system: A roof top unit, simulated as a packaged single zone system (PSZ) is used, and is composed of:

- direct expansion coil and reciprocating compressor (COP = 3.1)
- in-duct gas furnace
- dry-bulb temperature economizer cycle
- constant speed fan; fan is off between midnight and 7:00 a.m., Monday to Friday, and all weekends and holidays
- outside air 0.13 cfm ft^{-2} floor area.

Thermostat settings:

- 70 F heating and 78 F cooling during occupancy (Monday to Friday, from 8:00 a.m. to 12:00 p.m.)
- outside occupancy the heating starts when the indoor temperature is lower than 32 F, and the cooling starts when temperature is higher than 108 F.